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A GIS-Based Decision Support System for Optimal Renewal Planning of Sewers

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Abstract

This paper discusses the development of a GIS-based Decision Support System (DSS) to support the renewal planning of sewer networks. The approach involves several steps addressing condition rating, risk assessment, and prioritization of sewers. It also incorporates a procedure for identifying and selecting the most suitable renewal technologies. A genetic algorithm (GA)-based multi-objective optimization technique is used to identify a set of feasible solutions, along with the associated costs and expected benefits in terms of condition improvement and risk reduction.

Keywords
Sewer networks, asset management, renewal planning, optimization.

Introduction

The sewer renewal planning process remains fundamentally heuristic and subjective in nature, and is still largely considered as much an art as it is science. The process is mainly documented in the form of guidelines or manuals of best practices, e.g., WEF and ASCE (1994), WRc (2001), and InfraGuide (2004). However, the application of these guidelines varies significantly between different municipalities, and few or no standards have been defined for performing most of the activities involved. As a result, the renewal planning has been typically performed in a manual and subjective manner, with limited or no software support.

A survey of commercial asset management software (Halfawy et al 2006a) concluded that the vast majority of existing systems focus primarily on managing day-to-day operational activities (e.g., issuing and tracking work orders, recording of service requests, etc.) and that commercial offerings of renewal planning software are very limited. This could be mainly attributed to: the lack of systematized, standardized, and quantitative models (e.g., deterioration, risk, prioritization, and optimization models); and the lack of adequate reliable data sufficient to support the application of such models. The need to systematize the renewal planning practices and to develop more standardized and integrated software solutions are widely recognized.

This paper proposes a new step-wise integrated approach that could potentially assist municipal professionals in developing optimized renewal plans that would identify the most appropriate renewal actions, while simultaneously optimizing the renewal costs, condition state, and risk of failure of the sewer network. The approach defines a systematic procedure to quantitatively assess and evaluate the costs and benefits of alternative renewal options, which

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helps reduce the subjectivity typically employed in the decision-making process. The implementation and example application of a GIS-based DSS are also presented.

Software Tools for Renewal Planning of Sewer Networks

Significant investments have been made in developing and deploying software tools to support various sewer renewal planning activities. Examples of these tools include Harfan and RIVA, among others (Halfawy et al 2006a). Another software in this category, which is less common in North America, is AQUA-WertMin (AQUA-WertMin 2007, Baur and Herz 2002). However, the use of these tools by municipalities is still rare, which may be attributed to the high cost and technical requirements for customizing and deploying these tools.

Many municipalities and consulting firms have also developed their own in-house renewal planning software to conform to their work practices and specific data and process requirements. Most of these tools are developed by customizing general-purpose tools such as spreadsheets, DBMS, CAD, or GIS software. Examples of such tools include UMA's sewer management system (SMS) (Homeniuk and Croft 2005). Halfawy et al. (2000) also described the development of a GIS-based software that supported integrated management and assessment of sewer networks inventory, condition, and hydraulic data.

Several decision models and software prototypes have also been reported in the literature. Many studies have proposed models to predict and assess sewer deterioration rates, risk of failure, asset prioritization, and selection of possible rehabilitation options. Most notably, the Computer-Aided Rehabilitation of Sewer Networks (CARE-S) research project (CARE-S 2007) was an international collaborative effort to develop a comprehensive suite of tools to support the renewal planning activities. Ariaratnam and MacLeod (2002) proposed a proactive rehabilitation infrastructure sewer management (PRISM) model that used linear programming to optimize allocation of funding for maintenance and repair of the sewer network. Abraham et al (1998) proposed an integrated sewer management system that used probabilistic Markovian deterioration models and deterministic dynamic programming to optimize the selection of sewer rehabilitation techniques. Fenner and Sweeting (1999) described a decision support model for rehabilitating non-critical sewers by using sewer performance and GIS data to rank variably sized grid squares into priority zones for rehabilitation action. Kleiner (2001) defined a semi-Markov process to model asset deterioration and a decision framework to optimize the scheduling of rehabilitation and inspection of large buried assets (e.g., trunk sewers). Fenner (2001) presented a review of several techniques employed in a number of countries for optimizing and prioritizing sewer rehabilitation strategies.

The Proposed Approach for Renewal Planning of Sewer Networks

The renewal planning problem can be defined as follows: what are the renewal actions (what assets to rehabilitate or replace, what methods to use, and when) for a specific planning horizon that would optimize the allocation of renewal budget by maximizing the network's average condition and minimizing risk of failure, subject to condition, risk, and budget constraints. This problem is tackled by adopting a step-wise algorithm where multi-year plans are optimized on a year-by-year basis. A typical plan establishes, for a given year and for each sewer segment, the most appropriate and cost-effective renewal action, if any. A plan would be used to update the sewers condition and risk levels and to develop renewal plans for subsequent years.

The proposed approach generates renewal plans on a segment level (i.e. manhole to manhole). The algorithm starts by classifying and subdividing the network into a set of homogeneous groups of sewers in terms of their current condition and deterioration pattern as well as their criticality (or expected consequence of failure). Then, for each group, a renewal plan will be developed for each planning period (e.g., one or more years). At the beginning of each period, sewer condition indices are re-evaluated using the deterioration model, taking into consideration any renewal actions that have been planned in previous years. The condition indices and deterioration models are used to estimate the remaining service life and calculate the likelihood of failure index. The consequence of failure is then determined, which, together with the calculated likelihood of failure index, is used to estimate the sewer risk levels.

Based on the condition and risk levels, a list of sewers prioritized according to their urgency of intervention is prepared. For each sewer on the priority list, the most feasible and cost-effective renewal actions are selected based on their technical and economical merits. These renewal actions are optimized, and a set of feasible optimal renewal plans is generated. The plans are further evaluated according to the budget constraints as well as their projected impact on the overall condition and risk levels. The decision-maker can carry out several iterations to evaluate alternatives and study the impact of various decision parameters until a renewal plan that meets all objectives and constraints is composed. The renewal plan is then applied in the form of delta tables to update the condition of the sewers for the following planning period. In multi-year planning scenarios, this process is repeated for every period in the planning horizon.

Software Implementation and Example Application

An integrated and modular sewer management software environment has been under development in collaboration with the City of Regina, Saskatchewan, Canada. More details about the software architecture, data and process models and software architecture can be found in Halfawy (2007) and Halfawy and Figueroa (2006c). The renewal planning application was implemented as a set of loosely coupled modules; each addresses one stage of the renewal planning process outlined above. Each module was implemented as an add-on to ESRI ArcGIS software. The modular architecture of the application would facilitate future enhancement and extension of the application.

Sewer renewal planning requires access to a multitude of data about the network inventory, condition, risk criteria, renewal methods, etc. Efficient representation, management, and sharing of these data sets can be efficiently supported through the use of a centralized integrated data repository (Halfawy and Figueroa 2006c). Accessing the data repository through a GIS interface significantly enhances the ability to explore, access, query, and edit data.

The software was designed to allow for easy customization to the specific practices and rules used in a particular municipality. All data and settings that can be considered as municipality-specific (e.g., prioritization rules, criticality factors and weights, costs of renewal methods, etc.) were not hard-coded into the software and were stored in an external database for possible editing. For example, information about various renewal methods is stored in a database that can be customized to the specific practices and data available at a particular municipality.

The prototype software was tested by developing a renewal plan for a group of sewers in the City of Regina, Canada. The City has an inventory of approximately 860 km of sanitary sewers and 755 km of storm sewers. Figure 1 shows the prototype GIS interface. The network was subdivided into a set of homogeneous groups. This example demonstrates the development of a renewal plan for one year (2008) for one of these groups using actual data as recorded in the City database. The group was defined to include vitrified clay sanitary sewers, with 200 mm diameter, and constructed between 1950 and 1955. This group included 249 sewer segments with a total length of 19.86 km. Only 39 sewers in this group were previously inspected and rated. The condition indices as recorded in the database were found to vary significantly, 2 sewers in condition state 1 (0.1 km), 17 in condition state 2 (1.5 km), 9 in condition state 3 (0.8 km), and 11 in condition state 4 (1 km).

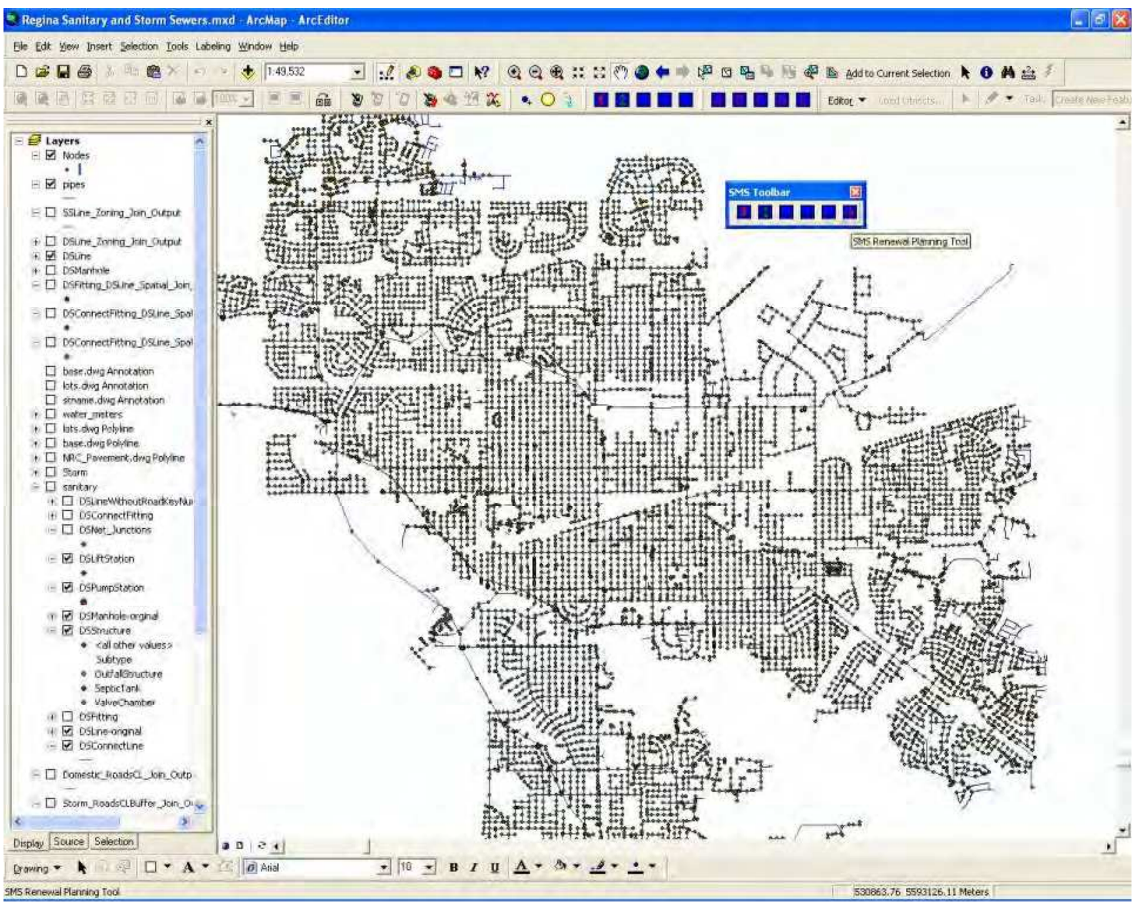

Figure 1: GIS interface of the sewer renewal planning DSS

Fitting a deterioration curve to the set of the condition data points can be performed. By analyzing data collected from several Canadian municipalities, a set of deterioration curves was developed by Newton and Vanier (2005). A database of these models was created and used to check if any previously defined curves approximately fit condition data for a particular group. If a sewer has two or more inspection records, a deterioration curve could be defined specifically for that sewer. However, in actual practice, adequate condition data to define deterioration curves for individual sewer segments are not available, and approximation and judgment are typically used to compensate for the data inadequacy. In this example, a deterioration curve from the library was found to reasonably fit the data points.

The deterioration curve is used to estimate the condition index of the sewers in the target year (2008). Although the deterioration curve indicates the average rate of sewer deterioration, individual sewers within the same group may exhibit different condition states at similar ages, which is evident in this particular group. Therefore, the prediction of future condition of a sewer should take into account the specific condition data of a sewer, if any is available. Once the sewers condition indices for the target year are predicted using the deterioration model, the remaining service life and likelihood of failure index can be established. The remaining service life is estimated as the number of years until a sewer reaches condition state 5, and the likelihood of failure index is the ratio between the sewer age at the target year and its age when it reaches condition state 5.

Next, the sewer risk indices are calculated. To simplify this calculation, sewers can also be grouped according to their criticality criteria. Similar to condition groups, sewers with similar criticality levels are grouped into risk groups. Applicable criticality criteria can be selected and weights and ratings assigned. The risk factor, which indicates the "level of criticality" can then be calculated. The risk indices are subsequently calculated by multiplying these risk factors by the likelihood of failure index calculated at the previous step. In this example, the sewer risk indices were found to range between 2.0 and 3.5.

Once condition and risk indices are determined for all sewers in the group, prioritization rules are applied to establish the "priority index" for each sewer. For the 249 sewers in this group, 11 sewers were found to need immediate intervention (priority index =5), no sewers with high priority (index = 4), 8 sewers with medium priority (index = 3), 230 sewers with low priority (index = 2), and no sewers were found to need no renewal action (index = 1). Sewers with priority index of 3, 4, and 5 are then considered for possible renewal actions.

The renewal methods selection procedure starts by identifying the applicable renewal category for each sewer, and retrieving the methods within these categories from the renewal technologies database. This database stores default information about renewal methods including their limitations (diameter range, soil type, pipe material, etc.), expected condition improvement, and cost. The default cost and improvement values are specified for each condition grade, since these values would depend on the type and severity of the defects. The user can eliminate some renewal methods or override their default values as they apply to a particular sewer or sewer group. For each sewer in the group, the system will then evaluate the applicability of various renewal methods and calculate costs and condition improvements.

The GA-based MOO module was developed using the Open Beagle library (Open BEAGLE 2007), and used to identify the Pareto fronts for the two main optimization criteria: condition-cost and risk-cost criteria. In this particular example, this calculation lasted for approximately 3 hours on a dual processor Pentium 4 (3.2 GHz) computer. The optimal solutions are further evaluated against the budget constraints as well as the minimum acceptable condition and risk levels ((i.e., weighted average) for the group. In this example, a budget scenario was given ($0.1-0.5 Million), and a total of 111 possible solutions were found to meet both condition and risk constraints. Figure 2 shows the cost-condition and cost-risk Pareto fronts between the minimum and maximum budget limits. For example, one solution (highlighted) with a total budget of $483,943 indicated that 11 sewers (with condition index of 5) would be replaced (total length = 0.95 km), while one sewer (with condition index of 3) will be lined (0.04 km). This solution will result in improving the average condition and risk indices of the group from 3.09 and 2.55 to 2.9 and 2.4, respectively. A decision maker may evaluate the impact of budget, condition, and risk constraints on the set of selected solutions, and experiment with different scenarios until a satisfactory solution is found. Scenarios may also be analyzed to show the relationship between the sewer system average condition/risk levels and funding levels (i.e. predict how different levels of funding would affect the overall network condition).

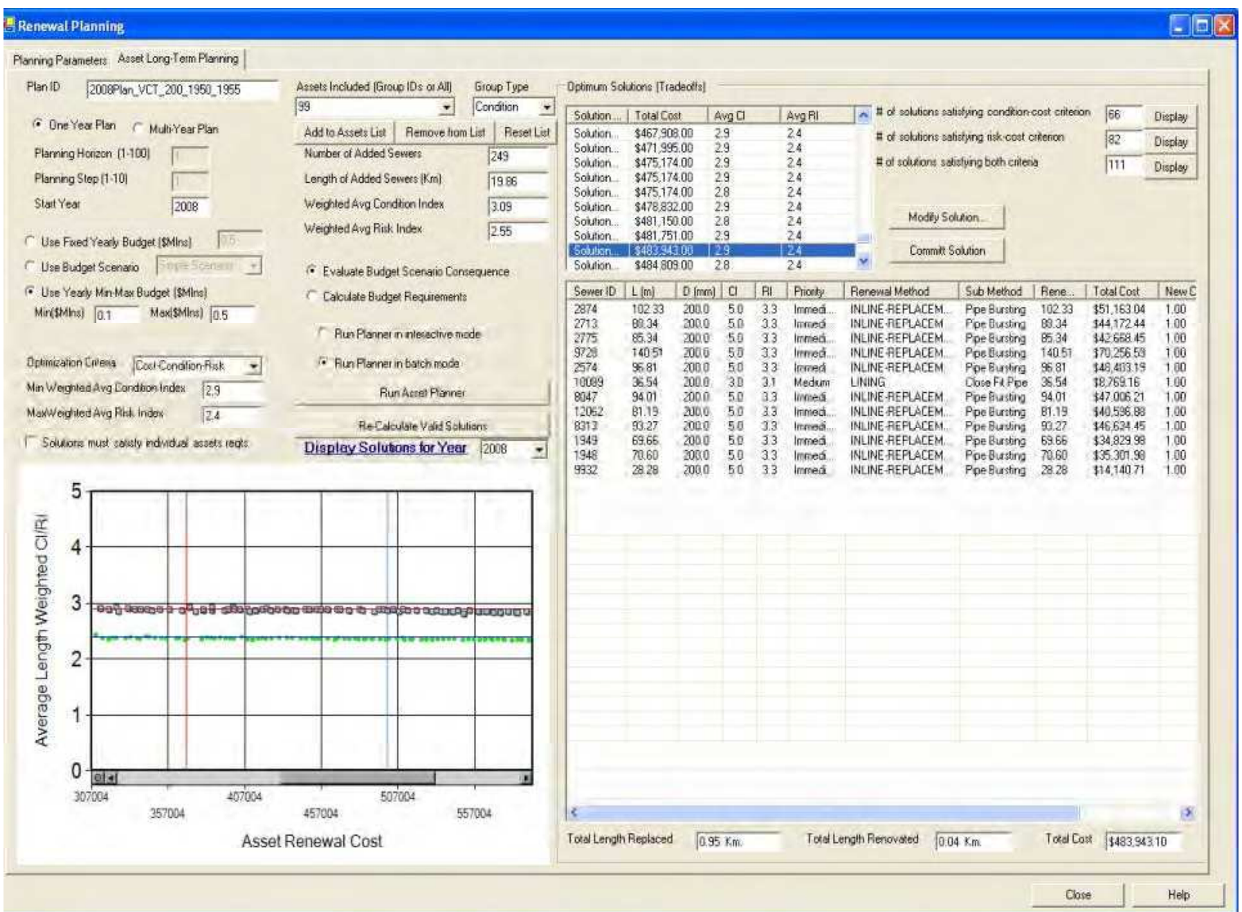

Figure 2: Cost-condition (red) and cost-risk (green) Pareto fronts and lists of valid solutions

Conclusion and Future Directions

This paper presented the development of a GIS-based software for optimal renewal planning of sewer networks. The software can potentially play a critical role to improve the planning and management of sewer networks. Although the proposed approach employed several simplified models (e.g., for risk assessment), it provided a framework and software tools for practitioners to systematize and optimize the renewal planning decisions. The approach integrated the three main criteria in the planning process: condition, risk, and cost. It also incorporated procedures for the evaluation and GA-based multi-objective optimization of renewal methods. The approach can be used to support short and long term planning scenarios, as well as network-level and project-level planning. To efficiently implement the proposed algorithm, an integrated data model was developed. The data model supported the integration and management of sewer data and enabled data sharing and exchange between various activities and software tools. A proof-of-concept GIS-based software was also developed and demonstrated using the City of Regina data.

In light of this study, some directions for future research can be identified. Substantial work still needs to be done to refine and extend the approach and fully develop the software. An obvious extension is the use of sewer hydraulic performance, in addition to structural condition, in asset prioritization, selection of renewal methods, and in the assessment of pre- and post-rehabilitation performance. Through industrial partnerships, the approach and software are currently being refined, tested, and validated.

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