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Pre-emption strategies for efficient multi-objective optimization: Application to the development of Lake Superior regulation plan

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ABSTRACT

A wide variety of environmental management problems are solved with a computationally intensive simulation-optimization framework. In this study, the “model pre-emption” strategy is introduced for increasing the efficiency of solving such multi-objective optimization problems. This strategy makes the optimization algorithm avoid the full evaluation of predictably inferior solutions, is applicable to many optimization algorithms, and does not impact the optimization results. Multi-objective pre-emption is used to optimize a new regulation plan for Lake Superior. The new plan is designed to mitigate extreme water levels and increase the total regulation benefits. The rule curve parameters defining the plan are obtained from a multi-objective, multi-scenario optimization problem. Results show that model pre-emption drastically increases the efficiency by up to 75%. The optimized regulation plan outperforms the current plan under the historical scenario. Notably, the optimized plan successfully handles an extremely dry scenario in which the current plan fails to maintain reasonable lake levels.

1. Introduction

Engineering design problems can often be cast as simulation-optimization frameworks. Example applications of simulation-optimization frameworks for designing water resources and environmental engineering systems include but not limited to the development of reservoir operation policies (Kim et al., 2008; Labadie et al., 2012), calibration of hydrologic models (Duan et al., 1992; Zhang et al., 2013), design of sorptive barriers (Matott et al., 2012), and design of pump-and-treatment systems (Finsterle, 2006). As outlined in Bennett et al. (2013), environmental and water resources design problems may have to be evaluated against multiple objectives simultaneously to meet all the design goals. Such problems can be solved in a multi-objective optimization (MO) formulation.

Some of the simulation-optimization problems embed computationally intensive simulation models, and therefore, the analysts must find an efficient optimization approach to solve such problems within the given (often limited) computational budget. Razavi et al. (2010) categorized the various approaches that tackle the limited computational budget issue in the simulation-optimization problems under the following four broad families: surrogate modelling (also sometimes called metamodelling and model reduction), utilizing parallel computing networks, developing and utilizing computationally efficient optimization algorithms, and opportunistically evading model evaluations. Among them, surrogate modelling appears to be the most popular topic in the research area with an increasingly large body of literature (Razavi et al., 2012). However, as pointed out in Razavi et al. (2010), the latter option which may be referred to as “pre-emption strategies” may be deemed as a much simpler (but probably not as efficient) alternative to surrogate modelling for circumventing computational burdens. Razavi et al. (2010) developed a deterministic “model pre-emption” strategy that increases the optimization efficiency by terminating the evaluation process of the objective function for solutions whose low quality becomes evident before the exact objective function value becomes available. The term “deterministic” in this context indicates that the application of this strategy would not involve any new source of stochasticity or approximation (unlike e.g. surrogate modelling), and it would lead to the exact same optimization result as when it is not applied while gaining considerable optimization efficiency. Interested

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readers are referred to Razavi et al. (2010) for more details about the model pre-emption in single-objective optimization. Matott et al. (2012) showed that in design problems where the monetary cost of a design (solution) can be evaluated independently from its performance (e.g. level of treating hazardous waste in sorptive barrier design problems) that requires the model simulation, the so called cost pre-emption can happen without running the computationally intensive simulation model. Therefore, Matott et al. (2012) distinguished between the model pre-emption and the cost pre-emption. Example applications of the cost pre-emption can be found in sorptive barrier design problems as in Matott et al. (2012) and in water distribution network design problems as in Tolson et al. (2009).

In this study, the model pre-emption concept is extended to MO problems. The developed multi-objective pre-emption strategy utilizes the dominance concept to adaptively and objectively define the multi-objective pre-emption thresholds and is deterministic in that it leads to exactly the same optimization results as when it is not applied. This strategy is applicable to a range of multi-objective optimization problems and algorithms. The suitability of MO problems and some popular MO algorithms are discussed in Sections 2.1 and 2.2.

The model pre-emption is used to increase the efficiency of a recently developed MO algorithm called Pareto Archived Dynamically Dimensioned Search or PA-DDS (Asadzadeh and Tolson, 2013) applied to the problems for developing a new regulation policy for Lake Superior. Lake Superior is the most up-stream lake in the Great Lakes river-reservoir system, the largest source of surface freshwater in the planet and forms a portion of the Canada–United States border. This system is often considered as two different segments, the upper Great Lakes and the Lake Ontario – St. Lawrence River, that are connected by the Niagara River. From upstream to down-stream, the upper Great Lakes are Lake Superior, Lake Michigan–Huron (considered to be a single lake for hydraulic purposes), Lake St. Clair, and Lake Erie that are serially connected by St. Marys River, St. Clair River, and Detroit River, respectively. Currently, there is only one set of control structures in the upper Great Lakes that is located at the outlet of Lake Superior to regulate its outflow. The upper Great Lakes system and its regulation plan impacts the diverse interests of more than 25 million people of the two nations. Clites and Quinn (2003) reviewed the Lake Superior regulation chronology from the first regulation plan approved in 1921 to Plan 1977A. Plan 1977A is the current regulation plan for Lake Superior and has been fairly closely followed since 1990.

At the direction of the International Joint Commission (IJC), the following objectives were identified in the International Upper Great Lakes Study (IUGLS) (2012) for developing alternative regulation plans for Lake Superior:

a) To enhance the health of coastal and riverine ecosystems
b) To protect shorelines and reduce flooding, erosion damages
c) To alleviate the impact of low water levels on the value of coastal property
d) To reduce the navigation costs
e) To maintain or increase the benefits of hydropower generation
f) To maintain or increase the value of recreational boating and tourism opportunities
g) To improve municipal-industrial water supply withdrawal and wastewater discharge capacity

Razavi et al. (2013) addressed the IUGLS goals by proposing a multi-lake regulation of the system with the main objective of evaluating the construction of new control structures on the Saint Clair and Niagara Rivers. They develop a multi-lake regulation plan that accounts for benefits and costs across the Great Lakes – St. Lawrence system in regulation of the exiting control structure and also two potential (hypothetical) control structures. This manuscript is the first study that develops a regulation plan in the form of a simple parametric rule curve to be described in Section 3.5.1 for Lake Superior with the aforementioned objectives without assuming any structural changes to the Upper Great Lakes system.

In practice, reservoir operation policies are heuristic rules that have been empirically developed and evolved over time. The work by Hufschmidt and Fiering (1966) appears to be the first study that proposed a systematic approach to develop reservoir operation policies in the form of desirable parametric rule curves. In this approach, various sets of parameter values are assessed by simulating the model to designate the best set of parameters defining the best rule curve. Similar parametric approaches that utilized global optimization algorithms to directly obtain optimal parameter values of the parametric rule curves can be found in Oliveira and Loucks (1997), Nalbantis and Koutsoyiannis (1997), Koutsoyiannis et al. (2002), Chen et al. (2007), Kim et al. (2008), and Afshar et al. (2011).

In an alternative approach, one could assume perfect foresight of the water supply sequences for the optimization period and directly optimize the release values. This approach would often be followed by a regression analysis to fit a rule curve to the optimal release values. Example applications of this approach include Young (1967), Bhaskar and Whitlatch (1980), Hiew et al. (1989), Karamouz et al. (1992), Malekmohammadi et al. (2009), and Labadie et al. (2012). This approach was called the high dimensional perfect foresight approach by Koutsoyiannis and Economou (2003) and its number of decision variables increases as the length of the optimization period increases. Therefore compared to the parametric approach, the high dimensional approach typically requires larger computational budgets for longer optimization periods. This is the main disadvantage of the high dimensional perfect foresight approach in reservoir operation problems, because often a long optimization period that represents various possible future water supplies is required to achieve a robust rule curve. Parameters of the proposed rule curve for regulating the Lake Superior outflow are directly obtained by solving the simulation-optimization problems to be described in Sections 3.3–3.5.

As noted in Labadie (2004), if the real-time data (inflow and demand forecasts) is available and the short-term (daily or subdaily) control of the reservoir is of interest, the long-term (monthly or seasonally) operating policies could be adapted for real-time control of the system. Example application of the real-time control of the reservoir include: effectively controlling floods as in Hsu and Wei (2007) and Malekmohammadi et al. (2010), increasing hydropower generation benefits as in Hayes et al. (1998), and/or developing cost-effective and risk-informed decision making tools for water quality management as in Mesbah et al. (2009). Since the Lake Superior control structures, i.e. gate settings, are operated in a monthly basis, the real-time control of the system is not considered in this study.

2. Model pre-emption in multi-objective optimization

In single-objective optimization problems, the model pre-emption is applicable when the full evaluation of a solution can be divided into a series of shorter sub-evaluations and the objective function is monotonically degrading as each sub-evaluation is performed. In such problems, the model pre-emption is referred to the early termination of a solution evaluation as soon as the objective function value of that solution becomes worse than a pre-emption threshold. A similar terminology is applicable to MO problems by defining the pre-emption thresholds on all objectives.