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A data warehouse-based decision support system for sewer infrastructure management

Taeil Park, Hyoungkwan Kim *

Department of Civil Engineering, Yonsei University, Seoul, Republic of Korea

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ABSTRACT

Since the inception of the Governmental Accounting Standards Board statement-34 (GASB 34) in the United States, local and state governing entities need to inspect sewer systems and collect general information about their properties. Application of the collected information in decision-making processes, however, is often problematic due to the lack of consistency and completeness of infrastructure data. In addition, most techniques involved in decision-making processes are relatively complicated and difficult to implement without a certain level of engineering experience and training. Consequently, the sharing and transferring of pertinent information among stakeholders is not smooth and is frequently limited. This study presents a decision support system (DSS) for the management of sewer infrastructure using data warehousing technology. The proposed decision support system automatically assigns appropriate inspection and renewal methods for each pipeline and estimates associated costs, resulting in effective and practical sewer infrastructure management from various perspectives, with corresponding levels of detail.

1. Introduction

Currently, most municipal agencies are facing challenges regarding the deterioration of underground infrastructures due to the lack of available funds and experienced workers for renovation. According to a recent report [1], underground infrastructures in the United States are now graded D− (on a scale of A to F and I), and up to $255 billion of funding is potentially required to keep the infrastructures running smoothly for the next five years. This means that most sewer systems are approaching a state of near collapse, and undetected defects are becoming increasingly more severe. In response, government agencies are paying more attention to the implementation of infrastructure management systems, which will enable agencies to manage and improve their sewer systems more efficiently and cost-effectively.

An infrastructure management system refers to a systematic approach that optimizes the maintenance, operation, preservation and improvement of physical assets throughout their service lives at minimum cost [2]. Such systems generally include the functions of inventory of assets, condition assessment, rehabilitation and replacement, prioritization, and investment decisions. The actual structures may differ for each agency, but the inherent concepts are the same. The series of aforementioned processes are linked to one another in stages through a shared flow of pertinent data. Thus, one key to a successful infrastructure management system is how well agencies organize, analyze, and utilize an enormous amount of data to ultimately achieve desirable service delivery.

Since data obtained by the business processes of infrastructure commonly provide predictable clues about the future performances of systems that guide long-term investment plans for the inspection and renewal of structures, this data should be safely stored while still being easily accessible for further analysis. The concept of a data warehouse well satisfies these requirements. As explained by Chau et al. [3], the objective of constructing a data warehouse is to provide a system that allows proper data to reach the right end user at just the right time. Thus, the primary purpose of the implementation of data warehousing for sewer infrastructure systems is to provide relevant and timely information to the infrastructure managers in an easily understood format so that customer service decisions can be made more efficiently and effectively. To managers of infrastructures, the phrase "data warehousing" does not merely indicate an efficient tool for data integration, but also implies the materialized format of a visualized, real-time management tool encompassing project design, rehabilitation and improvements.

The expected roles of data warehousing in sewer infrastructure management systems would include reasonable allocation of resources to meet required services, projection of the overall state of sewer lines, and identification of potential risks within sewer systems. To assist with these performances, this study presents a prototype Decision Support

* Corresponding author at: Dept. of Civil Environmental Engineering, Yonsei Univ., Seoul, Republic of Korea.
E-mail address: hyoungkwan@yonsei.ac.kr (H. Kim).

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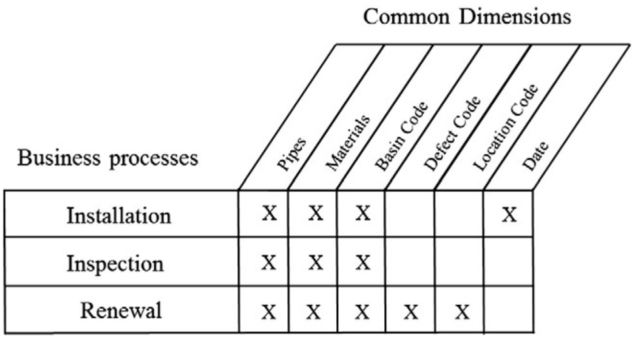


Fig. 1. Bus matrix for sewer pipe data warehouse.

Table 1
Descriptions for dimensions used in sewer pipeline data warehouse.

Name of dimension	Descriptions
Pipes	The information of the pipes dimension can be obtained during the installation process. The dimension includes pipe identification, size (diameter), length, depth, and unit type.
Basin code	Basin code has one hierarchy: basin code ➔ sewer shed. This dimension is typically assigned by geographic location.
Location code	Location code represents the usage of the area above the pipeline. This attribute is the most important to determine the proper renewal technology under given conditions
Defect code	Defect code has one hierarchy. Applications ➔ condition grade ➔ specific code. Here, application is divided into two categories: structural and functional. Structural defect includes most physical deficiency in sewer pipelines, whereas functional represents all defects affecting hydraulic capacity (serviceability) of sewer pipelines. For condition grade, one to five rating system is used; one is the best condition and five is the worst condition.
Material	Material has one hierarchy. Material ➔ material category

System (DSS) using data warehousing. Its core functions are to automatically determine the most appropriate options for inspection and renewal of sewer pipelines under specific conditions and to simultaneously estimate associated costs. Additionally, it provides utility managers with an analysis platform for comprehensive understanding of sewer infrastructure systems from various managerial points of view.

There have been recent efforts toward the development of decision support systems for renewal of pipelines in underground infrastructures, including AUTOCOP, PipeADDIN, H_2ONET designer, CARE-S, CARE-W, and SIROCO. AUTOCOP was an evaluation program that used the Analytical Hierarchy Process (AHP) and a group decision model to process the various sets of criteria and sub-criteria of the decision problem [4]. AUTOCOP was applied to the selection of suitable renewal methods through the comparison of four alternatives: open-cut, micro tunneling, pipe bursting, and cured in place pipes.

PipeADDIN was mainly composed of three models: the pipe load model, the pipe deterioration model, and the pipe break model [5]. PipeADDIN computed the loads and stresses on a water main, estimated corrosion-induced deteriorations, and assessed vulnerability based on critical safety factors in order to prioritize pipes for future renewal.

H_2ONET designer was an AutoCAD-based graphical tool utilizing a variation of the Genetic Algorithm to determine which alternative had the lowest cost while still satisfying hydraulic requirements for networks [6]. CARE-S and CARE-W were developed to assist governmental utilities in making better financial decisions by establishing multi-decision criteria including technical and economic conditions [7,8]. While CARE-W was mainly intended for larger water companies with sufficient data, the primary objective of the SIROCO initiative was the provision of a water pipe prioritization tool for small- and medium-sized water distribution companies with limited data [9]. SIROCO utilized the Weibull model and Monte Carlo simulation to estimate probabilities of pipe breaks during any given period of time.

Although these previous efforts provided advanced decision support functions for underground infrastructure management, data warehousing has been rare. Compared with other DSSs, a data warehouse-based DSS is relatively simple and easy to use. This study presents a user-friendly, computerized DSS for sewer pipe management utilizing the input of expert

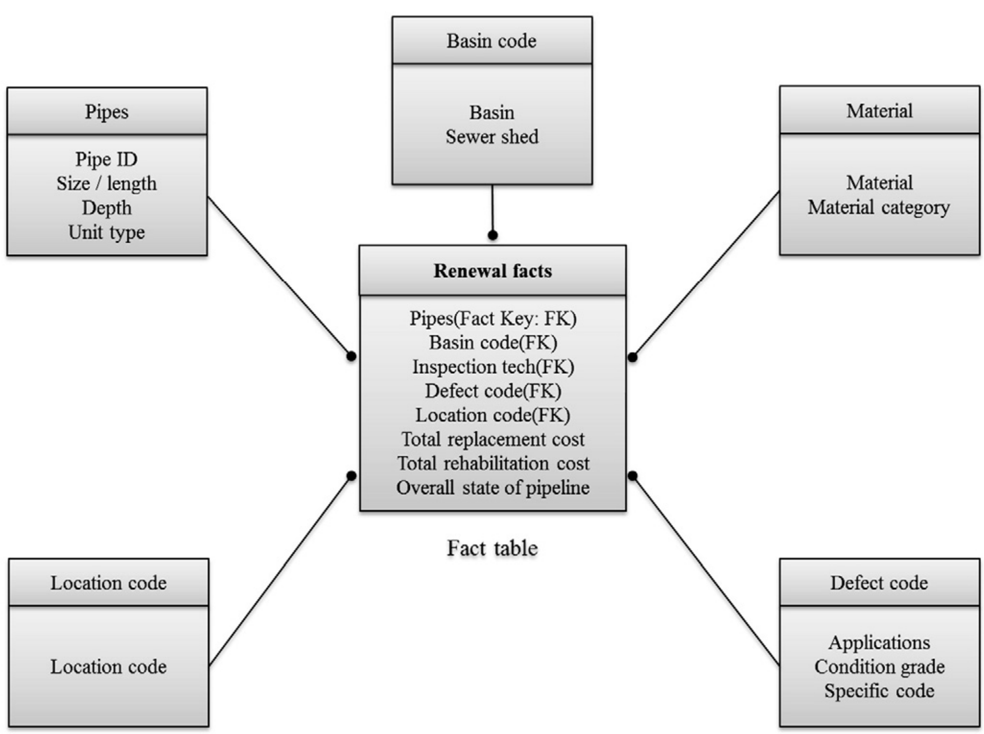


Fig. 2. A star schema for renewal.

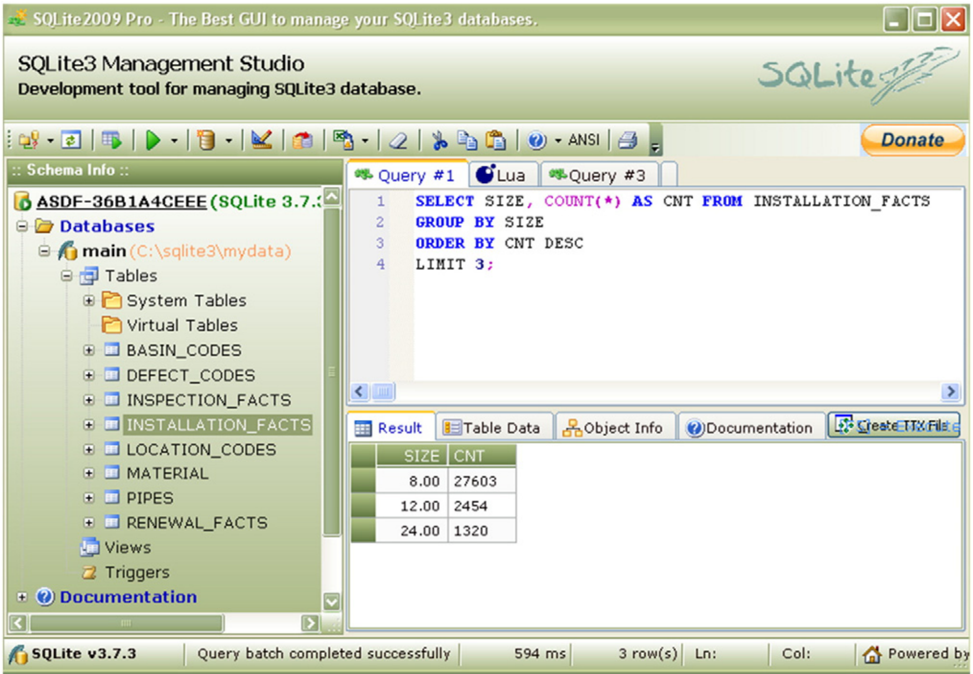
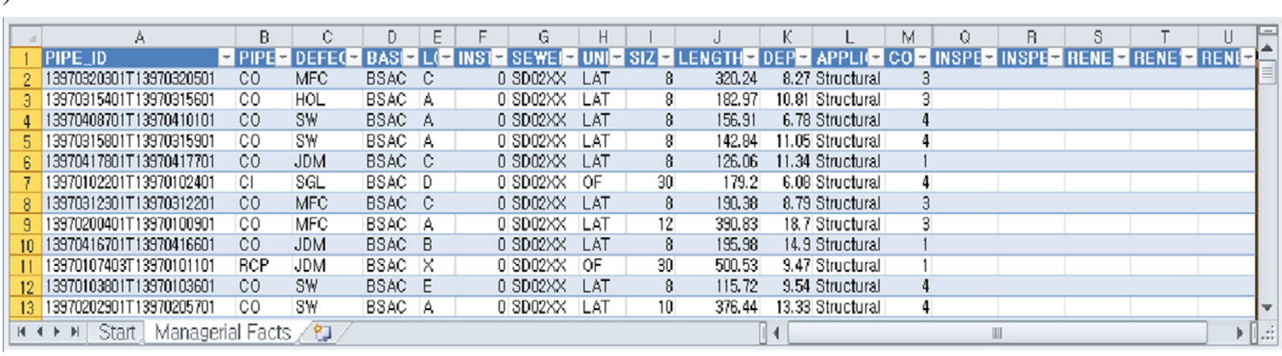


Fig. 3. Demonstration of retrieving information from data warehouse.

opinions and specifications of inspection and renewal methods within the framework of the DSS. This feature leads to enhanced applicability of the system under limited utility data.

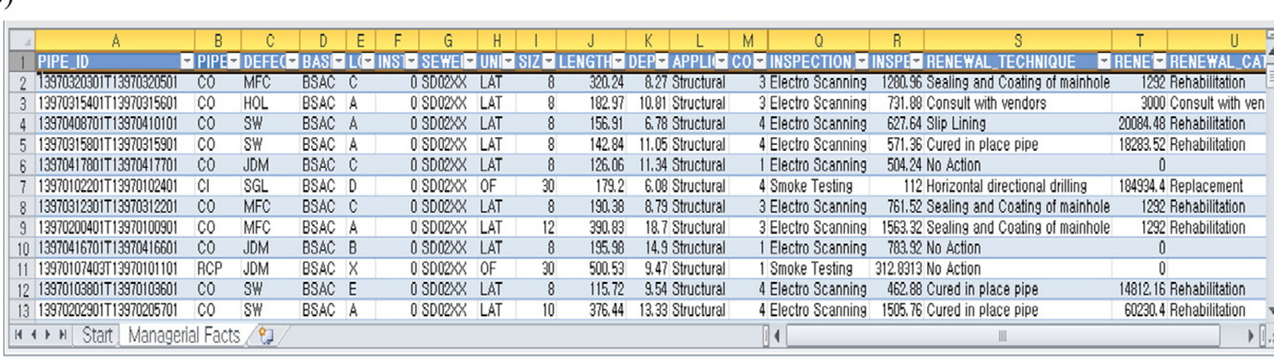
The primary objective of this research was to develop a condensed but effective sewer infrastructure management system in the form of a data warehouse. The data warehouse was combined with decision support modules to allow the intelligent processing of any given sewer management system. Accordingly, an agency could comprehensively understand its current status, estimate budgetary requirements, and easily produce ad hoc reports about infrastructures with the appropriate level of required detail; this would lead to the reduction of inherent risks over the entire infrastructure systems through the reasonable allocation of resources.

(a)



	PIPE_ID	PIPE	DEFEC	BAS	LO	INST	SEWEI	UNI	SIZ	LENGTH	DEP	APPLI	CO	INSPE	INSPE	RENE	RENE	RENE
2	13970320301T13970320501	CO	MFC	BSAC	C	0	SD02XX	LAT	8	320.24	8.27	Structural	3					
3	13970315401T13970315601	CO	HOL	BSAC	A	0	SD02XX	LAT	8	182.97	10.81	Structural	3					
4	13970408701T13970410101	CO	SW	BSAC	A	0	SD02XX	LAT	8	156.91	6.78	Structural	4					
5	13970315801T13970315901	CO	SW	BSAC	A	0	SD02XX	LAT	8	142.84	11.05	Structural	4					
6	13970417801T13970417701	CO	JDM	BSAC	C	0	SD02XX	LAT	8	126.06	11.34	Structural	1					
7	13970102201T13970102401	CI	SGL	BSAC	D	0	SD02XX	OF	30	179.2	6.08	Structural	4					
8	13970312301T13970312201	CO	MFC	BSAC	C	0	SD02XX	LAT	8	190.38	8.79	Structural	3					
9	13970200401T13970100901	CO	MFC	BSAC	A	0	SD02XX	LAT	12	390.83	18.7	Structural	3					
10	13970416701T13970416601	CO	JDM	BSAC	B	0	SD02XX	LAT	8	195.98	14.9	Structural	1					
11	13970107403T13970101101	RCP	JDM	BSAC	X	0	SD02XX	OF	30	500.53	9.47	Structural	1					
12	13970103801T13970103601	CO	SW	BSAC	E	0	SD02XX	LAT	8	115.72	9.54	Structural	4					
13	13970202901T13970205701	CO	SW	BSAC	A	0	SD02XX	LAT	10	376.44	13.33	Structural	4					

(b)



	PIPE_ID	PIPE	DEFEC	BAS	LO	INST	SEWEI	UNI	SIZ	LENGTH	DEP	APPLI	CO	INSPECTION	INSPE	RENEWAL_TECHNIQUE	RENE	RENEWAL_CAT
2	13970320301T13970320501	CO	MFC	BSAC	C	0	SD02XX	LAT	8	320.24	8.27	Structural	3	Electro Scanning	1280.96	Sealing and Coating of mainhole	1292	Rehabilitation
3	13970315401T13970315601	CO	HOL	BSAC	A	0	SD02XX	LAT	8	182.97	10.81	Structural	3	Electro Scanning	731.88	Consult with vendors	3000	Consult with ven
4	13970408701T13970410101	CO	SW	BSAC	A	0	SD02XX	LAT	8	156.91	6.78	Structural	4	Electro Scanning	627.64	Slip Lining	20084.48	Rehabilitation
5	13970315801T13970315901	CO	SW	BSAC	A	0	SD02XX	LAT	8	142.84	11.05	Structural	4	Electro Scanning	571.36	Cured in place pipe	18283.52	Rehabilitation
6	13970417801T13970417701	CO	JDM	BSAC	C	0	SD02XX	LAT	8	126.06	11.34	Structural	1	Electro Scanning	504.24	No Action	0	
7	13970102201T13970102401	CI	SGL	BSAC	D	0	SD02XX	OF	30	179.2	6.08	Structural	4	Smoke Testing	112	Horizontal directional drilling	184934.4	Replacement
8	13970312301T13970312201	CO	MFC	BSAC	C	0	SD02XX	LAT	8	190.38	8.79	Structural	3	Electro Scanning	761.52	Sealing and Coating of mainhole	1292	Rehabilitation
9	13970200401T13970100901	CO	MFC	BSAC	A	0	SD02XX	LAT	12	390.83	18.7	Structural	3	Electro Scanning	1563.32	Sealing and Coating of mainhole	1292	Rehabilitation
10	13970416701T13970416601	CO	JDM	BSAC	B	0	SD02XX	LAT	8	195.98	14.9	Structural	1	Electro Scanning	783.92	No Action	0	
11	13970107403T13970101101	RCP	JDM	BSAC	X	0	SD02XX	OF	30	500.53	9.47	Structural	1	Smoke Testing	312.8313	No Action	0	
12	13970103801T13970103601	CO	SW	BSAC	E	0	SD02XX	LAT	8	115.72	9.54	Structural	4	Electro Scanning	462.88	Cured in place pipe	14812.16	Rehabilitation
13	13970202901T13970205701	CO	SW	BSAC	A	0	SD02XX	LAT	10	376.44	13.33	Structural	4	Electro Scanning	1505.76	Cured in place pipe	60230.4	Rehabilitation

Fig. 4. Operation of decision support modules: (a) imported data from the data warehouse by clicking “Import from data warehouse;” (b) selection of methods and estimation of the costs by clicking “Decision/Estimation.”.

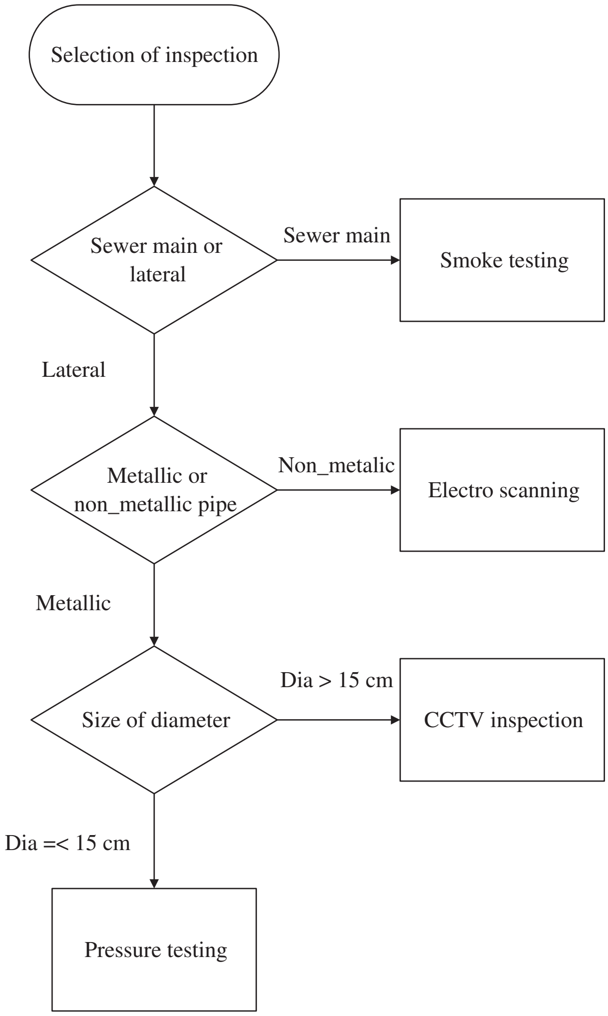


Fig. 5. Algorithm and logics for the selection of inspection techniques.

2. Evolution of data warehouses in infrastructure management

In the 1990s and early 2000s, the most frequent research topics in data warehousing were the development of conceptual frameworks, designs, and system architectures. Delvin and Murphy from IBM [10] introduced the basic concept of the data warehouse to address various problems associated with business processes and information architecture that define the flow of data from operational systems to decision support environments. Originally, operational systems were developed to support daily business operations by maintaining and updating databases for order entry, billing, accounting and payroll. Delvin and Murphy [10] pointed out the limitations of operational systems for decision support and emphasized the need for more analytical information systems. Later, researchers modified this concept into the modern data warehouse.

Inmon [11] published the book "Building the Data Warehouse" to provide fundamental characteristics, designs, structures and other features of an effective data warehouse. He established a concrete definition of a data warehouse, which is most widely used in describing the basic features of data warehouses. Codd et al. [12] introduced the idea of online analytical processing (OLAP) to resolve problems that arise from the application of operational systems for decision support. OLAP is treated differently from online transaction processing (OLTP) with regard to the size, complexity, applicability, and time horizon of relevant data. Typically, OLTP focuses on day-to-day activities such as order entries and bank transactions which store specific values for individual fields [13]. On the other hand, OLAP handles values which represent a historical view of the entity over an extended time horizon [14]. Thus, as indicated by previous studies, a data warehouse provides a summarized and consolidated view of the relevant data rather than a detailed and individual view [13,15].

In the mid-2000s, application of data warehouses in the construction industry began to emerge. Chau et al. [3] investigated the application of the warehouse in construction management and developed a prototype Construction Management Decision Support System (CMDSS) to predict future inventory patterns and trends, with less query time. The CMDSS was used in the construction project of a student dormitory at Hong Kong Polytechnic University, resulting in the conclusion that the application of a data warehouse in construction management as a decision support system was promising because it allowed for multi-view-based interactions between systems and users.

Ahmad et al. [16] developed a prototype decision supporting system using data warehousing technique to determine the most appropriate site for residential house. By incorporating the GIS software and AHP tool into the data warehouse, the authors could consider the spatial and business factors for the decision making. Rujirayanyong and Shi [17] developed a Project-oriented Data Warehouse (PDW) for contractors using client–server architecture. They categorized construction data into four groups, including performance, materials, estimates, and bidding/contracts, with 16 dimension tables and ten fact tables. The PDW was reported to have properly captured the nature of the construction business, and it served as an efficient management tool for construction data obtained during the life cycle of the facility. Fan et al. [18] proposed an equipment data warehouse linked with a web-based decision support system. The data warehouse allowed for efficient updating of the equipment data and provided a flexible and powerful environment for problem identification, problem investigation, and pattern discovery, which resulted in better management decisions. The equipment data warehouse integrated data from disparate sources and assisted users in obtaining valuable insights into equipment management from interactive analysis of discovered knowledge. Moon et al. [19] presented a cost data management system by adopting OLAP and data warehouse technologies. To consider the uncertainties in construction cost estimate, they identified the correlation between construction work item based on the probability analyses of the historical cost data. Chou and Tseng [20] applied data warehousing to estimate the maintenance costs of a transportation project in Taiwan. They constructed a data warehouse using cost data from the Taiwan Public Construction Commission and developed a prototype expert system based on statistical prediction modeling. The system estimated the total cost of the project, reflecting project design, road width, traffic volume, environmental factors, and working area.

3. Structural design for the sewer data warehouse

One of the critical processes in designing a data warehouse is to determine what data should be extracted and loaded into the data warehouse from the various data sources. Rujirayanyong and Shi [17] introduced two strategies for the identification of project data sources: the need-based approach and the availability-based approach. In the availability-based approach, any data about operational systems that is currently available is selected and uploaded to the data warehouse. The need-based approach, however, investigates the potential need for future analysis of data by considering the business nature of the system. In our study, the need-based approach was utilized to develop an optimal data warehouse to improve existing sewer management systems. This approach was chosen because, in sewer management, needs were relatively clear whereas the available data were scarce.

The next step is the structural design process. Usually, this process is composed of four steps, including selection of business processes, declaration of granularity, determination of associated dimensions,

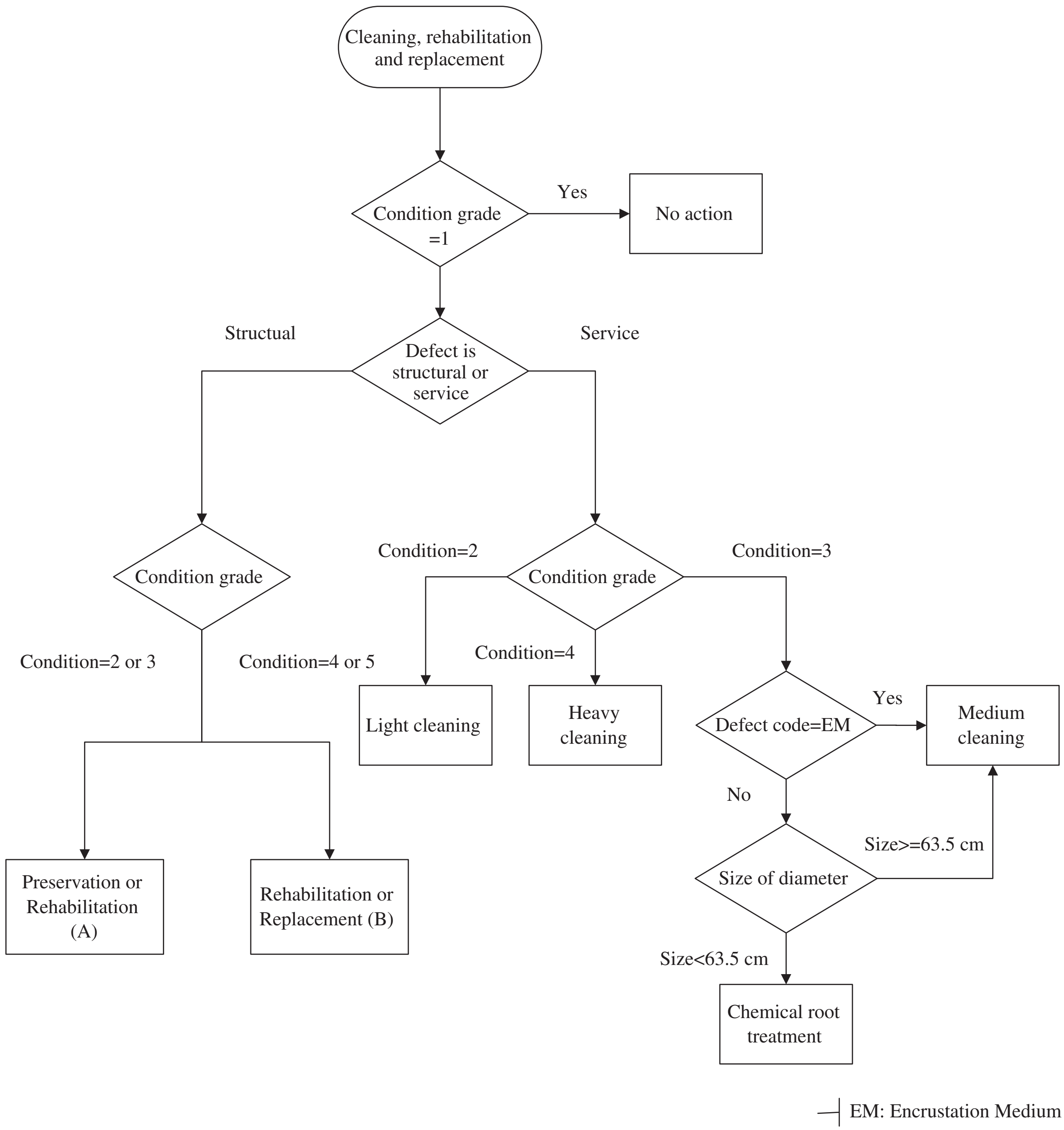


Fig. 6. Algorithms and logics for the determining renewal techniques.

and identification of the facts [21]. The selection of business processes requires understanding of business requirements and associated data for the systems. Granularity refers to the required level of detail for information stored in a data warehouse [22]. In general, the level of detail is subject to the interests of users and to the amount of relevant data collected. Once the granularity of the fact table is determined, the related dimensions are reasonably obtained based on the nature of the fact table. Facts reflect the objective of the data warehouse and, accordingly, should be composed of data useful for decision makers.

In our study, implementation of the proposed data warehouse followed the basic procedures discussed above. In the current practice of sewer management, the main business processes are installation, inspection, and renewal activities. These processes, along with the corresponding dimensions, can be represented by the data warehouse bus matrix (DWB), which is shown in Fig. 1. The data warehouse bus structure was first introduced by Kimball and Ross [21] to ensure consistency in data warehouse design. In data warehouse architecture, the matrix row represents the relevant business processes that users elect to monitor. On the other hand, matrix columns represent conformed dimensions against which business processes are measured. As shown in Fig. 1, the installation process is measured against four common dimensions, including pipes, materials, basin codes, and dates, whereas the renewal process is measured using five common dimensions.

The successful construction of a bus structure for sewer pipe management requires several aspects of effective structural design. First, the bus structure should include all pertinent business processes. The list of processes need not be limited to the three shown in Fig. 1; depending on the specific condition of the particular infrastructure, other processes, such as policy making and maintenance, may be included as needed. Second, the associated (common) dimensions should be identified and consistently standardized to avoid excessive work on the collection of data. Finally, the architecture of the bus structure should provide a foundation for useful

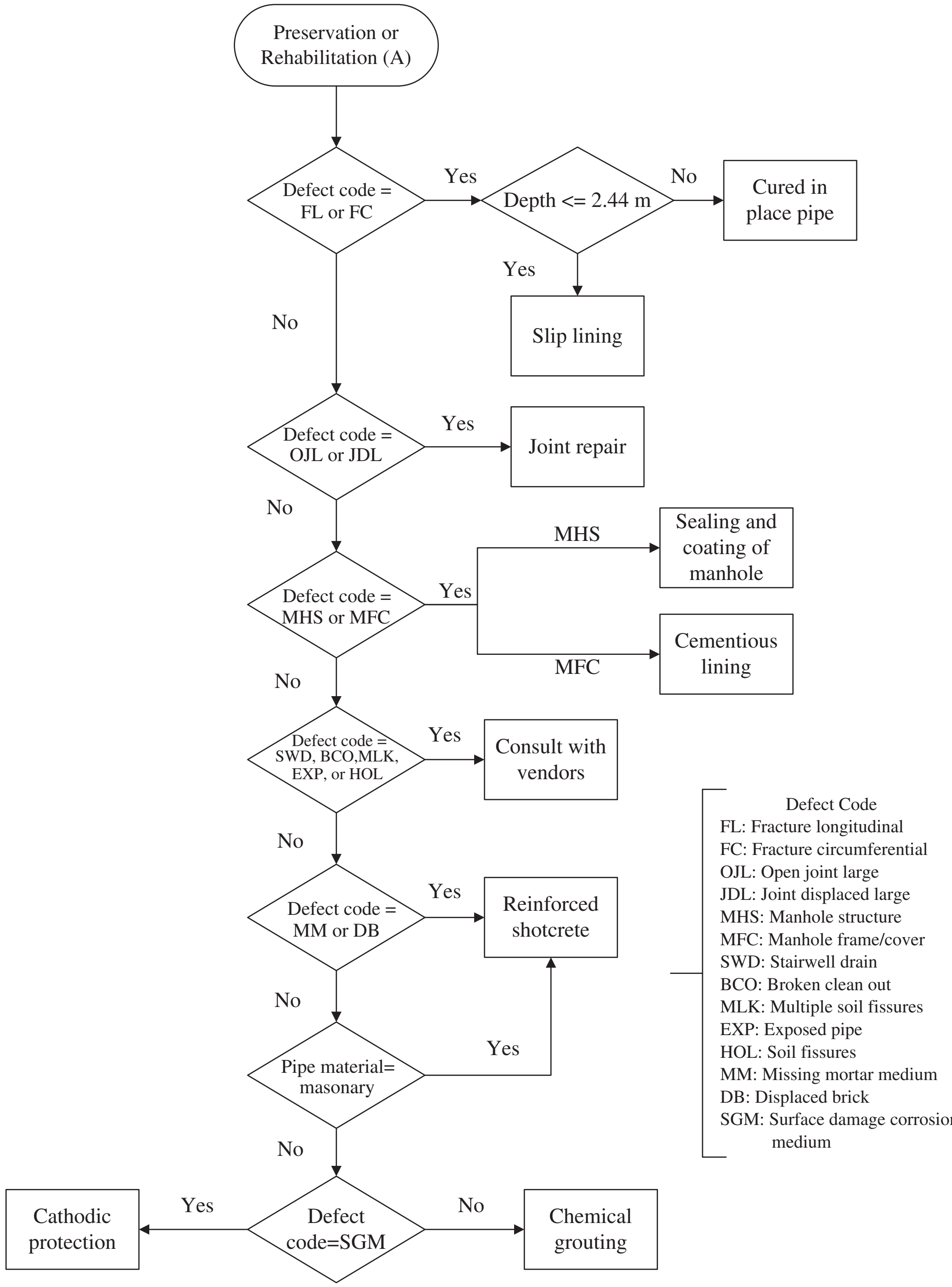


Fig. 7. Algorithms and logics for module A.

interaction among the data marts or organizations. As shown in Fig. 1, well-developed common dimensions, such as pipes, materials, and basin codes, are all shared by the three main business processes, which allows for smooth interaction and integration of sewer management processes.

4. Multidimensional modeling for the sewer data warehouse

The multidimensional aspects of a data warehouse are well represented by a star schema and a fact table which defines all related dimensions. A fact table is located at the center of a star schema and includes two types of information — dimension keys and facts [22]. In data warehousing, the multidimensionality of a star schema is often implemented by multidimensional cubes. The star schema for processes of renewal is presented in Fig. 2 and includes one fact table and five dimension tables. The fact table for renewal provides the total replacement costs, total rehabilitation costs, and overall states of pipelines. The related five dimensions are pipe properties, basin codes, location codes, material, and defect codes. These multidimensional features of the system allow for online analytical processing (OLAP) from a historical perspective. Descriptions and concept hierarchies for each dimension of the proposed DSS are summarized in Table 1.

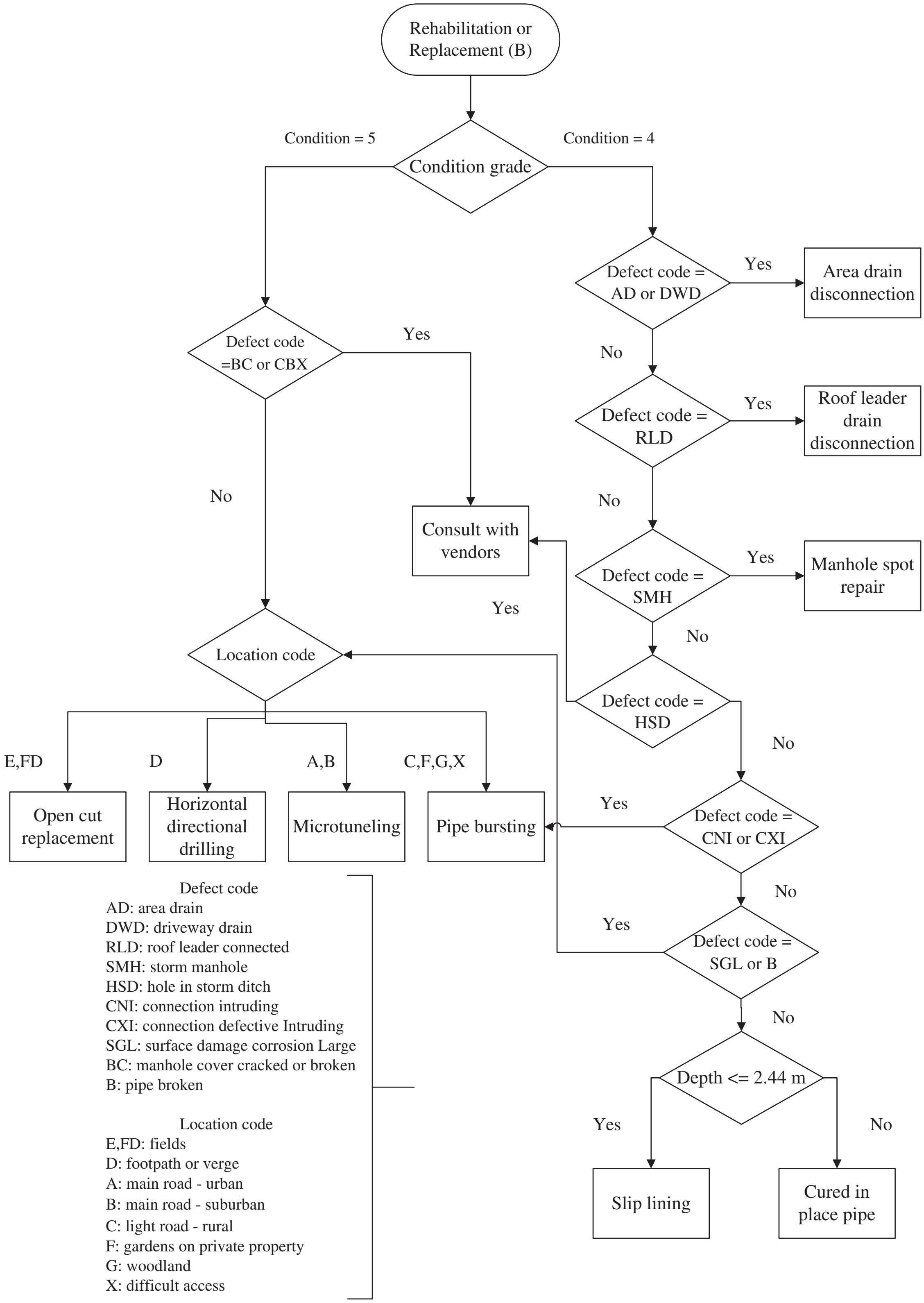


Fig. 8. Algorithms and logics for module B.

Online analytical processing (OLAP) can include multidimensional data analyses through the manipulation of data hierarchies and points of view in data cubes. These analyses are conducted via roll up, drill down, slice and dice, and rotation or pivoting operations, which enable users to see pertinent facets of the data with differing levels of granularity.

5. Development of the decision support system for sewer infrastructure

The proposed system for sewer management includes four decision supporting modules: import, decision/estimation, report, and export modules. As developed for this study, the decision support system

Table 2
Summary of the managerial reports provided by the report module.

List of reports	Descriptions
Installation	This report provides the information about when pipes were installed. The information can be grouped by sewer basins and sewer sheds. Examination of overall distributions for the age and condition of the pipelines can indicate the expected useful life of pipeline.
Pipe property	This report describes which materials and diameters are mostly used for installed pipelines. The information is grouped by sewer basins and sewer sheds. This report provides a general trend of the pipe installation and assists future scheduling for the additional installation to meet customers' demand.
Condition state	This report describes the overall status of the existing pipelines. This option assists agencies in understanding potential risk embedded within the sewer system and further establishing long-term investment plans.
Inspection planning	This report shows the inspection methods suggested by the expert system. This report assists agencies in determining which method is applicable to the given conditions.
Inspection budget	This report presents an approximate cost for the total inspection of the designated area. This feature helps agencies reasonably allocate financial resources for the infrastructure management activities.
Renewal planning	This report provides the idea about which renewal method is the most effective under the surrounding conditions. This aspect enables utility managers to plan the renewal project.
Renewal budget	This report provides agencies with the estimated costs of the selected renewal methods. Thus, the overall budget allocation for the renewal of sewer pipelines can rationally be conceived. Agencies can control the timing of investment subject to the fund availability.

was equipped with a user-friendly graphical user interface (GUI) in the Microsoft Excel environment for effective handling of infrastructure information. SQLite (structural query language) version 3.7.3 (Fig. 3) was used to implement the import and export modules of the system. Once the "import" button on the GUI was clicked, the infrastructure data stored in the data warehouse was transferred to the Excel environment. Subsequently, the "decision/estimation" module appropriately determined the most appropriate options for inspection and renewal methods without any additional support from experts. At the same time, the "decision/estimation" module computed approximate costs for inspection and renewal of each pipeline. Use of the "report" module enabled the system, with the help of the Excel pivoting tool, to provide seven different types of managerial reports for various users with diverse levels of detail. For example, a range of users, such as policy makers, project schedulers, and project engineers, could use the system at varying management levels, such as city, sewer basin, and sewer shed. Finally, estimated costs and selected methods of inspection and renewal were exported to the data warehouse through the "export" module.

Although the SQL-based data warehouse was able to accommodate and visualize valuable information, it provided limited applicability for data analysis due to compatibility issues with other software and prevalence issues for users. Thus, Microsoft Excel software was adopted in this study to overcome these shortcomings. Since Excel is one of the most widely used software for data analysis, it provides an extremely flexible environment for sewer management. Once data was exported to Excel, users could analyze the data from various points of view with built-in functions. Moreover, in the proposed decision supporting modules, the linkage between the data warehouse and Excel was easily accomplished using Visual Basic for Application (VBA) programming. As a result, the decision supporting modules provided enhanced flexibility for data analysis.

The decision/estimation module assisted decision making for the selection of inspection and renewal methods within sewer infrastructure management systems. The function of the module not only identified the most effective alternatives for inspection and renewal under given conditions, but also estimated associated costs for the techniques, as shown in Fig. 4. While most existing decision supporting tools for renewal require some additional information specified by experts to obtain reasonable consequences, the proposed DSS produced optimal results with only the information stored in the data warehouse. A type of expert system, explained below, was implemented to select optimum inspection and renewal methods. Accordingly, the DSS was able to be effectively utilized by users with relatively low levels of experience and knowledge in sewer infrastructure management.

The system grouped available renewal methods into three categories: preservation, rehabilitation, and replacement. According to GASB 34 [23], preservation activity is defined as "treatment that extends the service life of any asset beyond its original designed service life but that does not increase the capacity or efficiency of the asset." Rehabilitation and replacement methods are considered as improvement techniques which increase the service lives of assets beyond their originally designed service life and which also improve the capacity or efficiency of the assets. As presented in Table 1, the condition of sewer infrastructure was rated on a scale of one-to-five, with one being the best and five the worst. Assuming the impact of each renewal method on the condition rating, the before and after statuses of sewer infrastructure could easily be monitored. This aspect of the proposed system could assist agencies in preparing financial statements for infrastructure based on accounting policies.

The algorithms and logic of the decision supporting modules for the selection of inspection and renewal methods are shown in Figs. 5 to 8. They were mainly established on grounds of interviews, specification of methods, and previous studies. The flowchart in Fig. 5 illustrates the algorithms and logic for the selection of an inspection method. Four prevailing methods were used for inspection: smoke tests, electro scanning, closed circuit television (CCTV) inspection, and pressure testing. Based on the unit type (sewer main or sewer lateral), material, diameter and unit cost of a pipeline, inspection methods were assigned accordingly. On the other hand, the selection of the appropriate renewal method was mainly affected by the defect code and condition grades of pipelines, as shown in Fig. 6. Initially, embedded expert opinions and specifications were used to determine the condition grade of a pipeline, and no action was required when the condition grade was one. The system then identified whether the defect code was structural or functional (service). If the defect code was functional, cleaning methods were applied. If not, renewal methods were applied.

Under structural defects, preservation or rehabilitation methods were used for condition grades of two or three, and rehabilitation or replacement methods were applied for condition grades of four or five, respectively, which explains the logic of the flowchart in Fig. 6. That is, modules A and B were enabled for pipeline conditions of two or three and four or five, respectively. To this end, the in-situ applications of renewal methods will vary somewhat according to the surrounding conditions encountered at different sites. The specific algorithms and logic for modules A and B are illustrated by the flowcharts presented in Figs. 7 and 8, respectively. The logic of module A was heavily controlled by the type of defects and pipe properties, whereas that in module B was mostly affected by surrounding conditions. Since the decision module was built upon information available in most sewer management systems, the proposed system is quite applicable to a wide range of sewer infrastructure management with a high level of consistency, regardless of the level of expertise of users.

The proposed system also provided various managerial reports through the "report" module. This module will impact investment decisions in various ways. The reports generated through the module provided fundamental information required for the successful operation of sewer systems with proactive management schedules. Further, the reports facilitated reasonable resource allocation according to the availability of funds. Detailed descriptions and benefits of the reports are summarized in Table 2. When users clicked the report module, a

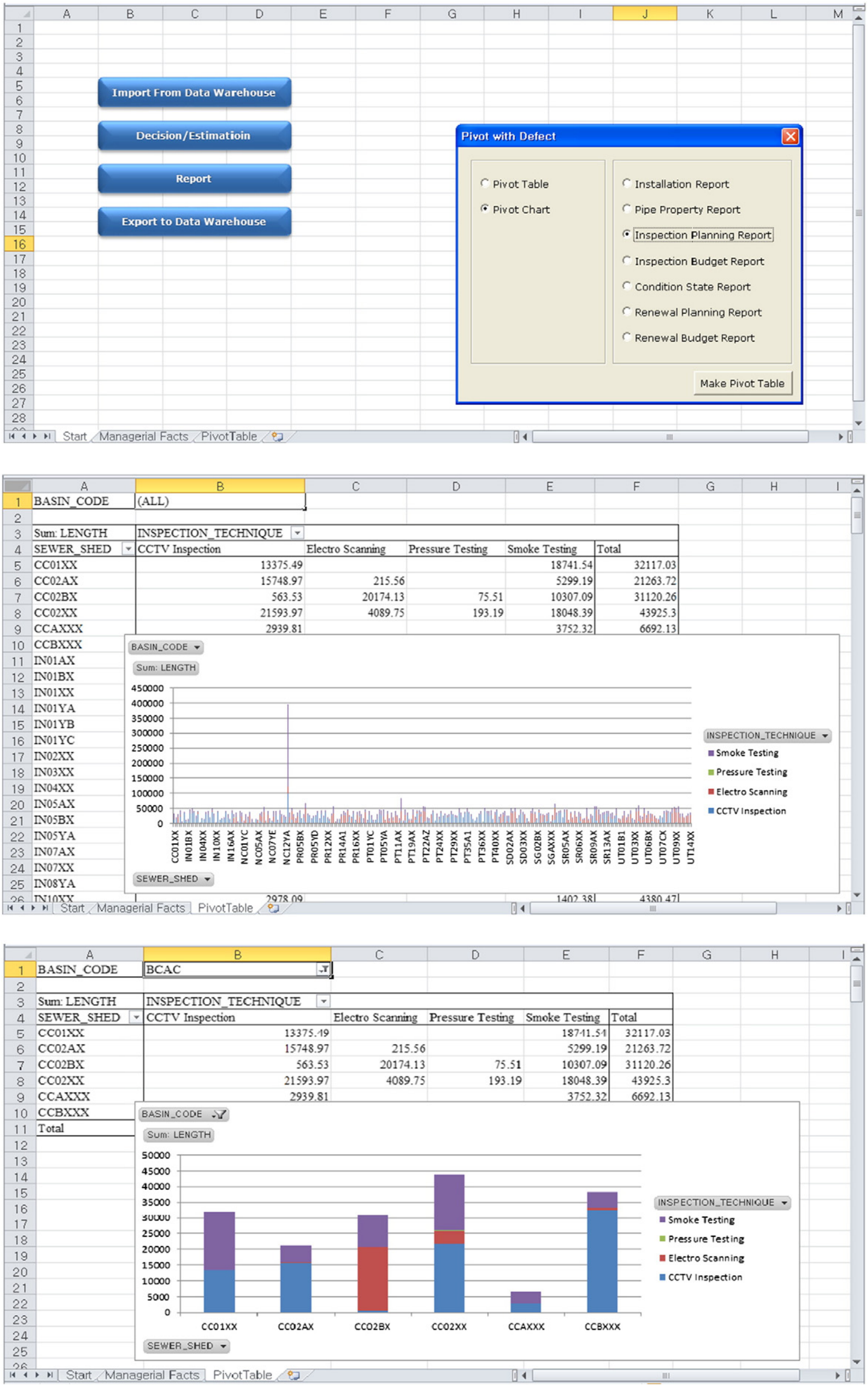


Fig. 9. Demonstration of the reporting function and the result with different level of detail.

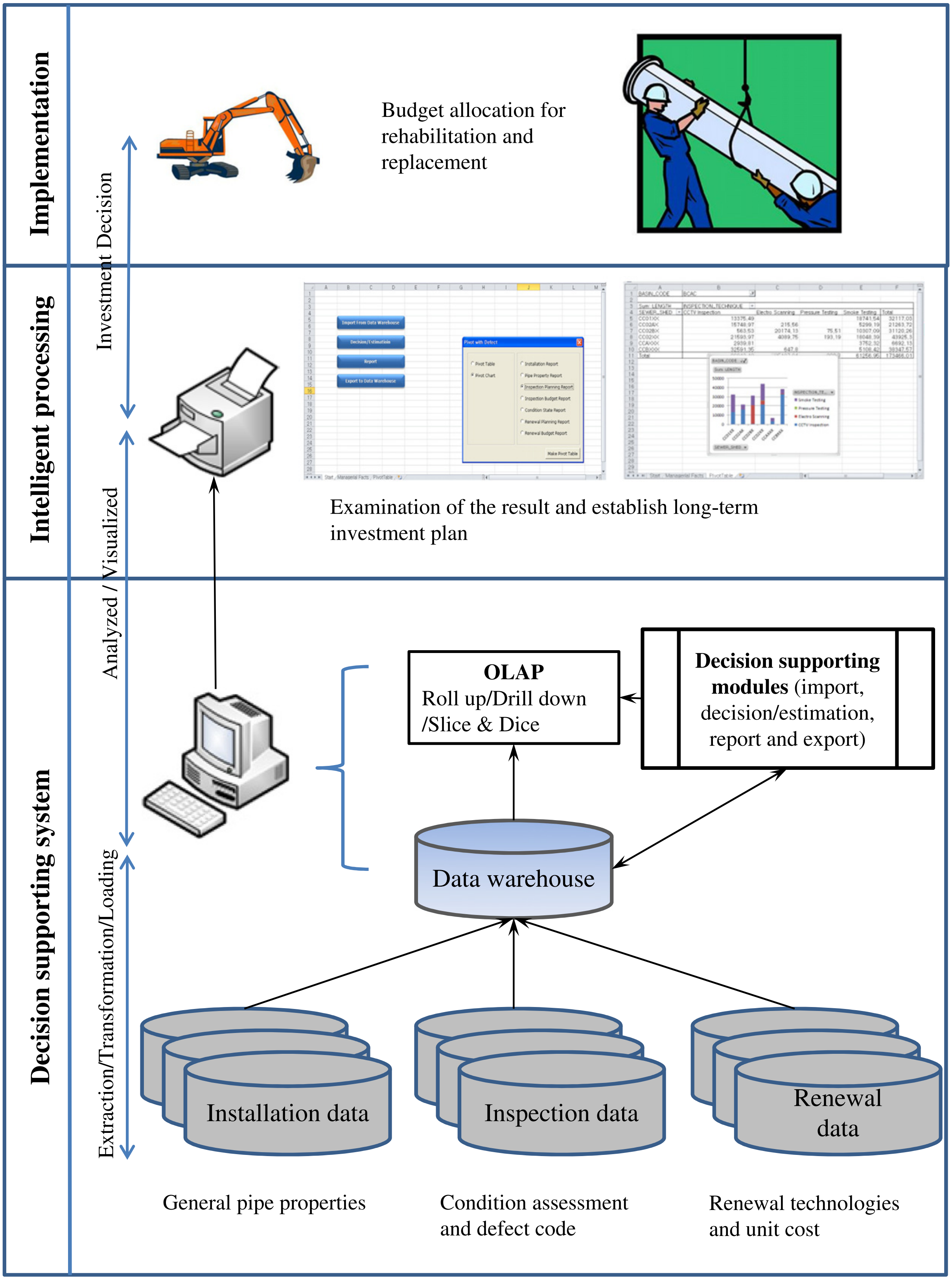


Fig. 10. Overview of the information flow within sewer infrastructure management system.

pop-up window displayed the range of options for managerial reports. Utility managers simply needed to choose the report best suited for any particular case after understanding the various objectives of the options. Moreover, as emphasized by the multidimensional modeling, the reports could be viewed from different perspectives with different levels of detail, thanks to the pivot table function. Execution of the aforementioned processes is presented in Fig. 9.

The "export" module enabled users to prepare an updated data warehouse. This module exported the information determined by the decision supporting modules back to the designated fact tables.

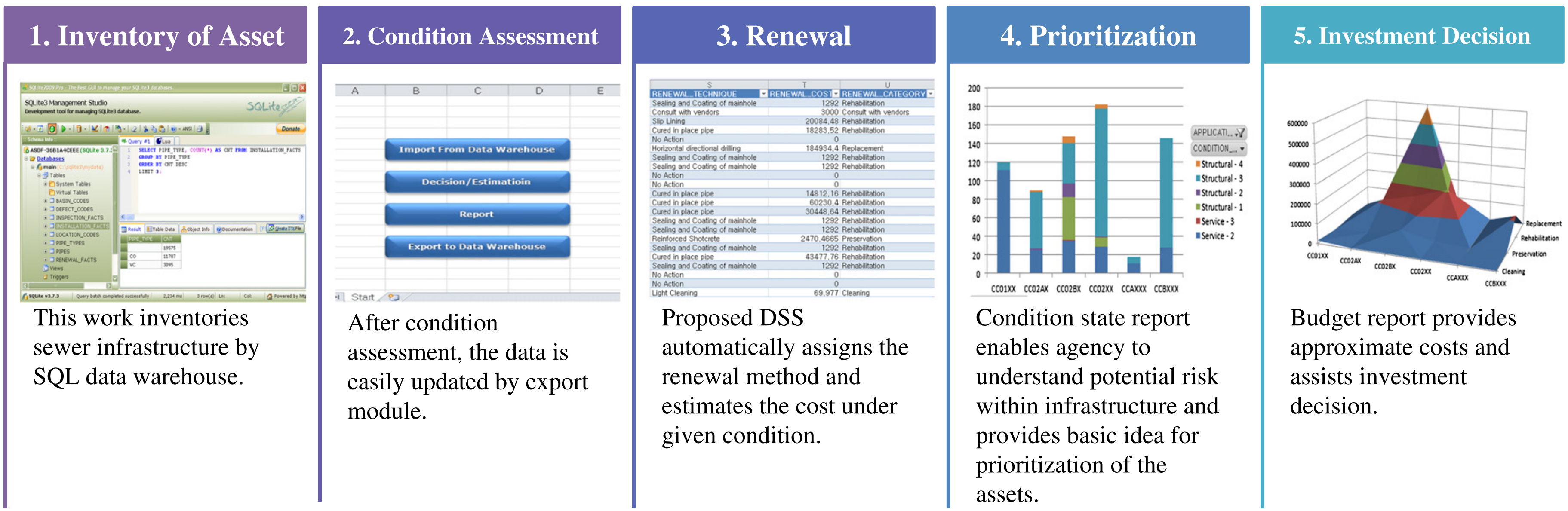


Fig. 11. Potential benefits toward the existing infrastructure management system.

After operation, users could retrieve the newly updated information from the predefined fact table. In addition, this module functioned to allow users to easily upload information about newly installed pipelines or the most recent data on assessment of conditions.

Fig. 10 shows information flow within a sewer infrastructure management system. Installation, inspection, and renewal data constitute the data warehouse, which was connected to the decision supporting modules. In the traditional sense of the three-tier database structure, the report module corresponds to an application program, while the decision supporting modules are likened to a database management system that accesses the data warehouse. The decision supporting modules combined with the data warehouse enabled resourceful OLAP. As a result, the system promoted an intelligent management of sewer infrastructure, based on statistical facts as well as the expertise of experienced engineers.

6. Potential benefits for existing sewer infrastructure management systems

This study accomplished the development of an effective sewer management system with improved analysis, information storage and retrieval, and visualization capabilities. Currently, most agencies have their own data formats. The attributes of collected sewer data and structures of databases vary by agency, and excessive redundant detail often exists in such databases. In addition, construction of a computerized sewer infrastructure management system requires extensive time and resources. As discussed, by constructing a standardized data warehouse, utility managers could significantly reduce the burden of collecting unnecessary information for inventory. They could also easily retrieve managerial information from various points of view according to user-defined levels of detail, and further achieve effective data management for sewer infrastructures. Consequently, the proposed DSS could provide stable but flexible storage of valuable information, reduce subjectivity in decision-making processes, accelerate the pace of data flow, and result in a better environment for strategic operation of infrastructure. In this regard, the expected benefits of the implementation of the proposed DSS are:

- Effective scheduling of long-term investment plans for inspection and renewal
- Reasonable allocation of financial budgets for inspection and renewal
- Improved consistency in decision-making processes
- Consistent decisions regardless of varying levels of user expertise
- A data-driven guide for the application of inspection and renewal technologies
- A portfolio of user-demanded managerial reports

Potential benefits of the proposed data management system for existing processes of sewer infrastructure management systems are presented in Fig. 11.

7. Conclusions

This study presents a simplified decision support system with the combination of a data warehouse and decision supporting modules. Efficient data structures, such as the bus matrix and star schema, were suggested in the optimal data warehouse for sewer infrastructure management. The data warehouse was connected with the decision supporting modules for strategic decisions about the inspection and renewal of pipelines, and the decision/estimation module determined the appropriate inspection and renewal methods as well as the associated costs under given conditions.

The VBA and Excel platforms provided a simple but powerful environment for data analysis. Despite the simplicity of the system, it could perform an outstanding job with general infrastructure information, such as pipe properties and defect codes, which were readily accessible for most agencies. In addition, the system could easily be utilized without arduous training or high-level expertise about the processes or structure of the system. However, the proposed system has some limitations. First, the decision criteria for the selection of inspection and renewal techniques may have to be refined to satisfy the particular site conditions of the infrastructure. For example, applicability of the techniques according to material types and diameter range needs to be verified and reflected in the system based on the most up-to-date information. Second, the proposed system currently recognizes only one defect in each pipeline. The proposed system may not be effective in the case where the pipeline has more than one defect and each defect should be handled with a different technique. Considering these deficiencies, further study is required to improve the applicability and accuracy of the system based on more real-life data. The proposed system is expected to significantly advance current practices of investment decisions for sewer infrastructure management, especially when the database is periodically updated for a comprehensive list of available inspection and renewal techniques, vendors, and prices.

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