A GRASPxELS approach for the multi-product pipeline scheduling problem

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1 Introduction

1.1 Research context

The pipeline is the most reliable and economical transportation mode for large amounts of liquid and gaseous material, and it is mainly used in petroleum industries to transport petroleum and derived products (Rejowski and Pinto 2003). Recently, it has been adopted for the transportation of liquid-solid slurry of phosphate ore in mining industry (Bamoumen et al. 2022). Phosphate ore is mined and beneficiated into phosphate rock. The mined ore is crushed and washed, creating a slurry before to be treated with fatty acids to cause calcium phosphate to become hydrophobic. It must be dried before being transported by rail or by sea. The use of pipeline allows substantial water and energy savings through wet delivery of phosphate ore. However, the construction of a pipeline involves significant costs and the scheduling of a multi-product pipeline system is a hard problem, whose complexity is NP-complete (Jittamai, 2004).

In this work, we focus on the multi-product pipeline scheduling problem. The objective is to arrange the sequence of batches of products to be transported through the pipeline on a predefined time horizon, by considering the inventory level at distribution center to ensure demand satisfaction, while minimizing associated costs. A GRASPxELS approach incorporates a randomized greedy algorithm with a repair process and an improvement procedure with batch sequence mutation operator and volume optimization operators is proposed to tackle this problem.

1.2 Problem definition

The pipeline considered in this paper consists of a straight multi-product pipeline that connects the upstream (pumping station) to a unique distribution center. Considering the following input parameters: 1) The number of products to be transported through the pipeline; 2) The planning time horizon (in days); 3) The pipeline specifications (diameter, length and pumping flow rate); 4) The inventory properties (initial inventory and storage capacity for each product); 6) The minimum and maximum volume size of batch; 7) The customer demand over the scheduling time horizon; 8) The matrix of compatibility for allowed product sequence between two consecutive batches; 9) the settling time.

The following assumptions are considered: a) the pumping flow is fixed over the planning horizon; b) The flow pumping rate is stable and the slurry flow is always turbulent; c) the pipeline must always be completely full during the planning time and the volume of batch cannot be compressed in the pipeline; (d) the settling period is hourly-based and is considered the same for all products; e) the pipeline stoppage could be caused only by the storage capacity saturation at distribution center ;f) All daily demand is uniformly distributed over the planning horizon.

The objective is to schedule a sequence of batches to ensure all daily product demand with a minimum total cost, while respecting the following constraints: i) At any time, the pipeline must be entirely full; ii) Product inventory at any time should respect its storage capacity, and should not be negative; iii) Flow conservation constraint: the entire input volume must be equal to the output volume; iv) The compatibility of two successive batches; v) Each batch contains only one product; vi) Upper and lower bounds on the volume of batch.

The rest of the paper is organized as follows: section 2 presents a literature review on the multi-products straight pipeline scheduling problems. In section 3, we detail the proposed approach, and section 4 provides a case study. Finally, section 5 describes the conclusion and perspectives of future work.

2 Literature review

In the literature, the multi-product pipeline scheduling problem has drawn the attention of many researchers over the last decades. Most of the existing work on pipeline scheduling concerns the petroleum industry. The multi-product pipeline scheduling problems can be classified according to the pipeline structure: straight pipeline, tree structure, and network. Moreover, the straight pipeline scheduling problems can be divided into the three following categories considering different topologies: One-to-One: pipeline with a single source and a single destination; One-to-Many: pipeline with a single source and several consecutively arranged destinations. In this paper, we focus mainly on the work related to the one-to-one straight pipeline scheduling problems.

2.1 Related works on the one-to-one straight pipeline scheduling problems

In the literature, (Shah *et al.*, 1996) and (Sasikumar *et al.*, 1997) are considered among the first works to tackle the one-to-one straight pipeline scheduling problem. (Shah *et al.*, 1996) developed a mathematical programming approach that divides the linear model into two sub models, which are solved successively. (Sasikumar *et al.*,1997) proposed a heuristic which gives the sequence of batches to be inserted in the pipeline, while considering a set of constraints including the demand and the inventory management.

(Relvas *et al.*, 2006) proposed a mixed integer linear program (MILP) that considered the inventory management at the distribution center and additional constraints such as the settling period of products. The proposed model has been evaluated on a real-world case study form the petroleum industry. In addition, (Relvas *et al.,* 2009) developed a heuristic to improve the efficiency of the linear model. The approach provides an adequate identification of feasible products sequences. (Cafaro *et al.*,2008) presented a MILP model with continuous time representation and discrete lot sizes. The model was evaluated using the case studies presented in (Relvas et al., 2006) with the fixed sequence, the mixed sequence and the free sequence scenarios. And it provided better results with less CPU time.

(MirHassani and BeheshtiAsl, 2013) presented a population-based heuristic composing a construction algorithm and an improvement procedure: the non-satisfaction of demand is tolerated in the construction step; the improvement procedure deals with a population of several best solutions and uses crossover operations between randomly selected solutions to renew the population. Several instances were randomly generated based on a real-life case study and the results show that the proposed heuristic provides feasible solutions with less computational time comparing to mathematical models.

(Relvas et al., 2013) proposed two MILP models considering different strategies on batch size: the Fixed Batch Size (FBS) the Variable Batch Size (VBS); The two models were tested by using a real-world case study and the results show that the VBS model were better in term of flexibility than those of FBS model, and with less computational time. Later, (Moradi and MirHassani, 2015) proposed a MILP model based on the work presented in (Relvas *et al.*, 2013). The authors presented a new formulation for batch sequencing, by fixe the number of daily batches to reduce the number of variables and constraints. The model provided better results using less CPU time.

(Kirschstein 2018) considered the pipeline scheduling problem as an Economic Lot Scheduling Problem (ELSP) with additional constraints. A heuristic method initially developed by (Dobson, 1992) was adapted and improved to tackle this problem, with an additional repair process to ensure the obtention of a feasible solution. The proposed heuristic was tested by considering case studies from chemical and petroleum industry, the results show that the heuristic provided feasible solutions for the scenarios considered.

(Dimas et al., 2018) proposed a MILP model that considers tanks management and settling periods for both of refinery and distribution center. The objective is to minimize the total operating cost, which is composed of the stock holding cost, the pumping cost, the cost related to the interface between successive batches and the cost related to pipeline stoppages. In addition, a solution procedure is proposed to reduce the number of variables and constraints to explore during the model solution, and is referred in the paper as the Feasible Space Reduction (FSR). The model was tested by considering three scenarios on a seven-day planning horizon.

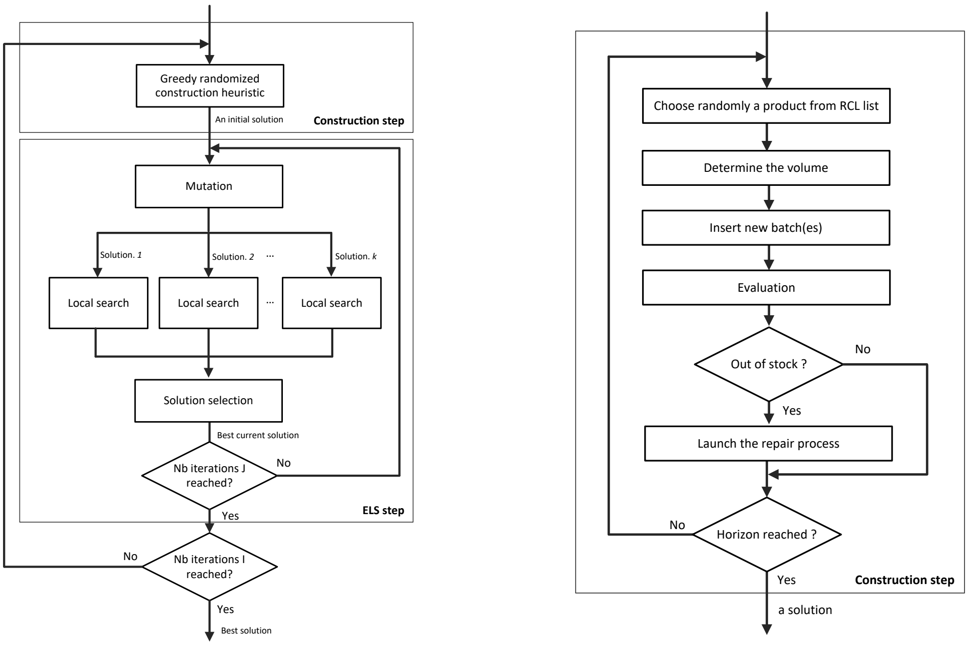
(Bamoumen et al., 2019) proposed a hybrid approach for the multi-product straight pipeline scheduling problem. The proposed approach is composed of a construction heuristic and a MILP model as a post-optimization procedure to adjust the volume of batches. It was evaluated on an instance from an operational pipeline on a one-month time horizon.

(Goudarzi et al. 2021) introduced a multi-objective model for the fuzzy multi-objective multi-product pipeline scheduling problem. The considered system consists of a single refinery, a unique distribution center and a multi-product pipeline. Some parameters of the system are formulated as fuzzy values: in order to determine tardiness and earliness penalty functions, four due dates are introduced for each product as a fuzzy due date. Two test scenarios are generated randomly with different products and flow rates. The obtained Pareto-optimal solutions are analyzed.

(Bamoumen et al., 2023) presented a MILP model with continuous representation for both time and volume formulation. A GRASP-like algorithm is proposed to tackle the straight pipeline scheduling. A set of instances was generated from a real case study. The results show that the proposed algorithm provides very competitive results comparing to the MILP model.

3 Proposed approach

The GRASPxELS is a hybridization of a GRASP with an ELS, in which the GRASP is a multi-start approach using a greedy randomized heuristic for generating initial solutions; and ELS is an extension of the iterated Local Search for solution improvement. The hybridization allows take advantages of both methods (Prins, 2009), (Duhamel *et al.*, 2010). As illustrated by Figure 1 (a), the proposed GRASPxELS approach is composed of a greedy randomized construction heuristic, an ELS step with a batch sequence mutation operator, a local search procedure, and an evaluation function.



(a) Schema of the proposed GRASPxELS (b) Greedy randomized heuristic

Figure 1: GRASPxELS approach

3.1 Greedy randomized construction heuristic

As illustrated by Figure 1 (b), the construction heuristic generates an initial solution by inserting interactively new batches. It chooses randomly a product from a restricted candidate list (RCL) for a new batch. After insertion of a new batch, the evaluation function checks the feasibility of the current solution. In case of infeasibility, a repair process which based on a remove-and-reinsert operator is applied. It uses a tree structure to identify an alternative path to replace newly inserted batches. A new batch is created for each product on the alternative path. A tabu list is employed to me memorize the explored paths to avoid repetitive search. The repair process repeats the same operations until a feasible solution is found.

3.2 Evaluation function

The evaluation function consists of determining the charging and discharging time of each batch, of updating inventory levels and calculating the related costs for a given sequence of batches. The evaluation is done in two steps: the first step uses the forward evaluation policy which aims to determine the charging and discharging time of batches as soon as possible, and updates the inventory levels.; the second step applies the backward evaluation policy. It pushes the discharging of batches as later as possible by constraints related to inventory levels and demand satisfaction.

3.3 ELS step and local search procedure

The ELS step starts with an initial solution (as best current solution) and perform the batch sequence mutation operator to generate a set of intermediary solutions. For each intermediary solution the local search with volume optimization operators is applied. The best obtained solution is selected as the current best solution and the ELS reiterates. Three volume optimization operators are proposed in the local search: the first one consist of reducing the batch size to avoid the stoppage of pipeline caused by the excess of capacity and to reduce the storage cost; The second one increases the volume of batches in order to reduce the pipeline stoppage duration; and the third one aims to transfer the volume between a pair of batches with same product. The local search procedure stops when the maximum number of iterations is achieved.

4 Computational experiments

The proposed approach is implemented in Java and all tests are performed on a PC with two AMD EPYC 7452 32-Core Processors and 500 GB of RAM under Linux (Ubuntu 20.04.5). The number of used cores is set to 1. The computational experiments have been carried out using the instances presented in (Bamoumen et al. 2023). These instances are generated using the real-world case study presented in (Cafaro and Cerdá, 2008). We consider a one-to-one straight unidirectional pipeline that transports six different products. The pipeline has a length of 147 km with a capacity of 18000 m^3. The average transfer rate of pipeline is fixed to 530 m^3/h. The settling time is fixed to 24 hours for each product. For each combination of time horizon (in days) $T \in \{8, 14, 20, 30\}$ and the number of products $P \in \{4, 5, 6\}$, we got a set of 10 instances. The performance of the proposed approach is evaluated by comparing to the MILP model presented in (Bamoumen *et al.*, 2023).

Conclusion

In this paper, we propose an GRASPxELS approach for the multi-product pipeline scheduling problem. The proposed approach is composed of a randomized greedy approach and a local search procedure. The construction method is a randomized greedy algorithm that choses randomly a product from a restricted candidate list (RCL) for a new batch. A repair process is proposed to favour the obtention of feasible solutions. The local search procedure uses batch sequence mutation operator and volume optimization operators. The computational experiments have been carried out using the instances of presented in (Bamoumen *et al.*, 2023) and the performance of the proposed approach is evaluated by comparing to the MILP model.

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