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USING MULTI-OBJECTIVE OPTIMISATION TO MAXIMISE MULTIPLE BENEFITS FOR SUSTAINABLE DRAINAGE DESIGN

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Sustainability has become the main focus of modern infrastructure design. Drainage design is no exception. The shifted design focus means the supporting documentation and computer-aided design software also require modification. For that purpose, a new decision support system that evaluates multiple aspects of drainage systems and narrows down feasible design options with optimisation techniques has been developed. This paper explains the optimisation component of the decision support system and then illustrates how it can be used to maximise multiple benefits for sustainable drainage design.

INTRODUCTION

For many years, drainage design was mainly about providing sufficient network capacity. This traditional approach had been successful with the aid of computer software and technical guidance (DoE/NWC, 1981). However, the drainage design criteria had been evolving due to rapid population growth, urbanisation, climate change and increasing sustainability awareness. Going forward, an alternative approach using a combination of traditional (e.g., pipes and storage) and green infrastructures (e.g., ponds, swales, wetlands) is recommended. In UK, drainage systems using this sustainable approach are generally regarded as Sustainable Drainage Systems (SuDS) (Woods-Ballard et al., 2007). Similar systems are called Low Impact Development (LID) or Best Management Practices (BMPs) (USEPA, 2006) in US and Water Sensitive Urban Design (WSUD) in Australia (Brown et al., 2007). In this paper, the term sustainable drainage system is used for consistency.

Although the concepts and guidance had already been communicated to decision makers and public for years, network capacity still remains a key design focus in many circumstances while uptake of sustainable design remains poor (Woods-Ballard, 2012). New guidance and computer software are needed to assist decision makers. For this purpose, a new decision support system has been developed by Chow et al. (2013). The system consists of two main components – a multi-criteria evaluation framework for drainage systems and a multi-objective optimisation framework. One can systematically quantify the performance, life-cycle costs and multiple benefits of different drainage systems using the evaluation framework. The optimisation tool can assist users to determine feasible combinations of design parameters such as sizes, order and type of drainage components that maximise multiple benefits. In this paper, the optimisation framework and its usage are illustrated with examples.

CHALLENGES

Despite years of effort in developing and promoting green design, many drainage design and practitioners still struggle to move away from the conventional approach. We summarise the key challenges below:

1. Legislative requirements for drainage design and approval are complex and they are evolving constantly with European Union directives.
2. Lack of common understanding and agreement. For example, in UK, survey showed that leading sustainable drainage experts disagree with the National Standards for Sustainable Drainage Systems due to incorrect or omitted technical details (Hydro, 2013, Woods-Ballard, 2012).
3. Uncertainty of long-term government support (Hydro, 2013).
4. Green designs lack well-documented, well-practiced and computer-aid decision support – unlike their conventional counterpart.
5. Benefits of green infrastructures are unclear to practitioners.

OUR VISION

In order to bridge the gap in the market, we decided to develop a new decision support system which allows straight forward, transparent and systematic green infrastructure selection for drainage design. We summarise our vision below:

1. Quantify different aspects of drainage performance as well as monetary measures.
2. Replace the complex, iterative and laborious checking process with a systematic evaluation framework.
3. Integrate the evaluation framework with existing drainage design software.
4. Combine the evaluation framework with an optimisation engine to create a decision support system that helps narrow down drainage design options.

METHODOLOGY PART I – EVALUATION FRAMEWORK

A systematic framework has been developed by Chow et al. (2013) to evaluate drainage designs. Figure 1 below gives an overview of the framework structure. Based on this evaluation framework, different aspects of performance and monetary measures of a drainage design can be quantified systematically. Chow et al. (2014) further explains the usage of this evaluation framework with a case study in Australia.

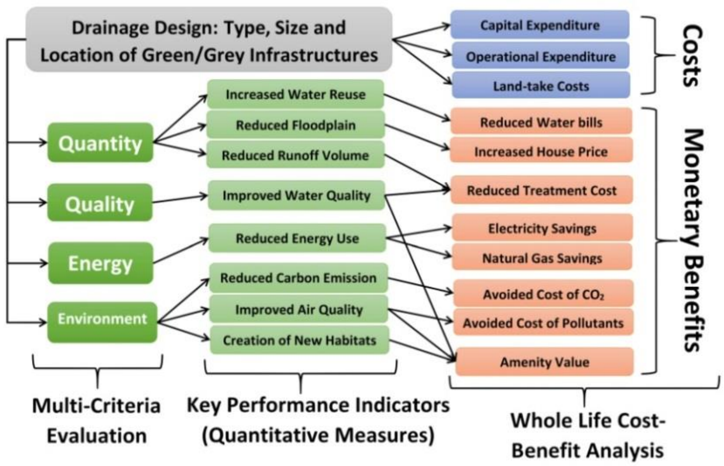

Figure 1. Overview of the systematic, multi-criteria evaluation framework.

METHODOLOGY PART II – OPTIMISATION

In order to evaluate the potential benefits of using optimisation for drainage design, a test bed model has been developed. This model was used to investigate the potential trade-off between different aspects of drainage system performance and monetary measures. This section explains the configuration of the test bed model as well as the optimisation process.

Procedures

Before implementing an optimisation engine into a full drainage modelling framework like XPDRAINAGE (XP Solutions, 2014), an investigation is needed to estimate the potential value of having the optimisation engine. The following steps have been taken:

1. Developing a simple mass balance model that simulates some of the processes in a full drainage model.
2. Connecting the test bed model with the multi-criteria evaluation framework (as described in previous section).
3. Connecting the test bed model with commonly used multi-objective optimisation algorithms. In this paper, Non-dominated Sorting Genetic Algorithm-II (NSGA-II) (Deb et al., 2002) was used for initial experiments. Further tests using other algorithms will be carried out in future.
4. Configuring and running the test bed model for different optimisation scenarios that mimic real-life decision making process in modern drainage design.

Simple mass balance model

Before testing the optimisation process with a full drainage model, a simplified mass balance model that only considers annual average estimates (e.g., annual runoff, retention, pollution removal etc.) has been developed. Assumptions such as average depth and slope are used to simplify the modelling process. Although the model cannot reflect the true complexity in a full drainage model, it gives annual performance estimates that can be linked with the evaluation framework. This is a much needed first step to look at the potential impact of choosing different drainage systems and size variation. Figure 2 below illustrates how the surface area of location is approximated using a fixed number of square blocks in the simple mass balance model.

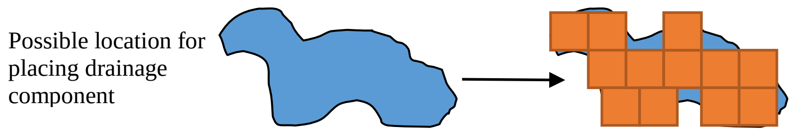

Figure 2. Approximation of surface area in the simple mass balance model.

Configuration of optimisation test bed model

For the initial optimisation experiments, a drainage system with three linearly connected locations has been set up. A schematic plan of the system is shown in Figure 3 below.

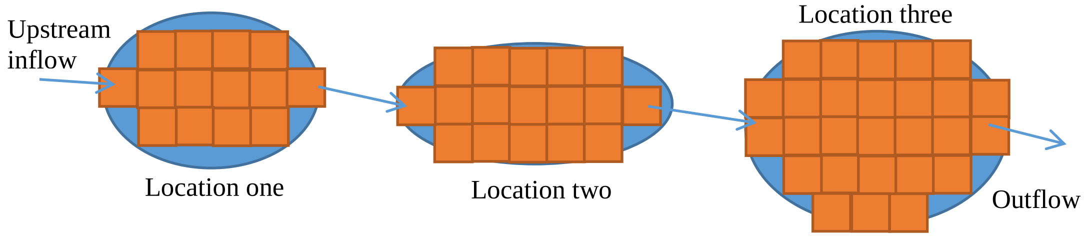

Figure 3. Configuration of test bed model for optimisation.

At each location, the optimiser can choose from 16 types of drainage systems (including swales, permeable pavement, retention pond, storage tanks etc.). The optimiser also has the freedom to utilise none or all surface area available. In other words, each location has two decision parameters (drainage component type and area in terms of number of blocks). For example, at location one, the first decision variable, component type, can be any integer between 1 and 16 while the second decision variable, number of blocks, can be any integer between 0 and 14. In this example, each block represents an area of $10m^2$ (making the blocks smaller, say $1m^2$, can provide better approximation of surface area at the expense of higher cost of computation).

Configuration of optimisation scenarios

Three scenarios, each representing a typical situation in real-life decision making, have been chosen for demonstration purpose. For example, the performance of runoff retention, total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) removals are selected as they represent a key trade-off between water quantity and water quality in design. Capital expenditure (CAPEX) and carbon emission are selected to show how the picture might change when economics and environmental factors are considered.

A simple constraint is set on the minimum runoff retention. As previous studies suggest, different sustainable drainage systems can achieve annual runoff retention ranging from 40% to 82.5% (CNT, 2010). A threshold of 75% annual retention is set for the purpose of initial experiments. Any solution that retains less than 75% annual runoff is dropped from the final results. The basic configurations of the optimisation runs are summarised in table 1 below:

Table 1. Configuration of three selected optimisation runs.

Scenario	Objectives	Constraint	Minimisation	Maximisation
One	Two	A valid solution must be able to retain at least 75% of annual runoff (mimicking flood management)	N/A	Runoff retention and TSS. removal
Two	Three		CAPEX	Runoff retention and TSS removal
Three	Five		Carbon emission	Runoff retention, TSS, TN and TP removal

RESULTS AND DISCUSSION

Scenario one: two-objective constrained optimisation

In the first scenario, the optimisation engine was configured to maximise both runoff retention and TSS removal. Figure 4 below shows the Pareto front of the run:

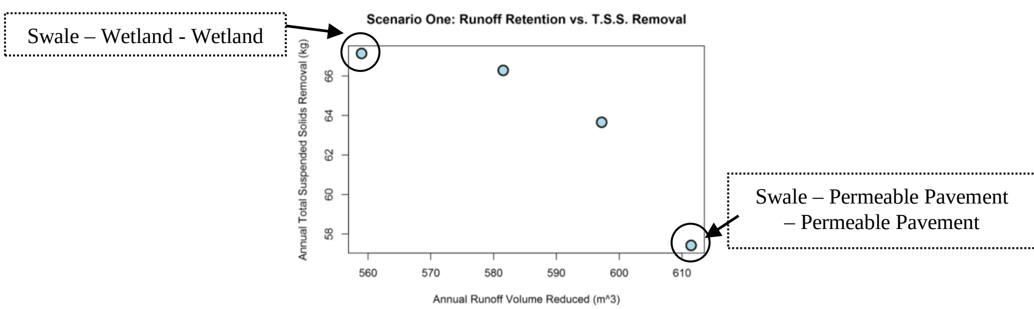

Figure 4. Pareto front from scenario one.

A simple and obvious trade-off between the two objectives can be observed from this run. This is explainable as some of the drainage components (wetlands) are better at solids removal than others (permeable pavement). Yet, those systems might not be as effective as others in runoff retention. Therefore, by combing different types of drainage components, one can design a system that handles both runoff retention and solids removal adequately. In this case, only four Pareto front solutions were observed due to the simplicity of the problem. The next two scenarios show that the number of solutions increases as more objectives are involved.

Scenario two: three-objective constrained optimisation

In the second scenario, one more objective was added into the mix. This time the optimiser was configured to consider three different objectives. In addition to runoff retention and TSS removal, CAPEX is also being minimised. By including a third objective, the number of two-dimensional Pareto front has increased from one in the previous optimisation to three in this run. The results are shown in figure 5 below:

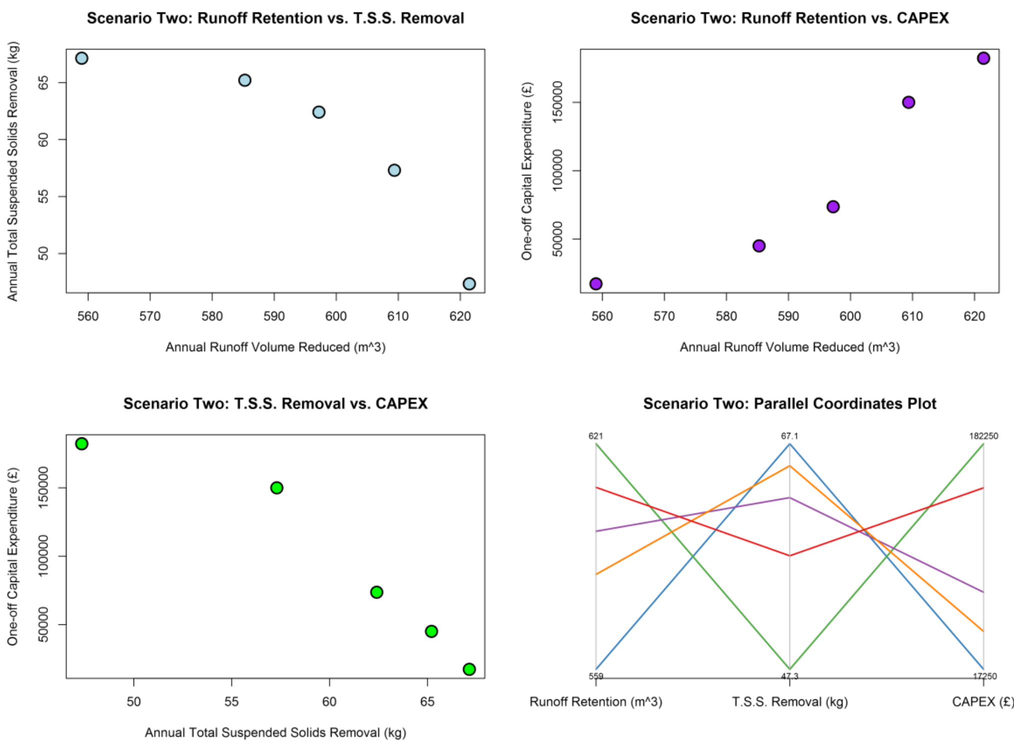

Figure 5. Pareto fronts and parallel coordinates plot from scenario two.

A clear trade-off between runoff retention and total suspended solids removal (top left) can still be observed. That is similar to the trade-off described in the previous scenario. Moving on to the next trade-off pair – runoff retention vs. capital expenditure (top right), there is also an obvious trade-off. Drainage design options that are better in runoff retention (i.e., permeable pavement components) incur higher material and construction costs. Yet, the increase in runoff retention also has a trade-off in successful solids removal. This is visualised in the first and third (top and bottom left) charts.

In order to make better use of all trade-off information, it is useful to visualise all trade-off solutions on the same graph. Parallel coordinates plot is one of the techniques suitable for this purpose (bottom right). By comparing the performance in multiple dimensions, decision makers can identify cost-effective options that are adequate for both runoff retention and solids removal.

Scenario three: five-objective constrained optimisation

In the final run, there are ten two-dimensional trade-off graphs in this five-objective scenario (compared to one and three in previous runs). In order to keep all initial experiments consistent, NSGA-II was used in this scenario. Algorithms which are more suited for optimisation with three or more objectives will be investigated in future. Results of this run are shown in Figure 6 below:

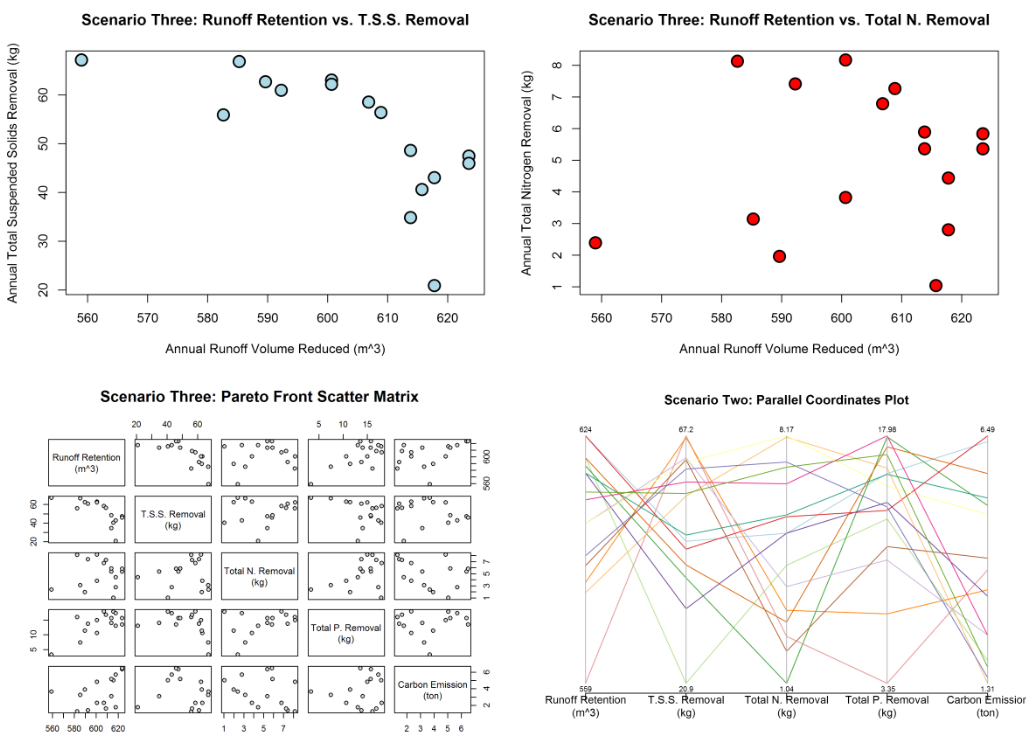

Figure 6. Pareto fronts and parallel coordinate plot from scenario three.

The relationship between runoff retention and TSS observed from the previous two runs still roughly holds in this scenario (top left). Yet, other trade-offs appear to be scattered. For example, there is no clear trade-off between runoff retention and total nitrogen removal (top right). The same scattered relationship is found in the rest of two-dimensional Pareto fronts.

This is valuable finding as it demonstrates that the relationships in most of the trade-off pairs are non-linear and complicated. This justifies the use of multi-objective optimisation techniques as well as adequate visualisation methods. Going forward, an integrated software platform that combines drainage design models (XPDRAINAGE), evaluation framework, optimisation engine and visualisation will allow decision makers to identify the most favourable trade-offs and design options efficiently.

CONCLUSION

As the focus of drainage design shifted from ensuring sufficient network capacity to maximising multiple benefits, new decision support tools are needed to assist decision making process. This paper illustrates the increasing complexity in the decision making process when multiple objectives are involved. Results from initial experiments show that the trade-offs between objectives can be complex and non-linear as more objectives are considered.

Further experiments are required to better understand the complex relationships between different objectives and the efficiency of different optimisation algorithms. Visualisation is also an important area for research and development. The long-term goal of the project is to fully integrate the evaluation framework, optimisation engine and visualisation techniques with drainage design software. This will streamline the workflow and provide evidence-based decision support throughout the drainage design cycle.

ACKNOWLEDGEMENT

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