A Decision Support System for the Design and Evaluation of Sustainable Wastewater Solutions

Brent C. Chamberlain, Giuseppe Carenini, Gunilla Öberg, David Poole, and Hamed Taheri

Abstract— The drive toward sustainable wastewater management is challenging the conventional paradigm of linear end-of-pipe solutions. A shift toward more sustainable solutions requires that information about new ideas, systems and technologies be more readily accessible for addressing wastewater problems. It is commonly argued that decision-making needs to involve engineers and other community representatives to define values and brainstorm solutions. This paper describes a decision support system (DSS) prototype that is designed to help community planners identify solutions which balance environmental, economic and social goals. The system is designed to be scalable, adaptable and flexible to allow fair assessment of new ideas and technologies. It supports the exploration of consequences of various alternatives and visualizes the trade-offs between them. Our DSS takes in modular descriptions of components and a description of a community context, automates the design of alternative wastewater systems, and facilitates evaluating how well each design satisfies the given context. It provides an adaptable platform from which new solutions can be designed without having to predefine how a single component fits within a specific system. Our DSS facilitates the exploration of alternative solutions by visualizing the effect of various trade-offs and their consequences in relation to the community's sustainability goals.

Index Terms— Logic Programming, Decision Support, Design, Environment, Interoperability. Wastewater

1 Introduction

A linear, end-of-pipe infrastructure design has dominated wastewater management in the western world since the industrial revolution [1], [2]. Population growth and urbanization in combination with concerns related to resource scarcity and global change have sparked an interest in more sustainable and cyclic approaches [3], [4], [5]. As a consequence, the past decades have seen a rapid growth of innovations based on the idea of waste as a resource rather than a liability, with a focus on water, energy and nutrients. The uptake of technical and institutional innovations is, however, slow. This is in part because the liability costs of public and environmental health may be significant. The slow uptake may also partly be due to the siloed institutional frameworks which are geared to augment supply (e.g. by building larger pipes) rather than to manage demand (e.g. by introducing low flush toilets). The challenge of providing robust management of domestic and industrial sewage is becoming increasingly urgent as the majority of sewage infrastructure in the industrialized world will require retrofitting and replacement in the near future and more than half of the people living in megacities in the developing world lack access to centralized sanitation services [6], [7]. Growing costs in combination with environmental concerns and the challenges involved in securing the quality and quantity of water heighten the urgency of the issue.

It has been repeatedly shown that successful implementation of robust wastewater management solutions is intricately tied to environmental, social, economical and political aspects at different scales and thus requires active engagement of a variety of experts, in addition to wastewater engineers [6], [8], [9]. Identifying 'the most sustainable solution' involves finding solutions that minimize negative effects, while maximizing benefits for local and global environments. The challenge is considerable; it is context-dependent and multi-dimensional in which competing objectives must be identified and trade-offs made. Decision makers are scrambling to identify the 'best solution' for their specific context: but they simply do not have sufficient resources to carry out an integrated analysis, and they generally settle on the traditional solution [10], [11], [12].

Guest et al. [12] discuss the challenges with sustainable wastewater management, and that it is necessary to bring in multiple perspectives when identifying possible solutions. Decision support systems (DSSs) can, for example, be designed to allow input from different parties involved in the decision making process as planners navigate through complex problems [13]. Several DSSs have been developed to aid decision making in wastewater management [14], [15], [16], [17], [18], [19]; see [20] for a review. According to Hamouda et al. [20], most DSSs focus almost exclusively on the technical and economic aspects of wastewater, while what is needed is a more

• *B.C. Chamberlain, G. Öberg and H. Taheri are with the Institute for Resources, Environment, and Sustainability at the University of British Columbia, Vancouver, B.C. Canada, V6T 1Z4 E-mail: brent.chamberlain@ires.ubc.ca, hamed.taheri@alumni.ubc.ca, goberg@ires.ubc.ca*
• *G. Carenini and D. Poole are with the Department of Computer Science, at the University of British Columbia, Vancouver, B.C. Canada, V6T 1Z4 E-mail: carenini@cs.ubc.ca,poole@cs.ubc.ca*

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comprehensive approach, which considers social, legal, environmental and other aspects of wastewater management [21]. We fully support the argument that there is a need for a DSS that allows input from a variety of experts and key-stakeholders when analyzing the impact of values, trade-offs and consequences

The purpose of this paper is to present a DSS prototype that we developed in order to help communities effectively explore the design space of sustainable wastewater solutions that is relevant for their particular context, and make it possible for them to identify solutions that balance environmental, economic and social needs. The system has been initially developed for planners and their consultants with the intent to be developed for use by the public. We hypothesize that such a system must be scalable, adaptable and flexible to allow fair assessment of new ideas and technologies. We also hypothesize that it would be most beneficial if the DSS allows users to explore the consequences of various alternatives under different scenarios and visualize the trade-offs between them. To enable the different parts to work together, the DSS should be based on a common language that allows the translation of different types of information and concepts between different users of the system. To accomplish this, we have developed a model-based group DSS (GDSS), which is designed to support brainstorming and idea evaluation, and to facilitate the identification of sustainable solutions to challenging multi-dimensional multi-stakeholder problems [13], [22], [23]. Our DSS is designed to accept three types of information provided by three separate groups:

1. Information about the physical components of a system that can be arranged to create a sustainable sewage management system. This information is provided by engineers, inventors, technology firms, et cetera.
2. Context specific information (regulatory, demographic, geographical, etc.) provided by, for example, planners (municipality, city, region, etc).
3. Information on values, preferences and predictions provided by various stakeholder representatives (e.g. elected officials, the public, special interest groups, NGOs).

The architecture of our DSS is based on three key premises. First, that the system is built on an open platform with an explicit vocabulary and taxonomy of the various technical and non-technical aspects of sustainable wastewater management. Second, that the system has the capacity to automatically generate alternative solutions. Third, that the system is able to effectively communicate the trade-offs between these alternatives and simultaneously allow users to explore how their values influence the outcome, i.e. which alternative is assessed to be the best solution and why.

The architecture of our DSS, along with a description of our methodology, are presented in the following section, accompanied by an explanation of how these three premises were addressed with specific examples of the DSS. In Section 3, we describe our approach in detail. Section 4, discusses the system in the context of sustainable wastewater management, possible improvements and next steps.

2 ARCHITECTURE OF THE DSS

The architecture of our DSS, as shown in Fig. 1, comprises several data structures and two software modules. The data structures are built on an ontology, derived from a number of imported domain-independent and domains-specific ontologies, which provide an explicit vocabulary and taxonomy for sustainable wastewater management. These structures include system components, the community context, user values, and the properties and relationships each of these have with each other. The design generation module can automatically generate a large number of alternative wastewater system designs. This module is useful for exploring the range of possible designs and encouraging brainstorming between technical and non-technical users. The decision aid module is an intuitive and interactive visualization system which allows users to easily select their preferred design(s) by comparing trade-offs between a subset of the solutions generated by the previous module.

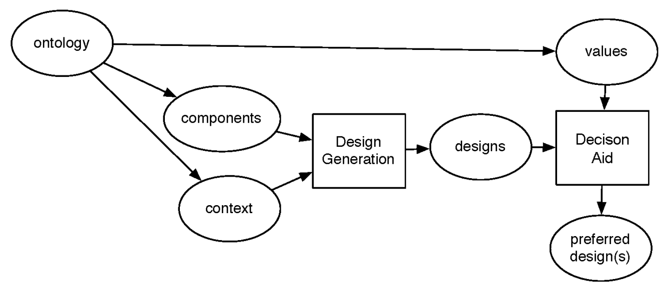


Fig. 1 The data structures (ovals) and two software modules (rectangles) of the sustainable wastewater decision support system.

2.1 Ontology

Planning the renewal, retrofitting or expansion of a wastewater system requires input from a variety of people with diverse knowledge and expertise. It is a well-known phenomenon that efficient communication among diverse groups is hampered by their use of different vocabularies and language constructs. Efficient communication is facilitated by the creation of a common vocabulary, which allows different groups to understand and communicate with one another. Computer-based ontologies are designed to specify the meaning of the vocabulary used in an information system [24]. Ontologies enable information sources to inter-operate at a semantic level and to facilitate the adherence of different information sources to a common terminology for the same things [24]. Such ontologies are expected to be defined by the domain community and evolve as a new vocabulary is defined. In many areas of science, scientists are developing ontologies for their field. Two examples include the Open Biological and Biomedical Ontologies[1] [25] for med-

[1] http://www.obofoundry.org

icine, and OneGeology[2] to define the vocabulary of geology and provide open access to geospatial map data.

An ontology for wastewater systems describes physical components, among many other concepts related to wastewater. Examples of physical components would include: pipe, activated sludge system and energy recovery system. A pipe is a type of transportation agent with properties, such as diameter and material, and relationships to other entities described using the same or different ontologies. Similarly, an activated sludge system would be a type of treatment system with properties such as operating temperature and volume capacity. An energy recovery system would be a type of resource recovery with properties such as operating temperature and recovery efficiency. There could be other ontologies that, for example, describe processes, community contexts, wastewater constituents and related indicators. A process ontology would include, for example, denitrification, disinfection, and odor removal. A few computer-based ontologies have been developed for wastewater systems [26], [27], [28], though these focus primarily on the technical aspects or operation and maintenance of a plant. These ontologies are not adequate by themselves for municipalities facing the challenge of renewing, extending or retrofitting their systems, as they do not include social, economic and environmental aspects.

Researchers in other domains have, however, developed conceptual models that relate various wastewater infrastructure and treatment systems to social, economic and environmental aspects [29], [30] (also see the Sustainable Sanitation and Water Management toolkit[3]). Drawing on this work, we have developed some prototype ontologies where the properties, which define physical components and wastewater products, are formally specified.

Fig. 2 shows a diagram of a simplified example of a traditional linear wastewater system, with specific parts of this system identified (e.g. settling tank).
In the ontology, settling tank is a subclass of Component. In the OWL Web Ontology Language[4], this would be written as:

subClassOf(SettlingTank Component)

Other examples of OWL which describe parts of the wastewater system in Fig. 2, include:

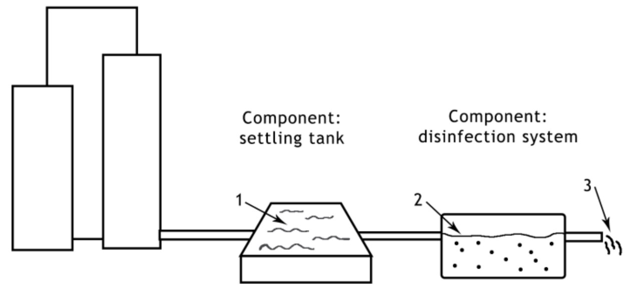


Fig. 2 Simplified example of linear end-of-pipe wastewater system. The numbers correspond to a product associated with each component and disposal method.

subClassOf(Component PhysicalObject)
subClassOf(Product PhysicalObject)

Describing the various parts of a wastewater system using an explicit definition of the properties, domains and ranges, enables other ontologies to interoperate and reuse these descriptions. For our ontology, we import the specification for defining quantities, units, dimensions and data types from [31], officially called Quantities, Units, Dimensions and Data Types in OWL and XML or QUDT. If there is some quantity we need to express in our ontology that is defined in QUDT, we use their definitions. For example, when we use a flow in our DSS, which is a volume per unit time, we use the QUDT name: **`Quantity:VolumePerUnitTime`**. For other units, such as money per time unit, we define our own terminology which we will publish so others can import these definitions. A list of some properties, their associated domains and ranges for our DSS can be found in Table 1.

Looking back at Fig. 2 there are three products, which have been labeled. The first product (1) represents the

TABLE 1:

EXAMPLE PROPERTIES, THEIR DOMAIN AND RANGES FOR THE PHYSICAL COMPONENTS IN THE DSS

Property	**Domain**	**Range**
BiologicalOxygenDemand (BOD)	Product	Quantity:Density
TotalSolids (TS)	Product	Quantity:MassPerUnitTime
Flow (Q)	Product	Quantity:VoumePerUnitTime
Nitrogen (N)	Product	Quantity:MassPerUnitTime
Phosphorus (P)	Product	Quantity:MassPerUnitTime
Capital	Component	Money
EnergyUse	Component	Quantity:HeatFlowRate
Temperature	PhysicalObject	Quantity:ThermoDynamicTemperature
Volume	PhysicalObject	Quantity:Volume
VolumeCapacity	Component	Quantity:VolumePerUnitTime
OperatingTemperature	Component	Quantity:ThermoDynamicTemperature

constituents in the settling tank. Say a settling tank contains 5% of *TS* (see Table 1 for a description) in the

[2] http://www.onegeology.org/
[3] http://www.sswm.info/
[4] http://www.w3.org/TR/owl-features/

wastewater. By the time the wastewater reaches the disinfection system, some of the *TS* would have been broken down, and more would have settled to the bottom of the pond. Thus, when the product reaches the disinfection tank (product 2), *TS* may be less than 1%. The final product (3) would then be released into a water stream, should *biological oxygen demand (BOD)* be low enough to meet local regulations.

The ontology is meant to facilitate the adherence to a common terminology. It is assumed that individuals who use the ontology will abide by the set standards, while also making suggestions for improvement. Such a standard ensures that the information being collected and the way it is organized will be consistent.

2.2 Components

A database of the various entities was then derived using the ontology. The database contains information about many physical components which is used to construct a model of a potential wastewater system. Here, we define 'components' simply as the pieces that can be organized together to create a sewage management system. Depending upon an individual's background such 'pieces' may be referred to as processes, technologies, components, modules, or combinations of these. In the real world, each component has a set of constraints or limitations, required inputs and outputs. Whereas the database uses descriptions of these components to specify the types of inputs, restrictions on the inputs, the types of outputs, and how the output is a function of the inputs and the operating conditions. An example component is presented in Fig. 3, showing the required descriptions.

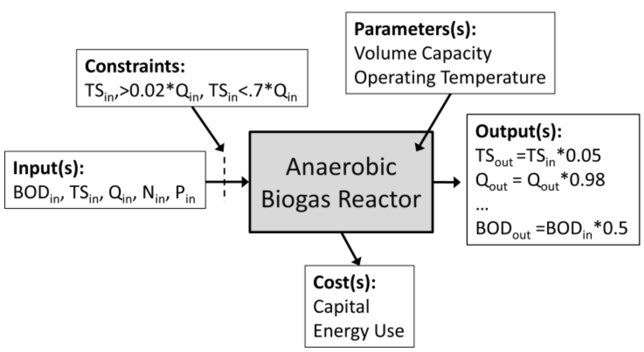


Fig. 3 Example of a component with the properties associated with the various parts of the component. In the diagram, the Input(s) and Output(s) are equal to Product(s).

2.3 Community context

Components are used to build a wastewater system, yet in order to identify the best system for a community, the information which defines a community context must also be given. A community context provides constraints that the system must attempt to satisfy. These constraints may depend on a community's population, climate, amount of land available, regulatory restrictions, et cetera, and would be structured based on the community context ontology. The context specific information would likely be known by the local planning department and various government authorities. In the present DSS, a community context can be based on a variable number of properties and constraints, such as the level of *BOD* (an indicator of effluent quality), *capital* available for construction and *energy use*. An example of a city community context is presented in Fig. 4.

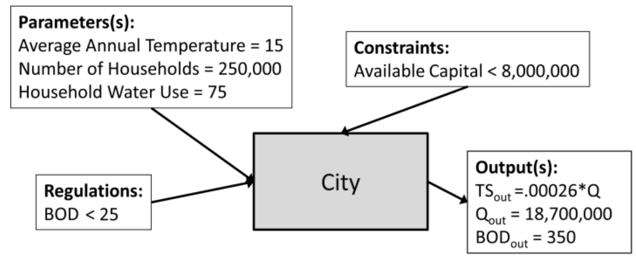


Fig. 4 Example of a community context with the associated properties.

2.4 Generating alternative wastewater solutions

The design generation module is one of two software modules in the DSS architecture (see Fig. 1). This module uses computational methods to facilitate the automatic creation of alternative wastewater system designs. The concept of computer-based design generation has existed for some time in wastewater management. In fact, as early as 1979, Rossman [32] developed a computer-based system for creating an arrangement of processes for a system. One of the most recent and complex automation methods uses a genetic algorithm for creating feasible wastewater systems [18]. Recently, there has been a push toward developing sustainable wastewater systems [12], but very few use computational methods for automating the design of these systems. One example can be found in Balkema et al. [21], where they use an integer programming optimization method.

In the DSS presented, a design is a set of components, arranged together in a way that is physically possible, which satisfy the constraints specified by the community context and treats the community's output (see Fig. 4) such that there are no remaining outputs from the completed design. A partial design is a set of components where components are connected together, but where some components may have some outputs that are not yet connected to a component. Initially we treat the community as a component that has an output (Fig. 5, start). A completed design (Fig. 5, complete) is a partial design where all outputs of components are connected to other components. Designs are generated by employing a depth-first branch-and-bound search [33] maintaining a current partial design and a cut-off bound.

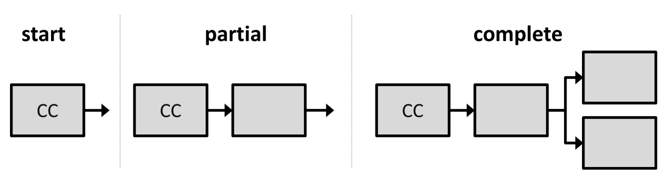


Fig. 5 Abstraction of starting, partial and completed designs. CC = community context, rectangle = component, arrow = output.

A component can be added to a partial design if the input type (see Product domain in Table 1) matches the type of the available output and the constraints of the new and existing components of the design are all satisfied (constraints include component constraints and parameters, see Fig. 3, and community context constraints, see Fig. 4). As components are added, the DSS maintains an estimate of the costs (utility and community constraints) of completing that design. It maintains a current partial design such that the actual cost plus the heuristic value is less than the cutoff. It then extends the current partial design with additional components (or reuses components) in all possible ways, in a depth-first manner. When solutions are found, the cutoff is reduced in a way to find a limited number of solutions which can be compared (e.g., if we want to find 10 solutions to compare, it can be set to the cost of the 10th best solution found so far). The pseudo code below provides context of how a design is constructed:

```
partialdesign = {community}
outputs = {community output}

repeat:
   choose output ∈ outputs
      & component such that type (output) = type (input)
      & all constraints are satisfied
   add component to partialdesign
   remove output from outputs
   if component not already in partialdesign,
    add outputs of component to outputs
until outputs = {}
```

The key difference between our system and most of the other previous DSSs, is that in the previous systems the inputs consist of a predefined set of rules which define the structure and order of components. Using a predefined structure requires evaluating the compatibility of any new component within the order of the existing structure. Compatibility matrices, trains (or series of components), and pair-wise look-up tables are methods employed by these systems. Our approach to design generation is based on a different principle: that the order and compatibility of components is discovered rather than dictated. Our system searches over combinations of components which are discovered to be compatible based on the component's ontology. The idea is that the components can be defined modularly, so that one component can be described without the need to evaluate how it fits with others.

The use of logic programming in the design generation module allows the exploration of possible system designs without constraining potential designs based on preconceived ideas of how components fit together. As the number of components increases, the complexity of the search will grow. When the system has reached this stage, we plan to use more sophisticated methods of constraint logic programming (CLP) [34], [35]. Recently, CLP has been used in DSSs to automate designs of constructed wetlands [36] (one of many possible effluent treatment/disposal methods), and in automating the assessment of environmental impacts stemming from development projects [37]. Both of these applications are intended to support decision making amidst complex problems with a large number of impact variables and possible designs.

Currently the module does not constrain the number of inputs, outputs, properties, conditions and costs associated with a given component. The aim here is to explore the space of possible designs and in the process confirm that the model could correctly construct designs.

2.5 A decision aid to support evaluation of trade-offs

The second software module of our DSS, the decision aid, supports the task of selecting a design that best satisfies stated values and priorities by exploring how the values, and trade-offs between designs, influence the evaluation of the alternative. For illustration, imagine a simple scenario where two alternative designs are produced. One design is relatively inexpensive, generates several new jobs, but has a rather negative environmental impact, risking long-term health effects. The other design has a low environmental impact, but is more expensive and does not create new jobs. In this scenario there is no clear win-win solution, so users would be forced to consider the trade-offs among economic, social and environmental criteria (i.e. the objective function created for the generation of alternatives). The problem is that humans are generally not very effective at considering trade-offs [38].

In the last forty years decision analysis has developed methods to support decision making with conflicting objectives [38], [39]. A common approach builds on three distinct interwoven phases [40].

The first phase involves the creation of a quantitative preference model, which is elicited through interaction with decision maker(s). This typically includes: what objectives are important, each objective's degree of importance (e.g., five new jobs may be equal to the decrease in odor from moderate to minimal), and the preferences for each objective outcome (e.g., a 10% decrease in odor is 30x more valuable than a 1% decrease). Singhirunnusom and Stenstrom [41], for example, used this approach to collect data from various experts to identify and weight criteria for selecting an appropriate wastewater system. Several elicitation methods for building a preference model have been developed, each striking a different balance between preference model complexity, accuracy and ease of elicitation. One method may, for example, ask decision makers to simply rank the objectives in order of importance, while another may ask specific, multi-leveled questions about preferences regarding two objectives [42], [43]. The decision problem and user experience, in combination with the accuracy of the model, determine the appropriateness of an elicitation method [42], [43], [44].

In the second phase, the decision makers analyze their preference model as applied to a set of alternatives. The model then assigns a score to each alternative, typically between zero and one, representing a range from the worst to best possible alternative.

In the third phase, the model's noise is reduced as this can be introduced in the elicitation process, resulting in a quantitative preference model that may not be sufficiently accurate. A sensitivity analysis is useful in this phase. This analysis can help answer "what if" questions, such as "if we make a slight change in one or more aspects of the model, does it affect the optimal decision? Why?" [38]. The result is a more reliable preference model that can accurately reflect the decision maker's preferences.

Several tools have been developed to support this decision analysis method. In most of these tools interactive information visualization plays a critical role, as decision makers often need to explore and analyze a large amount of information. Examples of these tools include: AHP Treemaps (TM) [45], an interface that uses a treemap visualization to inspect preference models; CommonGIS (CGIS) [46], a tool for interactive exploration and analysis of geo-referenced data which provides two visualization techniques for visualizing preferences, utility signs and parallel coordinates; the Visual Interactive Sensitivity Analysis (VISA) system [47], a commercial tool for decision analysis, which stresses visual analysis with a special focus on sensitivity analysis techniques; and ValueCharts [48], which aim to combine simple visualization and interactive techniques to support the decision maker in analyzing their own preference model and its application to a set of alternatives.

Two independent studies [49], [50] have compared existing tools analytically (i.e., with respect to a task model) and identified ValueCharts as the most effective tool, especially for non-technical decision makers. ValueCharts has been tested in three user studies. While the results of one of these user studies were inconclusive (see [50] for possible explanations), other evaluations have shown ValueCharts to be quite effective [43], [49], [51]. Finally, ValueCharts have also been applied and successfully tested as a component of a sophisticated interface for querying event sequences [52]. Based on these observations, we have adopted ValueCharts as the second software module of our DSS.

Below, we provide a brief introduction to ValueCharts. Fig. 6 shows a ValueChart for a relatively simple decision involving five design alternatives for wastewater management.

The objectives are arranged hierarchically, and are represented in the bottom left quadrant of Fig. 6, where the quality of a rural waste water system is decomposed at the first level of the hierarchy, into its social, environmental and economic criteria. The height of each block indicates the relative weight assigned to the corresponding objective; its percentage (in decimal value) of importance is also given. For example, the maintenance cost is considered to be $1\frac{2}{3}$ times more important than the capital cost in the current preference model.

On the right of each leaf/primitive objective the corresponding value function is displayed. This function expresses the preference for each domain-value for that objective as a number in the [0,1] interval, with the most preferable domain-value mapped to 1, and the least preferable one to 0. For instance, in Fig. 6, high odor has value 0 while no odor has value 1. Similarly, the value function for maintenance cost decreases from 1 to 0 as this cost varies from \$10000 to \$50000. As shown in the bottom right quadrant, each column represents a design alternative. Each alternative has a label (e.g., Design 4) and the

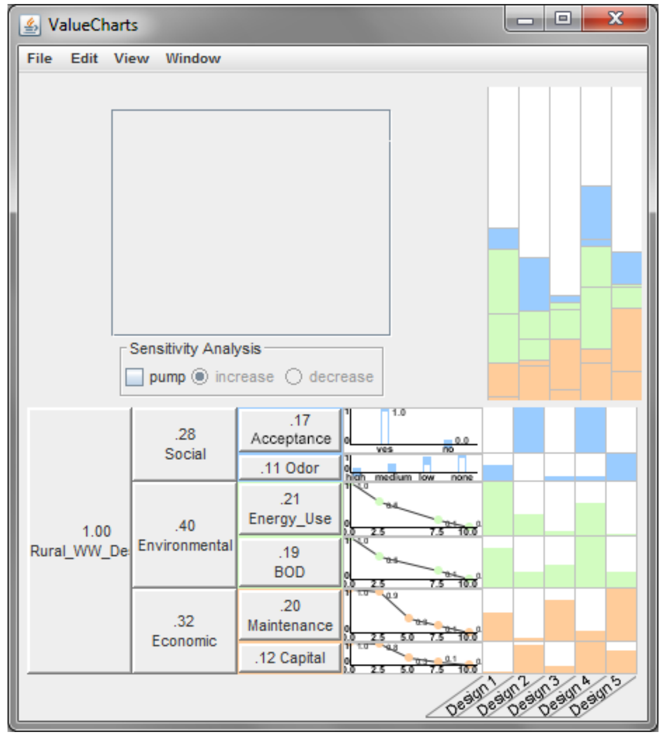


Fig. 6 An example decision scenario showing five designs and six evaluation criteria representing the social, environmental and economic values hypothetically identified by the user.

cells above a label specifies how the corresponding alternative fares with respect to each objective. More precisely, the amount of filled color relative to cell size depicts the alternative's value of the particular objective (here we have converted the original colors to greyscale). So, for instance, Design1 has the highest capital cost (lowest preferability), but it generates one of the lowest levels of BOD (high preference). In the upper right quadrant all values are accumulated and presented as vertical stacked bars, displaying the aggregate score of each alternative. In this model, Design 4 is the best alternative, the one with the highest aggregate score.

Several interactive techniques are available in ValueCharts to further enable the inspection of the preference model. For instance, sensitivity analysis of objective weight is enabled by allowing the user to change the vertical height of the corresponding block. In the next Section we describe the application of ValueCharts to a much more complex and realistic Wastewater decision problem. In this context will discuss sensitivity analysis in more detail.

3. Example Outputs and Applications

The outcome of our methodology provides a framework for a DSS containing an ontology, database of components, community contexts, an automated method for generating alternatives, and an interactive visualization system to evaluate trade-offs between some of the generated alternatives.

We have created 25 unique components, modeled after examples found in [29], [30]. Examples of these components include: single pit, dehydration vault, septic tank, anaerobic baffled reactor, anaerobic biogas reactor, a variety of stabilization and settling ponds, constructed wetlands, and numerous disposal methods including reuse of treated feces and urine. Each includes the specifications shown in Fig. 3, and all have associated treatment functions (which define the outputs). A component can contain a variable number of inputs, and can produce a variable number of outputs. All components have a *capital cost*; some are based on the *volume capacity* property, and others are associated with flow (Q). The former include infrastructure such as pits and wetlands, while the others are intended to account for reuse or disposal methods (e.g. groundwater recharge, irrigation and landfill discharge). Many of the components do not require energy to operate. Operating an aerated pond requires electricity and the operation of an anaerobic biogas reactor may require some heating. These costs are associated with the property *energy use*. Since many of the components allow for different operational conditions and those conditions affect the level of treatment and their energy use, we model these using two properties: *operating temperature* and *volume capacity*. From our 25 unique components, we can generate a wide range of possible alternative solutions.

The number of solutions is contingent on the particular community context established. We tested several scenarios and a few of these are discussed below. For instance, consider a poor rural community in a developing country, with no running water. For this scenario, the input to the system would be primarily excreta (the combination of feces and urine) with some other organics. Say for example that for 1000L/d of this input (Q), 10% consists of feces and other organics(TS). In addition, the community has a limited budget of \$1000 (which is defined by the property: *capital*). With these parameters, the alternative generator finds three possible solutions of which one is shown in Fig. 7. However, if the community is able to add an additional capital of \$500, then another alternative solution becomes available, as shown in Fig. 8. Note that in the two examples provided it was assumed that in domains with ranges consisting of "UnitTime", time is represented by one day.

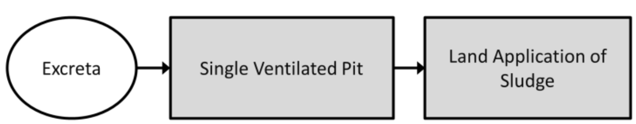


Fig. 7 Example solution for rural community (Q=1000L/d, TS=100L/d, Capital=\$1000). Two other solutions are possible, instead of the Single Ventilated Pit, a Single Pit or Double Ventilated Pit can be used.

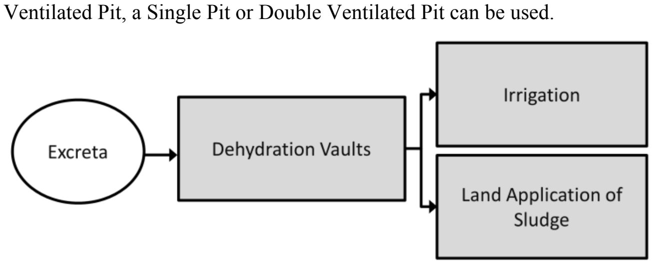


Fig. 8 Example solution for rural community (Q=1000L/d, TS=100L/d, Capital=\$1500).

In this solution, the combination of dehydration vaults and irrigation is introduced. The difference between the set of solutions in Fig. 7 and Fig. 8 is that dehydration vaults separate urine from feces at the source. So, unlike the variations of pits, which are intended to allow drainage of much of the liquid from urine into the ground, the dehydration vaults actually collect urine, providing two potential products for reuse. The urine can be stored, and, as suggested, used for irrigation. The dehydrated feces and some of the urine are then directed to a land application. As we continue to modify the parameters of this context, the possible solutions change. Even an adjustment as simple as increasing the capital to \$3000, provides 43 possible solutions.

In another scenario, we investigated if the model would find any potential solutions for a mid-size city (250,000 households) in an economically undeveloped country. In this particular scenario, we assumed that a household produces roughly 75L/d of wastewater (Q). Here we assume that the wastewater from all households is piped into to a single location (a centralized system). Since the constituents of wastewater in this community are very different from a small rural community, this was reflected in the properties of the original input. Here we calculate Q as 18,700,000L/d, and TS of 5,000L/d, the city budget is \$8,000,000.

Before running the model, we placed another bound on the system, which restricted the number of component combinations to five (regardless of the cost). This was done in an effort to reduce the amount of time the system would take to process all possible combinations. For instance, though it may be possible to connect numerous small wetlands together, we preferred the system to select a fewer number of large wetlands necessary to treat the wastewater. Though the cost difference is little to none between the two options, the former would require the model to explore an unnecessarily large space of possible solutions. With a restriction of five possible components, the model found 190 alternatives. Increasing the number of components to six, resulted in 946 solutions; seven resulted in 17,818 alternatives; eight results in 142,186 alternatives. Of these solutions, most included combinations of a digester, stabilization pond, and some form of wetland. One example solution is shown in Fig. 9.

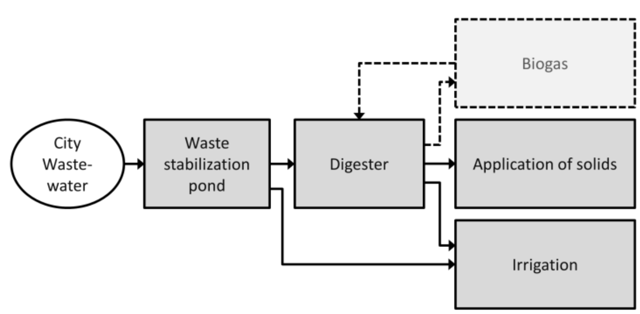


Fig. 9 Example solution for a large city (Q=18,700,000L/d, TS=5,000L/d, Capital=\$8,000,000).

It is common for many municipal waste treatment facilities to include waste stabilization ponds to separate the input product into two outputs. These outputs are commonly referred to as the effluent (primarily water) and the sludge. The sludge contains a large amount of the solids that can be converted to energy if managed appropriately. The way in which our model expresses the difference between the effluent and sludge is merely the ratio of TS to Q. There is no specific ratio that separates the two definitions, because ultimately the model only cares about the properties of the product. The products separated by the waste stabilization pond have the following ratio of TS/Q: the output directed to irrigation is roughly 0.5%, whereas the output directed to the anaerobic biogas reactor (shown in dashed border) is 10%. Though the properties describing the outputs may be simplified, they are sufficient, in this case, to allow the model to infer which component can manage each of the various outputs.

In the case of the digester, there are three outputs. One is a product that shares similar properties as the effluent originally destined for irrigation, as it too is eventually applied in such a way. The other is a product which could be used for composting or other applications of solids. Though it is not (yet) being explicitly modeled, these solids are those not digestible, which is why they had to be separated after they had been in the digester for the component's specified length of time. There would traditionally be another component following the digester, called the separator, which would separate the 'solids' from the 'liquid' material. However, in this model, the specific digester used here actually supplies this function. It would

TABLE 2:

STATIC EVALUATION OF SIX ALTERNATIVE RESOURCE RECOVERY SOLUTIONS BY CONSULTANTS FOR THE CITY OF NORTH VANCOUVER. [53]. TOP PORTION DESCRIBES THE ALTERNATIVES (NOT PART OF THE ORIGINAL MATRIX), BOTTOM PORTION SHOWS THE FINAL RANKING AND CRITERION EVALUATION.

		Scenario					
		1	2	3	4	5	6 (base)
	WW Treatment (Centralized/Distributed)	D	C	C	C	C	C
	Municipal Waste Diversion to System	70%	70%	90%	90%+	70%	N/A
	Heat & Electricity Recovery	Y	Y	Y	Y	N	Y
	Industrial Waste Heat	Y	Y	Y	Y	N	N
	Chip or Buy Wood for Gasifier	Chip	Chip	Chip	Chip	Buy	N/A
	Scope of Resource Recovery	All Waste	All Waste	All Waste	All Waste	All Waste	WW Only
	Rank	**6**	**3**	**1**	**2**	**4**	**5**
	Net total	37▼	—	8▲	5▲	7▼	34▼
Economic	Change management	▼▼	—	▼	▼▼▼	▲	▲▲
	Complexity	▼▼▼	—	▼	▼▼	▲▲	▲▲
	Energy independence	▼▼	—	▲	▲▲▲▲	▼	▼▼▼▼
	Captial cost	▼▼▼	—	▲▲	▲▲▲▲	▼▼	▼▼▼▼
	Net value	▼▼	—	▲	▲▲▲	▼	▼▼▼▼
	Jobs	▲	—	▲	▲▲	▼	▼▼
	Tax burden	▼▼	—	▲▲▲	▲▲▲▲	▼▼	▼▼▼▼
	Supplier & competitive readiness	—	—	—	—	—	▲
	Earthquake risk	—	—	—	—	—	▼▼
	Contract risk	▼	—	▼	▼▼▼▼	▼	▲
	Projection risk	▲	—	▼	▼▼▼	—	▲
	Finance risk	▼▼	—	▲	▲▲	—	▼▼
	System risk	▼▼	—	—	—	—	▲▲
Environmental	Change management	▼▼▼	—	—	—	—	▼▼
	Airshed	▼	—	▲	▲▲	▼	▼▼
	Creeks & streams	▲▲	—	—	—	—	—
	Groundwater	—	—	—	—	—	▼
	GHG reduction	▼	—	▲	▲▲▲	—	▼▼▼▼
	Reduced water consumption	—	—	—	—	—	—
	Renewable fuel use	▼	—	—	—	—	—
	Waste diversion	—	—	▲	▲▲▲	▼▼	▼▼▼▼▼
	Adaptability & resilience	▲	—	▲	▼▼	—	▼▼
	Contamination & ecological risk	▼▼	—	—	▼	—	▼▼
	Environmental management	▼▼	—	▼	▼▼▼	—	▼▼▼
Social	Change management	▼▼	—	▼▼	▼	▲	▲▲
	Community planning	▲▲	—	—	▼	—	—
	Jobs	▲	—	—	—	—	▼▼
	Odour	▼▼	—	—	▼	—	▼
	Disturbance	▼▼▼	—	▼	▼▼	▲	▲▲▲▲
	Municipal policy alignment	▼	—	▲	▼▼	—	—
	Metro policy alignment	—	—	▲▲	▼	▼	—
	Provincial policy alignment	—	—	▲	▲▲▲	—	▼▼▼
	Statutory compliance	—	—	—	—	—	—
	Taxpayer financial capacity	▼▼	—	▲▲	▲▲▲▲	▼	▼▼▼
	Community acceptance risk	▼▼▼	—	▼	—	—	▲
	Government capacity risk	▼▼▼	—	▼▼	▼▼▼	▲	▲▲

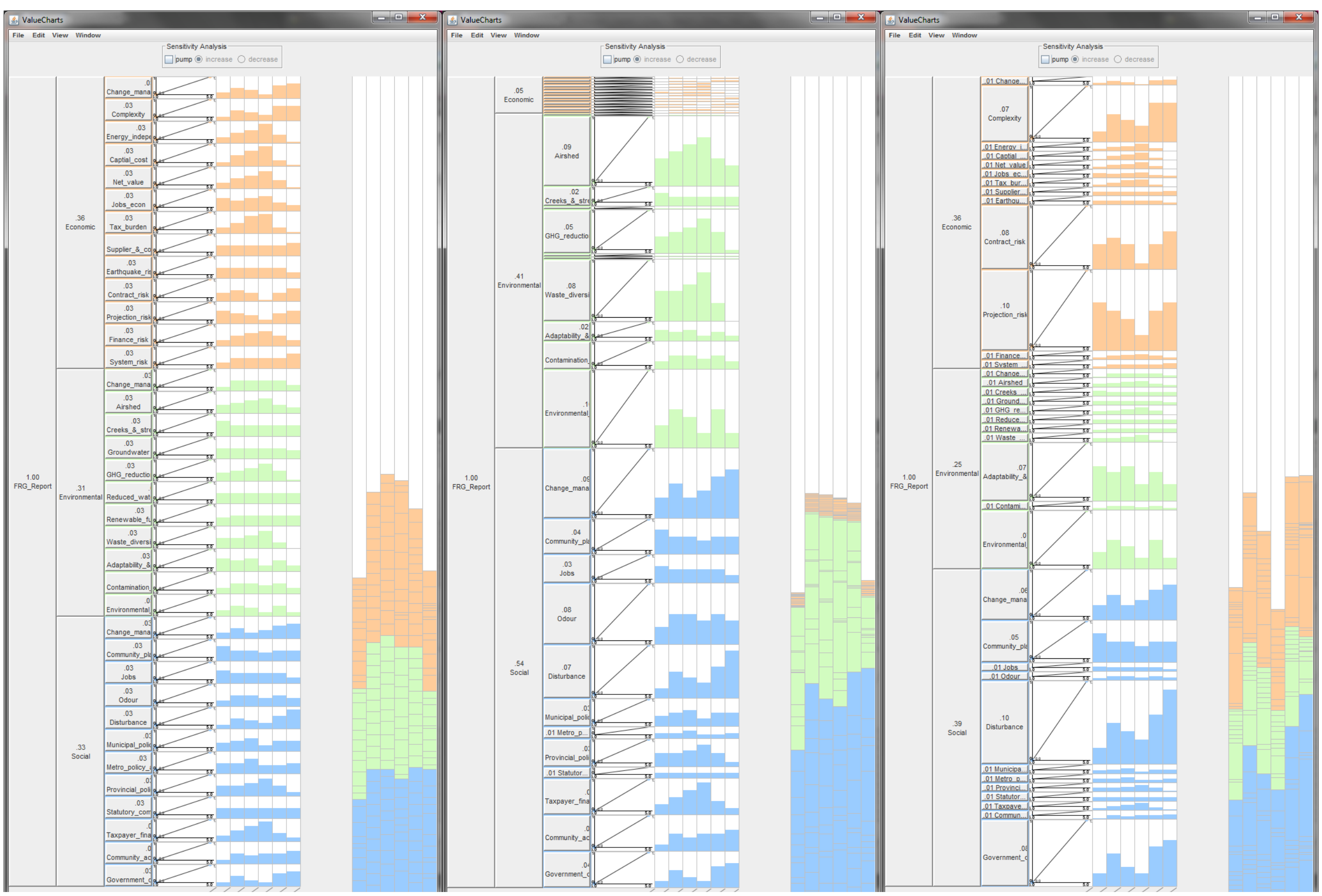
be very easy to add a digester that had an output of combined solid/liquid, and then add another separator component to support this function.

The third output from the digester is biogas. The production of biogas depends on the operating temperature, volume and concentration of *TS* in the component. In Fig. 9, we show how the biogas product could be reused directly by the digester (dotted line). Our model does not explicitly specify where the biogas can be reused within the model, it merely calculates the difference in the energy required to maintain the operating temperature and the energy produced by the system. Thus, the diagram is only showing a possible use for the biogas.

Once the alternative generator has produced a number of alternative designs, the second software module of our DSS, the decision aid, helps users evaluate a subset of the alternatives with respect to the community context and their own preferences. We will now give a specific example of how this module can help users evaluate the differences between alternative solutions and the impacts of changing preference models on this process. Instead of drawing on the previous, relatively simple, examples produced thus far by the alternative generation module, we apply the decision aid module to a recent evaluation, in order to demonstrate the scalability and viability of the decision aid module to more complex decision scenarios. The evaluation is from a report delivered to Metro Vancouver (Canada), which compared six wastewater alternatives for the city [53], as outlined below.

The Fidelis Resource Group (FRG) was tasked by Metro Vancouver to assess possible alternatives for Integrated Resource Recovery, evaluate these alternatives across economic, environmental and social criteria (i.e. estimating the triple bottom-line (TBL) [54]), and to make a recommendation for the most desirable option. The report includes a matrix that shows the assessment of the six alternative solutions (Table 2). The left panel lists the thirty-six criteria used in the report, grouped as 'economic' or 'environmental' or 'social'. The table on the right shows how each alternative (a column) was assessed with respect to each criterion (a row). The assessments are specified as either gains / losses / or no-changes with respect to the status quo (i.e. alternative #2). The matrix makes it possible to compare the alternatives. For instance, the alternative in column one is worse than the status quo in most of the economic criteria, while the alternative in column four is much better than the status quo on most of the economic criteria. The number of arrows provides a quantitative assessment of how much better (or worse) the alternative is as compared to status quo.

We applied ValueCharts to the information contained in the matrix (see left instance of Fig. 10). In ValueCharts, the criteria are listed on the left side, and the associated quantitative assessments are presented as bar charts on the right, instead of arrows. ValueCharts does not, per se, distinguish between a status quo alternative vs. other alternatives, but such a distinction can be easily conveyed, for instance, by adding a dashed line in each cell for the corresponding assessment of the status quo alternative (see Fig. 11 for an example), so that it is clear which alternatives are gaining/losing with respect to the status quo and by how much. Finally, the cumulative assess-



ments of the alternatives are visualized in ValueCharts by the stacked bars on the right.

The example shows that ValueCharts offer several improvements, when compared to the static matrix shown in Table 2. It not only allows different criteria to be assigned different weights, but it also supports interactive adjustments of the weights so that users can explore the trade-offs between the different criteria. For instance, Fig. 10 depicts three scenarios showing economic (black), environmental (dark grey) and social (light grey) factors. The figure depicts: the same information as that given in the original FRG report, in which all three types of criteria are weighted equally (left), a scenario where environmental and social criteria are weighted more heavily (center), and a scenario where specific criteria were selected (right). The outcome of different weight applications are shown by the cumulative bar charts, where each column effectively depicts the overall evaluation of a different wastewater system as a sum of its evaluations on the three types of criteria. It is clear that each weighting scheme can rank alternative wastewater systems quite differently. The ease with which one can visualize the impact of changing weights facilitates analysis and discussion on the pros and cons of the different alternatives and thus support a more informed final decision.

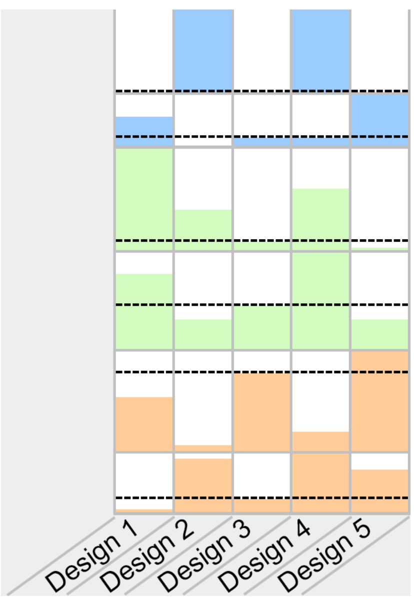


Fig. 11 ValueCharts example in which Design3 is the status quo.

4. Discussion and next steps

Guest et al. [13] discuss the challenges in moving forward with sustainable wastewater management, where decisions being made are based on feedback from engineers as well as other involved parties. They propose a framework that would allow inclusion of various stake-holder groups as part of the decision process, but clarify that this is a challenging endeavor. In light of these challenges, a DSS can prove to be a valuable tool. However, most DSSs built to support decisions in this field focus primarily on the technical and economic aspects. Only a few have moved in the direction of a design approach guided by a sustainability-oriented analysis [21]. In this paper, we have presented a prototype for a DSS which can support decision analysis in which sustainability is the central focus. Our DSS is unique in that we use an explicit ontology, which helps to define criteria, components, products and community contexts. This ontology enforces a set of underlying rules that provides structure for adding criteria and components. This structure feeds into the design generation module and enables us to scale the DSS to include additional components without having to define where they fit within a treatment system. Rather, the system is able to build these compatibilities during run-time, and dynamically construct solutions for a given community context. Most importantly, our DSS integrates an interactive visualization system which allows users to change preferences in real-time and explore the trade-offs between the set of alternative solutions. The integration of the various data structures and the two modules provides the basis for a DSS, which can be used to support the decision process identified in [13], targeted for sustainable wastewater management.

Although the framework is well-defined, the tool is still a prototype and must be further developed to be useful in real applications. Nevertheless, we have laid the groundwork for a DSS which addresses the criteria found in Hamouda et al. [20]: that an advanced level of reporting should not only include the presentation of an optimal solution and the associated costs and definition parameters, but it should also enable comparison of alternatives and perhaps provide alternative solutions in the case that an input variable changes. The framework of our DSS is well-suited for the type of reporting proposed by Hamouda et al. [20], because the method that creates alternative solutions feeds directly into the interactive decision aid. In this way, when a preference model changes, the DSS could quickly locate a new optimal solution. This kind of interaction has the potential of greatly enhancing the user's experience of brainstorming solutions and understanding how their preference model affects the presented solutions.

Previous studies suggest that ValueCharts are a very effective set of visualization and interactive techniques when comparing alternatives. However, in applying this tool to the field of wastewater management a number of improvements can be made. The present design does not, for example, allow exploration of the proposed designs. Interaction with potential users suggest that it would be helpful if ValueCharts was adapted to display a diagram for each alternative, showing the components and their connections. We are in the process of expanding the interface to show diagrams of the designs, so the user can explore the various properties, conditions and costs for each component. Adding this layer may help to improve the sense of realism as it may be difficult to trust that a computer is capable of making appropriate suggestions.

Also, many wastewater decisions must be made with the geographical context in mind. Adding a spatial layer to the interface to show the existing infrastructure and potential alternatives (particularly with decentralized systems) would probably increase users' uptake of the aid. A spatial layer has the benefit of increasing understanding among both the technical and non-technical groups, and may help to better define the preference model.

The third area for improvement lies between the decision aid and alternative generation system. In situations where users must compare alternatives, displaying the top subset of optimal solutions might actually encumber brainstorming. In some of our pilot tests, we found that the top subset of the optimal solutions often shared similar characteristics. In a decision process where brainstorming is important, it may actually be more valuable to show not just the 'best' solutions, but a diverse set of good solutions. However, it is a major challenge to design an intelligent agent which can select this kind of subset based on the list of possible alternatives and the preference model at a given time, especially when the preference model is allowed to change dynamically. Yet this development would be a substantial advancement in wastewater DSSs.

Improvements can also be made to the design generation module. One aspect of management that is currently not modeled is the transportation of product(s) between components. Conceptually, the mechanisms for transportation are fairly simple and not extensive, but the parameters which influence the costs and capabilities of a transportation method are highly dependent on spatial phenomena. Distance is a major variable in transportation cost. The length of pipe, ditch or other forms of transportation drives much of the costs associated with this variable. However, topography, land value and geology also interact with distance to determine the cost of transportation. The major aim with the proposed tool is to help planners brainstorm systems that challenge the existing paradigm. It is therefore important that a DSS has the capacity to consider various combinations of centralized and decentralized solutions, even if this adds a possibly complex new dimension to alternative generation. Our method for generating alternatives is based on a modular approach of combining components to form a system. This modular approach can facilitate the exploration of the different arrangements of components between available locations for infrastructure. However, in order to provide a realistic costing mechanism, the costs of transportation must be appropriately dealt with.

The prototype is able to find a solution when all outputs have been managed. In the previous section, in which we highlighted an example of a city context, as we explored options which allowed up to eight different components to be combined together, there were well over 100,000 possible alternatives. This large number is partly due to the fact that the current system does not combine similar output products derived from different components. If the model could infer that output streams should be combined based on proximity, then the number of components necessary to build a solution would be reduced and it would increase the efficiency of the system.

One of the most crucial next steps for our DSS is to continue developing the ontology and expand the database of components. We have been working on defining a more complex ontology which can describe a fuller set of properties for the various components. Ideally, we should be able to adopt previous ontologies and import component databases from earlier software systems. However, most wastewater management simulation and DSS software, which describe components and their functions in great detail, were not developed to interoperate with other software or be openly shared. Exceptions exist, such as WAWTTAR [14], which includes a database of wastewater system components that can be openly accessed. We have begun mining information from WAWTTR and similar databases in order to expand our ontology and integrate the various components into our database structure.

The largest challenge is to ensure that the functions are well defined and understood. The functions for treatment are well understood by engineers, but there are other functions which are less understood or quantified. For example, the emission of green house gases (GHGs) are not quantified for all components. While in the case of a biogas reactor, these calculations are well known because they are important for measuring energy capture efficiency, for components such as aerated ponds, the emission of GHGs are less understood.

5. Conclusion

The decision support system described in this paper is intended to help planners integrate feedback from engineers, elected officials, and others, and facilitate exploration of possible wastewater solutions that meet their community's goals and best fit their values. The DSS supports many of the planning processes suggested by [13], particularly by promoting brainstorming, by evaluating alternatives and by informing users of how changing values influence their preferred design. The aim is to develop a DSS that supports the planning and decision making process from a sustainability-oriented analysis approach, rather than the more common technical/economic approaches [20].

Our DSS consists of a combination of data structures and two software modules. The data structures are defined by an ontology, which has the advantage of facilitating the adherence of different information sources to a common terminology [24]. This lays the foundation for collaborative work involving individuals from different backgrounds, both technical and non-technical, so that they can contribute to the ontology and databases openly without having to understand in detail how their contribution is related to that of others. The design generation module uses these data structures, and is able to modularly design alternative wastewater solutions. Whereas other DSS often use a predefined set of rules specifying how various components in a system fit together, our DSS discovers the compatibility dynamically. The solutions derived from this module are then evaluated using the decision aid module, ValueCharts, to interactively explore trade-offs between these solutions.

In this paper, we have developed a DSS prototype that, when fully developed, can effectively help community planners explore the design space of sustainable wastewater solutions that is relevant for their particular context, and identify solutions that balance environmental, economic and social needs. As the shift toward sustainable wastewater management continues to emerge, we anticipate that tools like ours can help improve innovation and help communities meet their sustainability goals.

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Brent. C. Chamberlain is a Postdoctoral Fellow in the Institute for Resources, Environment and Sustainability at the Univ. of British Columbia. He will be an Assistant Professor at Kansas State University beginning Fall of 2013. He received his Ph.D. in Forestry, developing automated geospatial tools to aid planners. He was awarded an Alexander Graham Bell Canada Graduate Scholarship from the National Science and Engineering Council of Canada, and has co-authored grants supporting academic-industrial partnerships to improve natural resource planning. Dr. Chamberlain's research spans a variety of fields including: landscape planning, forestry, geographic information science, computer science and environmental psychology. His research focuses on improving decision making by developing tools and methods to better inform decision makers.

Giusppe Carenini, Ph.D. received his Ph.D. at the University of Pittsburg and is an Associate Professor in Computer Science at the Univ. of British Columbia. He is a member of the UBC Institute for Computing, Information, and Cognitive Systems (ICICS) and an Associate member of the UBC Institute for Resources, Environment and Sustainability. His work on natural language processing and information visualization to support decision making has been published in over 80 peer-reviewed papers. Dr. Carenini was the area chair for "Sentiment Analysis, Opinion Mining, and Text Classification" of ACL 2009 and the area chair for "Summarization and Generation" of NAACL 2012. He has recently co-edited an ACM-TIST Special Issue on "Intelligent Visual Interfaces for Text Analysis". In July 2011, he published a co-authored book on "Methods for Mining and Summarizing Text Conversations". Dr. Carenini has also extensively collaborated with industrial partners, including Microsoft and IBM. Giuseppe was awarded a Google Research Award and an IBM CASCON Best Exhibit Award in 2007 and 2010 respectively.

Gunilla Öberg is a Professor at the Institute for Resources, Environment and Sustainability, at the Univ. of British Columbia. Dr. Öberg finished her five year term as director of IRES in 2011. Before arriving at UBC, she was the founding director of the Centre for Climate Science and Policy Research at Linköping University, Sweden. She is acknowledged for her ability to lead complex interdisciplinary environmental projects involving experts in the social sciences, humanities, natural sciences and engineering. In 2010 she authored a book titled "Interdisciplinary Environmental Studies – A primer", published with Wiley and Blackwell. Current research interests: Sustainable wastewater management in growing urban areas; Interdisciplinary research and education; chlorine biogeochemistry. She is a member of AAAS, AGU, International Water Association and Canadian Water Association.

David Poole is a Professor of Computer Science at the Univ. of British Columbia. He has a Ph.D. from the Australian National University. He is known for his work on assumption-based reasoning, diagnosis, relational probabilistic models, combining logic and probability, algorithms for probabilistic inference, representations for automated decision making, probabilistic reasoning with ontologies, and semantic science. He is a co-author of two AI textbooks, Artificial Intelligence: Foundations of Computational Agents (Cambridge University Press, 2010), and Computational Intelligence: A Logical Approach (Oxford University Press, 1998), co-chair of AAAI-10 (twenty-Fourth AAAI Conference on Artificial Intelligence) and co-editor of the Proceedings of the Tenth Conference in Uncertainty in Artificial Intelligence (Morgan Kaufmann, 1994). He is an associate editor of AI Journal and is on the editorial board of AI Magazine. He is the secretary of the Association for Uncertainty in Artificial Intelligence, and is a Fellow of the Association for the Advancement Artificial Intelligence (AAAI).

Hamed Taheri is a PhD student at the Institute for Resources, Environment and Sustainability, Univ. of British Columbia. He did his M.Sc. research in discovering knowledge from a complex database about the effects of supply and demand policies on groundwater resources. He was a GIS manager in ITOK Co., Iran, where he was working on different spatial analysis tasks in Water and Wastewater systems. His research focuses on applying a artificial intelligence, data mining and information visualization methods to support decision making in complex environmental systems.