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Innovative Applications of O.R.

Planning of multi-product pipelines by economic lot scheduling models

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ABSTRACT

In chemical and petroleum industry pipelines are one of the most important means of transportation. However, flexibility of pipeline transport systems is limited by many restrictions. Therefore, the planning of pipeline operations is a crucial part of logistics management in these industries. A particularly challenging problem is the pipeline scheduling which is concerned with finding the sequences, times, and sizes of batch injections in pipeline systems. This paper specifically studies the underlying core scheduling problem by assuming a simple multi-product pipeline system. It is shown that finding a sequence of batches which minimizes stock holding and setup costs in the long run is an $\mathcal{NP}$-hard scheduling problem, namely a variant of the economic lot scheduling problem (ELSP) with additional constraints. Therefore, a powerful heuristic for the sequence-dependent ELSP is adapted and extended to meet the requirements of the outlined pipeline scheduling problem. The application of the heuristic is illustrated by case studies from chemical and petroleum industry.

1. Introduction

Pipelines are one of the most efficient modes transport w.r.t. energy consumption and, hence, variable transportation cost (van Essen, Croezen, & Nielsen, 2003). However, building pipelines incurs high investment costs. Moreover, origins and destinations are fixed once a pipeline is build and pipelines can only be used to transport liquefiable products. Hence, pipeline systems are highly inflexible and mostly used to serve unidirectional transport needs with high and steady transport demands. Traditionally, pipelines are designed for one product only, e.g., in the case of crude oil or natural gas transports. This allows optimizing the pipeline's technological configuration e.g., with respect to the energy consumption for transport. However, in chemical and petroleum industry multi-product pipelines are commonly used if the products intended to be transported are chemically similar. A necessary condition is, for example, that chemicals to be transported do not react with each other. This implies an increased flexibility, a (potentially) increased pipeline utilization and, hence, increased attractiveness of pipeline transports.

However, the more products are to be transported the more complex planning becomes. Apart from pure technical restrictions like storage or pumping capacities, also other restrictions need to be considered. This includes, for instance, safety stock requirements or pipeline inspection routines. In case of multi-product pipelines, restrictions for different products interfere and increase the complexity of pipeline operations planning. Important in managing pipeline supply systems is to balance stock holding cost and transport costs as the lack of flexibility of pipeline systems is typically encountered by keeping (safety) stocks. In case of multi-product pipeline systems, additionally set-up or product-transition times as well as costs have to be considered when switching from one product to another. Hence, besides traditional trade-offs between stock holding and transportation costs, managing multi-product pipeline systems also has to cope with the sequencing of product batches on transport systems with limited capacity. In combination, this states a highly challenging planning problem which is encountered on a daily basis e.g. in petroleum and chemical industry.

In this paper we focus on a comparatively simple problem outline in order to highlight the basic complexity of managing any multi-product pipeline system. We assume a unidirectional one-to-one pipeline system for multiple products with constant demands per time unit is considered as it appears e.g., in chemical industry to supply large-scaled production sites (Kirschstein, 2015). It is shown that the optimal sequencing and scheduling of product batches w.r.t. to stock holding and setup cost can be obtained by solving a variant of the economic lot scheduling problem (ELSP, Lopez & Kingsman, 1991) which has to be adapted according to the product separation technology of the pipeline system under study.

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Table 1
Classification of literature on pipeline scheduling.

Reference	Sys. type	Scale	Flow	Objective	Model	Solution meth.
Magatão, Arruda, and Neves (2004)	1t1	(*d*, *d*)	bi.	(*i*, *c*)	(*l*, *l*)	solver
Magatão, Arruda, and Neves (2005)	1t1	(*d*, *d*)	bi.	(*i*, *c*)	(*l*, *l*)	decomp.
Magatão, Arruda, and Neves (2011)	1t1	(*c*, *d*)	bi.	(*i*, *c*, *h*)	(*l*, *l*, *l*)	decomp.
Relvas, Matos, Barbosa-Póvoa, Fialho, and Pinheiro (2006)	1t1	(*c*, *c*)	uni.	(*u*)	(*l*)	solver
Relvas, Barbosa-Póvoa, and Matos (2009)	1t1	(*c*, *c*)	uni.	Multiple	(*l*)	heur.
Relvas et al. (2013)	1t1	(*d*, *d*/*c*)	uni.	(*u*, *h*)	(*l*, *l*)	solver
Moradi and MirHassani (2015)	1t1	(*d*, *c*)	uni.	(*h*, *u*, *i*, *b*)	(*l*, *l*, *l*)	solver
Moradi and MirHassani (2016)	1t1	(*d*, *c*)	uni.	(*p*, *i*)	(*l*, *l*)	solver
Rejowski and Pinto (2003)	1tm	(*d*, *d*)	uni.	(*p*, *h*, *i*)	(*l*, *l*, *l*)	solver
Rejowski et al. (2004)	1tm	(*d*, *d*)	uni.	(*p*, *h*, *i*)	(*l*, *l*, *l*)	B+C
Rejowski and Pinto (2008)	1tm	(*c*, *d*)	uni.	(*p*, *h*, *i*)	(*n*, *n*, *l*)	solver
Cafaro and Cerdá (2004)	1tm	(*c*, *c*)	uni.	(*p*, *h*, *i*)	(*l*, *l*, *l*)	solver
Cafaro and Cerdá (2008)	1tm	(*d*, *c*)	uni.	(*p*, *h*, *i*, *u*, *b*)	(*l*, *l*, *l*)	solver
MirHassani (2008)	1tm	(*d*, *d*)	uni.	(*i*)	(*l*)	solver
MirHassani and Jahromi (2011)	1tm	(*c*, *d*)	uni.	(*p*, *h*, *i*)	(*l*, *l*, *l*)	solver
Mostafaei, Castro, and Ghaffari-Hadigheh (2015)	1tm	(*c*, *d*)	uni.	(*p*, *i*, *b*)	(*l*, *l*, *l*)	solver
Moura, de Souza, Cire, and Lopes (2008)	mtm	(*c*, *c*)	bi.	–	–	CP
Cafaro and Cerdá (2009)	mtm	(*c*, *c*)	uni.	(*p*, *b*, *u*, *i*)	(*l*, *l*, *l*, *l*)	solver
Cafaro and Cerdá (2010)	mtm	(*c*, *c*)	uni.	(*u*)/(*p*, *b*, *i*)	(*l*)/(*l*, *l*, *l*)	solver
Magatão et al. (2015)	mtm	(*c*, *c*)	bi.	(*b*)	(*l*)	decomp.
Mostafaei et al. (2016)	mtm	(*c*, *c*)	uni.	(*p*, *i*, *b*)	(*l*, *l*, *l*)	solver

As the ELSP is known to be hard to solve and available heuristics cannot be applied directly to the proposed ELSP variant, a heuristic is proposed based on the powerful ELSP heuristic published in Dobson (1992).

In the next section a literature review is provided and the current work is categorized. In Section 3 mathematical formulations for objectives and technological constraints in pipeline management are derived. Afterwards, the derived formulations are used to formulate a ELSP-type optimization model. In Section 5, a heuristic is described which adapts the approach of Dobson (1992). The application of the heuristic is illustrated by means of a case studies in Section 6. The paper finishes with a conclusion.

2. Literature review

While one-product pipeline systems are comparatively easy to manage, multi-product supply system typically imply a serious level of complexity due to setup costs as well as a commonly used processing asset with limited capacity. Literature on pipeline planning for multi-product systems is primarily focused on specific applications in chemical or petroleum industry. Table 1 shows the literature on hand categorized according to certain criteria.

The column “sys. type” categorizes the papers according to the network structures one-to-one (1t1), one-to-many (1tm), or many-to-many (mtm), i.e., referring to the number of injection and retraction points. Column “flow” indicates whether a unidirectional or bidirectional material flow is considered. Column “scale” refers to the modeling of time and pipeline which are either subdivided into a number of discrete slices (d) or handled continuously (c). “Objective” summarizes the aspects modeled as the planning objectives whereby p indicates pumping cost, h holding cost, b backlogging cost, i costs for interface processing, u pipeline utilization, and c product changeovers. Directly related to the objectives is column “model” where entries l and n refer to linearly or non-linearly modeled objectives, respectively. Finally, the solution methodology employed in the papers is reported in the last column where “solver” refers to commercial standard solvers, “B+C” a brach-&-cut algorithm, “heur.” a heuristic approach, and “decomp.” indicates a decomposition of the planning problem.

The literature review shows a heterogeneous set of papers on pipeline operations management. Historically, pipeline supply planning started with discrete models formulating time and pipeline as a sequence of slices which are passed successively. However, this type of formulation has the disadvantage that model complexity increases with increasing number of time periods (i.e., time horizon). Continuous time formulations are more flexible and can be solved for large time horizons. Hence, continuous formulations are prevalent in most recent research. Most of the literature applies the proposed models to real-world case studies and solve the models with standard solvers like CPLEX. However, there are also some heuristic and decomposition procedures which rely mainly on the decomposition into (1) batch allocation, (2) batch sizing and (3) batch scheduling. The objectives pursued also vary heavily. In rather short-term models maximizing pipeline utilization is a sufficient proxy for minimizing pumping cost. The longer the considered time horizons are, the more cost aspects are taken into account. Most prominently, this includes stock holding costs as well as setup or interface processing costs. All papers consider a limited time horizon and a set of products with consumption and production data for each product. The final outcome of the reviewed literature is a schedule for the considered time horizon providing detailed information when and where which product is to be injected into and retracted from the pipeline system in which quantity. Hence, all papers model pipeline systems from an operational perspective.

Table 1 shows that a lot of different approaches has been published mostly tackling challenging real-world problems. Most models are formulate as MILPs, i.e., all constraints and objectives are linearized. To solve even large problem instances mostly commercial standard solvers are used. However, particularly when additional planning parameters like pump rates are variable, tailor-made solution approaches are required whereby decomposition procedure dominate. Thus, improvements of decompositions approaches w.r.t. solution quality and run times are open issues particularly for *mtm* pipeline system (see Magatão, Magatão, Neves, & Arruda, 2015 or Mostafaei, Castro, & Ghaffari-Hadigheh, 2016). Another issue is the incorporation of uncertainty in pipeline scheduling. Except for Moradi and MirHassani (2016) considering demand uncertainty for a one-to-one pipeline, this aspect has not been addressed so far in literature. In the light of highly volatile electricity prices as well as technical and supply risks, is seems reasonable to investigate the effects of stochasticity more closely in order to obtain robust schedules. All references cited in Table 1 focus on operational scheduling problems with discrete customer orders