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Development of a Waste-to-Energy Decision Support System (WTEDSS)

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Abstract

Rapid increase in urban population has created the need for the development of efficient Decision Support Systems (DSS) guiding municipal planners to mitigate urban sprawl, pollution and waste generation, unsustainable production and consumption patterns. To ensure sustainable urban planning, a DSS must provide not only an optimal planning solution based on input assumptions, but must also help to identify concrete city challenges, determine available resources (e.g., land and energy sources) and highlight any implementation constraints. It must support the creation of flexible interactive scenarios for urban development and their realistic representation in an urban context.

This paper presents a Waste-to-Energy Decision Support System (WTEDSS) that identifies the optimal long-term deployment strategy for waste-to-energy infrastructures under future uncertain operational conditions and then directly assesses its feasibility and integration into an urban environment using 3D visualization. The WTEDSS is designed as an interactive and analytical waste management planning tool integrating four modules: data analytics, optimization, simulation and a user-friendly graphical interface. Emphasis is placed on the development and integration of the optimization module and 3D urban simulation, which provides users with decision support based on 3D visualized optimum facilities deployment plans. The optimization module receives calibrated data and solves a model based on inputs obtained from the user interface. The simulation platform developed in Unity 3D provides a friendly real-world environment for studying and understanding the facility deployment process over time and space, while also considering uncertainty.

Keywords

Waste-to-energy, optimization, decision support system, Unity, game-based platform

1. Introduction

The amount of municipal waste produced around the world is accelerating along with the rapid rise in population and industrialization. According to the World Bank report *What a Waste* [1], solid waste generation by the world's cities will increase from about 1.43 billion tons per year in 2012 to about 2.43 billion tons per year in 2025, and the number of people living in cities by 2050 will be equal to the population of the whole world in 2000. Waste is a by-product of urbanization. To avoid "urban-mining", it is urgent and necessary for cities to improve municipal waste management (MWM) performance with effective systems and efficient strategies.

Besides the challenge of increasing waste volume, urban planners also face the problem of sustainable development. An unsustainable waste system may pass the impact of waste disposal on to the next generation, and it requires more resources than the waste system can produce on its own [2]. To ensure the sustainability of MWM systems, special attention has been paid to waste-to-energy (WTE) technologies [3]. WTE technologies convert non-recyclable waste to useable heat, electricity, fuel, bio-energy and compost products, simultaneously solving the waste increase and fossil energy exhaustion problems [4]. When making decisions for long-term deployment plans, municipal planners should not only focus on technology selection, but also consider economic factors (fixed capital cost, operating cost and revenue of recovered resources), social influence (e.g. system safety, land use) and environmental aspects (e.g. emissions, energy production) [5]. Thus, a Waste-to-Energy Decision Support System (WTEDSS) for WTE infrastructure configuration is instrumental and crucial for municipal planners to achieve sustainable MWM systems.

Decision support systems (DSS) are computer-based applications that perform information analysis, system modelling and simulation to help users make decisions. For the past decade, DSS and similar integrated information

systems have been widely developed and applied in the different sub-regions of MWM systems, such as spatial DSS to determine the location of electrical and electronic waste treatment plants [6] and vehicle routing and scheduling programs for waste collection [7]. As urban planners' involvement in MWM mainly focuses on siting waste treatment facilities [2], an intelligent DSS should not only provide spatial information about candidate sites for present use, but also the long-term strategies of the facilities at each site to ensure sustainable development. The WTEDSS introduced in this paper provides optimal long-term configuration and adapts to flexibility from an economic point of view, as it considers locations, type of technology, environmental impact and numerous cost factors. To provide the most practicable option to urban planners, the WTEDSS is specifically real-world oriented with a 3D city simulation module that provides a game-based decision-making environment and visualizes the optimal solution in a real-world model. The WTEDSS comprises four modules and is integrated as an intelligent and easy-to-use application.

The rest of the paper is organized as follows. In Section **Error! Reference source not found.**, background information about WTE and related DSS are introduced. Section **Error! Reference source not found.** presents the framework of the WTEDSS and its technical platform integration. Section **Error! Reference source not found.** presents the user flows with subsystems functionalities, and the findings and discussions can be found in Section 5.

2. Background of waste-to-energy and related decision support systems

WTE is the process of generating energy via various treatments of waste. Widely applied WTE treatment technologies include gasification, anaerobic digestion (AD), composting and incineration [1]. To choose the most appropriate WTE technology to deploy, urban planners need to resolve the conflict of being cost-effective or environmental friendly. For example, incineration can significantly reduce waste volume (up to 90%), but the combustion process may produce serious pollutants (NO_x, SO₂ and dioxin) [1]. Most WTE infrastructures can be deployed at both backyard (on-site) and large-scale (off-site) waste treatment facilities (WTFs). For selected technologies, urban planners face a problem of where and when to deploy WTFs associated with WTE infrastructure capacity. For example, centralized off-site facilities benefit from economies of scale associated with construction costs, but have increased transportation costs and emissions. In contrast, decentralized on-site facilities contribute to the local area and reduce transportation costs. Achieving the optimal deployment strategy involves multiple disciplines and consideration of technical, environmental and economic factors. Due to this complexity, there exists a need to develop and apply DSS for MWM planning.

Since 1996, many intelligent MWM DSS have been proposed and developed based on the SAS and MATLAB platform, which can perform complex data analysis but may lack UI design options for application development. Chang et al. (1996) [8] developed a DSS for waste recycling and incineration facilities based on SAS. Fiorucci et al. (2003) proposed a DSS for various possible waste treatment infrastructures using MATLAB. This DSS presents the final MWM system configuration with a set of binary decision variable values [9]. A DSS that includes simulation techniques can better evaluate the performance of systems and configuration and assist decision makers to achieve the most appropriate strategy. ReFlows, which was proposed by Abeliotis et al. (2009) [10], simulates the material and financial flows of the MWM system and allows examination of the effects of different strategies. ReFlows provides a user interface in an Excel spreadsheet and transcribes the rules and calculations in MATLAB. The spreadsheet interface allows high transparency of the model calculations, but users may be confused by the complex model and have input issues. Yao et al. (2013) [11] established the MWM DSS using MATLAB. The system outputs are displayed as a table, bar chart, and distribution of municipal solid waste (MSW) and ash resulting from incineration visualized in a 2D map. Comprehensible system output is the key for decision makers to gain support. 2D graphic methods for data visualization used in traditional DSSs can help decision makers understand data characteristics and the effects of a strategy, but a 3D approach with realistic models is the complement of 2D graphic methods. The 3D approach has advantages when presenting the geographical environment, transportation routes, spatial relationships between facilities and their status information [12]. WTEDSS used the Unity engine to create a 3D real-world environment platform, and is integrated with an optimization module to provide simulation in a gamification interface.

Most existing DSSs primarily focus on mathematical models, and so few consider the usage of the software and user operations. However, planners and decision makers may not have a thorough understanding of the overall mathematical model and optimization process, and the lack of instructions and visualized information may cause the DSS to be too complicated for users to operate. A contemporary and real-world oriented DSS should integrate the

data, optimization model and simulation in a friendly graphical user interface, provide a long-term strategy and visualize the result in a comprehensible manner.

3. Waste-to-energy decision support system

WTEDSS is designed to assist decision makers to achieve an optimal long-term waste management planning strategy, including candidate sites selection, technology selection, transportation scheduling and WTFs scale (decentralized on-site and centralized off-site) problem solving.

3.1. System framework and technical platform

WTEDSS consists of four main components: data analytics, optimization, simulation and graphical user interface (GUI). Figure 1 shows the complete framework of WTEDSS with the modules and their integration methods. The four modules are integrated seamlessly as a simple but reliable WTEDSS. The information gathered from the user interface (UI) is stored in the system and sent to other modules. The data analytics module performs statistical analysis and sends the calibrated data to the optimization module and simulation platform. The optimization module calculates the optimum strategy with the model and sends the optimum solution to the UI and simulation platform. Then the solution and calibrated data will be visualized in 2D UI with charts and tables, as well as in a 3D simulation environment. WTEDSS also generates a report of the optimum output for the user.

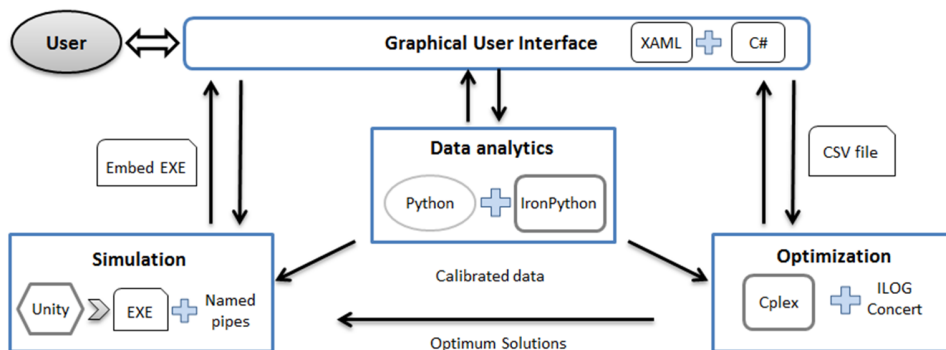


Figure 1: Framework of WTEDSS

WTEDSS is a standalone Windows application built with the .NET framework 4.5 using Windows Presentation Foundation (WPF). The appearance of the application was created by using Extensible Application Markup Language (XAML), combined with a managed programming language (C#) to implement its behavior. Such technology facilitates the integration of a graphical user interface (GUI) and other application layer components, which greatly increases the efficiency of UI development and reduces maintenance costs as well.

Each subsystem is developed based on a different engine, with each engine having its specialty and essential techniques for the specific module. Each subsystem in WTEDSS is designed to be able to perform its own functions in isolation, while also being able to be integrated and work as one system. The data analytics subsystem is built based on Python. Python has strong statistics support and powerful data visualization libraries, which help the subsystem to perform high level data analysis and dynamically visualize data. We used the CPLEX optimizer for the optimization subsystem. The CPLEX optimizer is a high-performance mathematical programming solver from IBM, and its fundamental algorithms enable the subsystem to solve optimization models quickly and accurately. The simulation subsystem was developed using a commercial game engine called Unity (or Unity 3D). Unity has a strong organized library written in C# and can be deployed on multiple platforms, which is needed for integration with other modules. The main advantages of Python, CPLEX and Unity compared to similar software are the .NET framework environment support with a comprehensive library for development and applicability for commercial use.

3.2 Integration of the subsystems

Integration of the data analytics subsystem is carried out by an open-source language that supports both .NET framework and Python libraries, namely IronPython. The UI of the data analytics subsystem was designed with a XAML script and linked with its code-behind (C# scripts). The C# scripts can execute the Python scripts for data analysis through the use of IronPython libraries. The integration of the optimization model that mathematically

addresses the optimal deployment plan for waste treatment facilities is carried out with the use of C# scripts. The optimization model is resolved with the use of the ILOG CPLEX Solver library. The optimization subsystem UI was designed with XAML and interactively connects with the model parameters to present the resolved optimal solution. The simulation subsystem is integrated by exporting the executable file (.exe) from Unity and then embedding the executable file as a child process in the main system. The simulation subsystem uses pipes for interprocess communication (IPC) with the main system. A pipe is a unidirectional data channel that can connect two processes, which commonly used for sharing data between processes in windows. For the optimization subsystem and data analytics subsystems, their UIs were created in the main system and communication can be easily implemented in the system through the model controller.

4. User flows and subsystems of WTEDSS

One specific objective of this work is to optimize WTFs configuration, thus defining the period, location, WTE infrastructures and capacity that should be deployed. The user flows presented in Figure 2 show how the user receives decision support in WTEDSS. The urban planner firstly needs to estimate the amount of waste to be managed, and can then find a strategy to optimize the transportation and disposal process.

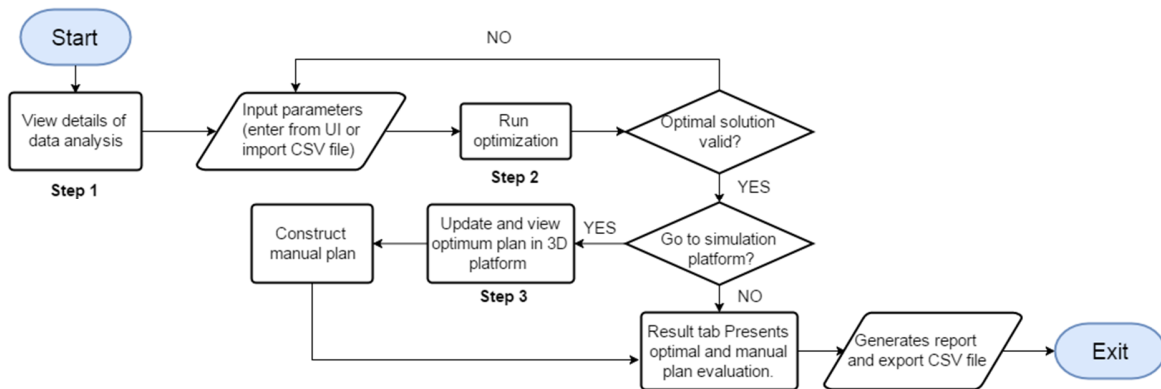


Figure 2: User flows of WTEDSS

Step 1: Data analytics

The data analytics module is designed to provide a current overview and future predictions of waste management related data, such as the waste amount (by sector, area, and waste type), numerical cost (land use cost, transportation cost and penalty for emission) and population. With a combination of geographic and socioeconomic data, the WTEDSS produces dynamic and comprehensive graphs to assist municipal planners to understand the waste generation pattern and management scheme. This overview is implemented by analyzing and visualizing current data, and predictions can be implemented by visualizing the results from the forecasting model based on usage trend data or historical data. The development data analytics module is currently under development; more details will be available in future work. Figure 3(a) shows the data analytics UI for waste distribution in Singapore.

Step 2: Optimization

With the knowledge from data analytics, users are ready to construct a deployment strategy with the necessary parameter inputs. To achieve the waste management system objective, mixed integer non-linear programming models are established to minimize the “absolute” expenses over the long-term WTFs configuration [13]. These “absolute” expenses are represented as the differences between the total costs (installation cost and operation cost associated with WTF unit capacity, which can be progressively deployed during the lifecycle) and revenues (from recovering waste-to-energy or materials). In this view, the main decision variables include locations of WTF, selection of technologies types and their capacities, transportation schedule and waste allocation from waste producers to WTFs. This decision-making is subject to certain constraints, e.g., (1) the capacity deployment at each candidate site is progressive and it cannot be reduced through time, (2) at each time step waste can be assigned and transported only to one WTF of sufficient capacity and (3) the total installed capacity cannot exceed the land space limitation at each candidate site. Figure 3(b) shows the UI of the optimization subsystem in the case of a small region with 10 food courts. The WTFs and WTE infrastructure related data are collected from users as well as GIS information about candidate sites and waste collection points. The user can import a CSV file into the system to

avoid the larger workload of input. The optimization subsystem outputs a strategy with important parameters and a detailed deployment plan, including technology and its units, the treated waste amount and its source per year.

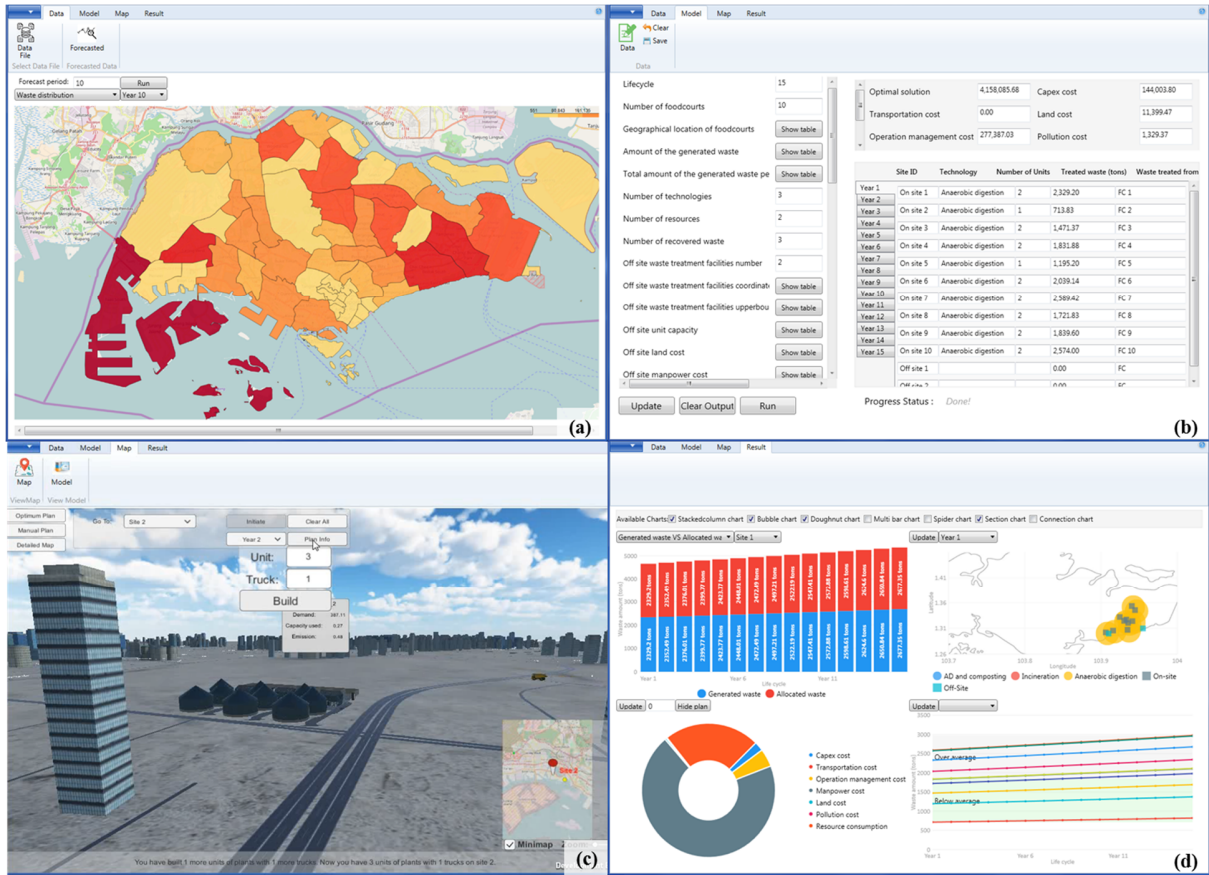


Figure 3: User interface for each module

Step 3: Simulation

After the optimization subsystem outputs the optimal configuration, the user may update the simulation platform. WTEDSS provides a simulation game environment to visualize the planning process and optimization solution. To bring the optimal strategy into real-world practice, the simulation subsystem uses real geographical data to simulate the region for the urban planner to have a big picture of the region they are managing. The simulation platform visualizes roads and buildings with their addresses and names displayed, and can also receive geographical information about waste collection points and WTF sites from the main system and visualize them in the 3D city for simulating transportation routes. These functions also enable the simulation module to evaluate different scenarios based on the information.

The simulation platform receives the optimal allocation plan and the user can view this plan in the 3D city. The user can view the optimal configuration for each year and understand how the WTE infrastructures units have been progressively deployed. Figure 3(c) shows the configuration of site 2 in year 2, which has 1 truck and 3 units of WTE infrastructures deployed; the user can further modify the number of units and trucks, and the changes can be sent back to the optimization subsystem for recalculation. A truck goes to a specific waste collection point according to the transportation route from the optimization plan. A dashboard for each WTF indicates the related information, such as the allocated waste amount, used capacity and emission factors for a specific year. The user can also find the plan overview in the plan info panel, and a mini-map in the lower right corner shows the site location on a 2D map. These functionalities can also be applied in the manual plan, where users can deploy WTE infrastructures units and trucks by themselves over the planning horizon. The manual plan function facilitates independence between subsystems, allowing the user to examine their plans and obtain the most practicable one. Manual configurations can

be saved and evaluated by the simulation engine, and the performance is presented in the results tab (Figure 3(d)). The results tab visualizes the optimization solution and information from the simulation module in comprehensive charts. It can also be used for comparisons of each scenario, which will be implemented in future work.

5. Conclusion

A prototype WTEDSS designed to assist decision-makers in drawing up the long-term optimal configuration of waste treatment facilities has been developed. The WTEDSS considers several unit processes, including waste collection, transportation and treatment technology. The subsystems of the WTEDSS are developed on different engines and then integrated, which allows the subsystems to be operated separately to increase the application's flexibility. The intuitive UI and simulation platform enable users who lack an adequate scientific background to retrieve information and receive decision support. Future development directions include a more advanced 3D simulation platform with a powerful engine to enable multi-scenario examinations in a real-world environment and a national level optimization and data analytics tool to provide detailed analysis and decision support.

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