Reducing Construction Carbon Emissions in Logistics: The Dynamic Bowser Routing Problem

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Abstract. This work presents the results from the project RECCEL (REducing Construction Carbon Emissions in Logistics), where our team collaborated with Costain, the major UK provider of transportation engineering solutions, and CENEX, a UK leading expert in low carbon transportation solutions. We investigate opportunities offered by telematics and analytics to enable better informed, and more integrated, collaborative management decisions on construction sites. The major barriers to a fully integrated low-carbon construction supply chain are identified. A set of solutions is outlined, including an Asset Monitoring Dashboard, to visualize and analyse the available data; and a decision support system for Asset Routing for Refuelling.

We focus on this later problem and we deal with the efficient refuelling of assets across construction sites. More specifically, we develop decision support models that, by leveraging on data supplied by different assets, schedule refuelling operations by minimising the distance travelled by the bowser truck as well as fuel shortages. Motivated by a practical case study elicited in the context of a study we recently conducted at the C610 Systemwide Crossrail site, we introduce the Dynamic Bowser Routing Problem. We investigate deterministic and stochastic variants of this problem. To tackle deterministic variants, we introduce and contrast a bilinear programming model and a mixed-integer linear programming model. To tackle stochastic variants, by leveraging on a new general purpose software library for stochastic modeling, we introduce a complete stochastic dynamic programming model, as well as a novel heuristic we named "sample waning." We demonstrate the effectiveness of our approaches in the context of an extensive computational study designed around information and data collected at C610 Systemwide and/or supplied by our project partners.

Keywords: Dynamic Bowser Routing Problem; Mixed-integer Linear Programming; Stochastic Dynamic Programming; Sample Waning; Construction.

1 Introduction

The UK National Infrastructure Plan comprises a pipeline of public investment in infrastructure worth over £100 billion to 2020 [7] and has clear aspirations for low-carbon solutions [5, 6]. In the context of a public-private partnership funded by Innovate UK, our team investigated opportunities offered by telematics and analytics to enable better informed, and more integrated, collaborative management decisions on construction sites. We considered a selection of Crossrail costruction sites at a strategic UK infrastructure project for which Costain is one of the main contractors.

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The field of Inventory Routing (IR), whose origins can be traced back to the work of [2], encompasses problems which combine vehicle routing and inventory management decisions. In IR optimisation is delegated to a central entity that jointly optimises all decisions. See [3, 1] for recent surveys. Stochastic IRP problems, in which customer demand is modeled as a random variable, include the seminal work by [4], and a number of more recent contributions [8, 9].

2 The Dynamic Bowser Routing Problem

We consider a construction site with M assets (e.g. generators, telehandlers, excavators, etc) all powered by a single type of fuel (e.g. diesel). The construction site map is given; more specifically, this map takes the form of a directed graph $\langle V, E\rangle$, where V is the set of nodes and E is the set of arcs; we assume this graph to be connected, but not necessarily fully connected. Nodes in V represents relevant locations across the construction site, while arcs in E represent distances between locations.

We consider a discrete planning horizon that comprises T periods. At each point in time, an asset $a = 1, \ldots, A$ can be found in one and only one node $v \in V$; in practice, on the basis of its GPS location an asset will be associated to the nearest node in the site network. We assume that asset location $l_t^a \in V$ at each time period $t \in T$ is known with certainty. Each asset a features a fuel tank with capacity c_a; fuel consumption $f_t^a \geq 0$ for an asset at a given time period $t \in T$ is given and known with certainty.

The construction site features a site cistern where an infinite amount of fuel is assumed to be available. There is a single bowser truck that can be used to refuel assets. The bowser features a tank with capacity c_b; when the bowser tank is empty, the bowser must return to the site cistern to refill its tank.

We model movements so that the bowser can only move from a node to an adjacent one within a single time period. We assume that refuelling of an asset takes a negligible time in relation to the size of time periods, and that refuelling can be performed if, at a given time period, both the bowser and the asset are located at the same node. If an asset stocks out of fuel, we enforce a penalty cost p per litre of fuel short at the end of a given period.

3 Methodology

Different models are proposed for the problem described in Section 2. First, we develop three reformulations: a bilinear programming model, a mixed-integer linear programming model, and a dynamic programming model that can tackle deterministic as well as stochastic variants of the problem. In order to numerically assess the performance of these formulations, we develop a comprehensive testbed comprising instances that tightly resemble real world scenarios observed in the context of our experience at Crossrail sites and we carry out a thorough computational study based on it. The proposed formulations are compared to a myopic heuristic that has been inspired by our discussion with site managers and by the analysis of the data obtained by fitting a logger on the bowser truck. Finally, we evaluate the impact of stochasticity.

4 Results

Our mathematical programming models scale well and can tackle instances of realistic size in reasonable time: less than 10 minutes on average. Our analysis demonstrates that a practice-inspired myopic heuristic is considerably suboptimal and can lead to refueling plans that are, on average, 79.4% more costly in terms of distance covered by the bowser, and that lead to an increase of 53.1% for asset fuel shortages. By using a stochastic dynamic programming reformulation for stochastic variants of the Dynamic Bowser Routing Problem we estimated the impact of stochasticity associated with fuel consumption, which leads to an increase of 17% in the objective value. Furthermore, we showed that a novel heuristic named sample waning, which we implemented in our `jsdp` library, can be employed to obtain near-optimal plans under asset fuel consumption or location uncertainty. In the case of fuel consumption uncertainty, this heuristic reduced the solution time from 48 minutes — required to solve the SDP problem to optimality — to few seconds.

5 Conclusion

We demonstrate that a myopic heuristics for asset refuelling, inspired by our conversations with site managers and by data obtained by logging a bowser truck, is considerably suboptimal. We demonstrate that our mathematical programming models scale well and can tackle instances of realistic size in reasonable in particular, the mixed-integer linear programming model appears to be the most efficient formulation. Finally, by leveraging on our stochastic dynamic programming reformulation, we demonstrate the impact of stochasticity and show that uncertainty can have a substantial impact on distance travelled by a bowser truck.

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