DEPARTMENT OF ENGINEERING MANAGEMENT

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Abstract

Most academic models for strategic design of batch production plants focus on minimising capital and operational costs. However nowadays, responsiveness is an important key performance attribute in operations management. The main metric for responsiveness is the delivery lead time (DLT), being defined as the time between ordering and delivering of a customer order, also called the order fulfillment cycle time. In the context of plant design, we consider delivering as loading at the plant, assuming the customer or 3PL to be responsible for transport.

In this paper, we aim to incorporate responsiveness in the design of a batch plant operating in a make-to-order (MTO) environment, by introducing a target DLT for the customer orders to be fulfilled over the strategic horizon. Additionally, as common for an MTO plant, non-dedicated storage tanks are installed, avoiding obstruction of production equipment while these customer orders wait for quality control and loading. Unlike most design models, the capital cost of these storage tanks is included in the objective function of our design model. Moreover, to design a MTO plant accounting for a target DLT for all individual orders, scheduling techniques are introduced, both in the mathematical model as in the heuristic needed to solve larger instances.

The effect of the target DLT on the batch plant design is examined for multiple problem instances with different planning horizons, number of orders and total amount to be produced. As expected, the design cost increases non linearly with a decreasing target DLT. To quantify the exact impact of a lower DLT, the cost of responsiveness is expressed as a percentage of the minimum capital cost found if no DLT's are specified. For our problems instances, it can be concluded that decreasing the DLT with 24 hours (1 day) incurs a capital cost increase between 0.82 % and 36.85 %.

Keywords Batch Plant Design, Make To Order, Non-dedicated Storage, Supply Chain Responsiveness, Delivery Lead Time, MILP, Heuristics

1 Introduction

Companies strive to design high-performance production plants that can achieve their long-term business objectives, as the construction, retrofitting or relocation of industrial facilities is expensive and time-consuming. These *business objectives* are based on a thorough analysis of their own capabilities and competitive environment. To translate these objectives into an operations strategy, the Supply Chain Operations Reference (SCOR) model defines five Supply Chain (SC) key performance attributes: responsiveness, reliability, agility, asset efficiency and cost effectiveness (APICS, 2017). Obviously, for manufacturing companies, these performance attributes must be reflected in the plant design. However, although being investigated over a long time, academic plant design models focus mainly on optimizing capital and operational costs (Sparrow et al., 1975; Grossmann & Sargent, 1979; Shah & Pantelides, 1992), and do not incorporate other strategic SC key performance indicators.

Therefore, we aim to introduce the concept of *responsiveness* in the optimisation models for strategic batch plant design (BPD). In the context of SC performance, responsiveness is explained as the ability to deliver products to the customer within a competitive delivery lead time (DLT). DLT stands for the time interval between placement and delivery of a customer order, often referred to as the order fulfilment cycle time (APICS, 2017). To incorporate responsiveness into the operations strategy, companies internally agree on a *target DLT* for each production plant (possibly differentiated for different types of customer demand). Operationally, this target DLT is used by the customer service department to determine a reliable loading date for each customer order, which is then considered as its due date for production planning.

In this paper, we focus on a multiproduct batch plant (Biegler et al., 1997) in a non cyclic *make-to-order (MTO)* environment. It should be noted that, in case of MTO, the DLT is equal to the production lead time, as products are only produced after order (Olhager, 2003). Moreover, in the typical B2B bulk production environments of these batch plants (e.g., chemicals, food, lubricants (Hill et al., 2016)), delivery is considered as loading at the factory, since transport is (mostly) the responsibility of the customer or 3PL, or is treated as a fixed transportation time. Hence, the target DLT of a customer order must cover the processing times on production equipment, the obligatory time for quality control, as well as the waiting times before production start and until loading at the storage tanks.

Indeed, as common for MTO batch plants, *non-dedicated (throughput) tanks* for finished products are installed to hold the customer orders until loading and prevent obstruction of production equipment. Unlike most design models (Barbosa-Póvoa, 2007; Verbiest, Cornelissens, & Springael, 2019), the capital cost of these finished product storage tanks is included in our objective function to minimise, on top of the cost for production equipment.

Last but not least, a suitable mode of operation must be chosen for our MTO batch plant. Since all customer orders must be scheduled within their proper target DLT (i.e., between their earliest start and due date), single product (SPC) and mixed product campaigns (MPC) are not appropriate. In fact, to assure the responsiveness of our plant design, the orders must be scheduled explicitly. However, the resulting schedule must not be optimized for a typical operational objective such as make span or lateness, but can be considered as a pure constraint satisfaction problem. Although, among others, Resource Task Network (RTN) formulations with discrete time representations are applicable for the design and scheduling of multiproduct batch plants (Verbiest, Cornelissens, & Springael, 2019), we will develop a new BPD model able to schedule the customer orders and taking into account the occupation of the finished storage tanks until their loading date. However, rather than diving into the batch plant design for complex multistage processes, for this research on responsiveness, we will focus on a rather simple but realistic production process.

In summary, this paper aims to provide answers to the following research questions: "How to introduce a target DLT for order fulfilment in the strategic design model of a make-to-order multiproduct batch plant with non-dedicated storage tanks?" and "What is the influence of a shorter target DLT on the design and capital cost of such an MTO batch plant?". Otherwise said: "What is the cost of responsiveness on the design of a multiproduct MTO batch plant?"

The remainder of this paper is organised as follows: a short literature review on strategic batch plant design, mode of operations and scheduling for batch plant design problems, can be found in section 2. The problem description and mathematical model for MTO batch plant design constraint by a target DLT, is described in section 3, while the heuristic needed to solve larger problem instances can be found in section 4. Section 5 contains the input data and findings, as well as a comparison between the results by the MILP solver and the heuristic solver. The paper ends with a conclusion section and ideas for future research.

2 Literature review

2.1 Strategic batch plant design

A batch plant typically produces discrete amounts of products (batches). The strategic BPD problem entails determining the optimal configuration (i.e., number, size and connectivity) of the main production equipment for each production stage, considering a target demand for products over a strategic horizon. Production processes and processing times are given, as well as the possible sizes (capacities) and capital cost of equipment units. In general, the outcome of the BPD problem provides also the guidelines for the required production plan, making use of the selected resources (i.e., timing of tasks, batch sizes and allocation of tasks to equipment).

A review on the BPD literature has been provided by Barbosa-Póvoa (2007), considering both multiproduct (flow shop) and multipurpose (job shop) batch plants, design options such as parallel equipment per proces stage and intermediate storage between stages, different modes of operation and solution methods. Most BPD problems determine the optimal design while minimising capital or investment cost (Sparrow et al., 1975; Grossmann & Sargent, 1979; Voudouris & Grossmann, 1992), others include the minimisation of specific operational costs (Knopf et al., 1982; Dietz et al., 2006). More recently, researchers have shown an increased interest in combining design and scheduling of batch plants and in network formulations for the BPD problem (Pinto et al., 2008; Verbiest, Pinto-Varela, et al., 2019).

Most aforementioned BPD problems are formulated as non-linear (Grossmann & Sargent, 1979; Modi & Karimi, 1989) or linear mixed integer programming models (Voudouris & Grossmann, 1992) and solved with mathematical solvers, (meta)heuristic (Sparrow et al., 1975; Modi & Karimi, 1989; Patel et al., 1991; Dietz et al., 2006) or combinations of both (Xi-Gang & Zhong-Zhou, 1997; Verbiest, Cornelissens, & Springael, 2019).

2.2 Storage policies and mode of operation for MTO batch plants

As explained in section 1, we focus on the design of an MTO batch plant. Although the difference between MTO and make-to-stock (MTS) plants is not made in the batch plant literature, the influence on the design is considerable in at least two aspects: the storage policies for the finished products and the mode of operation. Indeed, in a typical multiproduct MTO environment with multiple (slightly) customized finished products, customer orders are produced in separate batches and stored individually in non-dedicated storage tanks until loaded in a bulk truck. These throughput tanks avoid obstruction of the production equipment and are also used for the quality control of these individual orders. Such in contrast to MTS plants, where in general a limited number of standard finished products are stored in a few large product dedicated storage tanks.

Regarding storage policies, different academic BPD models incorporate infinite intermediate storage (Patel et al., 1991; Birewar & Grossmann, 1989) or even optimize the size and cost of non-dedicated storage vessels between different process stages (Modi & Karimi, 1989). Only in multiperiod BPD models, the end-of-period inventory of finished products (and raw materials) is introduced, as well as the related inventory costs (Bhatia & Biegler, 1996; Moreno & Montagna, 2012; Fumero et al., 2016; Verbiest et al., 2021). However, including the sizing and/or capital cost of non-dedicated storage tanks for finished products in the design seems, to the best of our knowledge, missing in the BPD literature.
Another important assumption in BPD models is the mode of operation. Most models implement single product campaigns (SPC), meaning every product is produced in a single series of batches, or mixed product campaigns (MPC), where a smart combination of batches of different products, often with complementary processing times, is repeated over the planning horizon (Biegler et al., 1997). Both SPC and MPC

are relevant modes of operation in an MTS multiproduct environment, certainly in a multi-period context (Verbiest et al., 2021; Moreno et al., 2007). Indeed, in case of MTS, production batches must meet the (periodical) sales forecast volumes, but do not have to consider other timing constraints. Consequently, these campaign modes are less appropriate to represent an MTO situation, since the requirements of individual customer orders are neglected completely. In fact, the planning mode better suited for BPD in an MTO context, can be represented by state-task-networks (STN) (Kondili et al., 1993) or resource-task networks (RTN) (Pantelides, 1994), as these models are able to schedule individual customer orders with intermediate due dates and specific quantities. The next paragraph refers to the literature on ''design and scheduling" of a batch plant.

2.3 Design and scheduling of MTO batch plants

As argued before, and in particular when introducing a target DLT, the design of a MTO plant must be combined with the scheduling of the customer orders. In fact, the network formulations STN and RTN, originally introduced for modeling scheduling problems (Schilling & Pantelides, 1999), can combine scheduling and design of a multipurpose batch plant (Shah & Pantelides, 1992; Barbosa-Póvoa & Pantelides, 1997; Lin & Floudas, 2001; Pinto et al., 2005, 2008) and multiproduct plants (Verbiest, Pinto-Varela, et al., 2019). The latter authors even combined RTN with decomposition approaches to reduce the computational complexity of these network models. Scheduling and design have also been combined without the use of STN or RTN for BPD models with one equipment unit per stage (Birewar & Grossmann, 1989; Bhatia & Biegler, 1996) or multiple parallel equipment (Fumero et al., 2011). Moreover, Vaselenak et al. (1987) proposed a superstructure representation, handling the design and scheduling in a subsequent manner, to not complicate the design problem. Still, most aforementioned literature on combined design and scheduling problems report performance problems for larger instances.

For this research, we prefer to keep the layout of our MTO batch plant as simple as possible (one stage process, one batch for each customer order), allowing us to focus on the introduction of the target DLT. Additionally, we will develop a design model that is able to schedule customer orders on production equipment within their target DLT, and occupy a storage tank while waiting for loading on their due date. Indeed, this waiting time can not be modeled as a process step of known duration. In fact, due to the strategic nature of our BPD, the scheduling of the customer orders is only used as a constraint satisfaction problem. Unlike as for operational scheduling, no attempts are made to optimize the production schedule for objectives such as minimisation of makespan (Blömer & Günther, 1998; Burkard et al., 2002), cycle time (Birewar & Grossmann, 1989) or maximisation of profit (Kondili et al., 1993; Ierapetritou & Floudas, 1998).

Moreover, to reduce the problem complexity, our BPD model will exploit a discrete time representation, with the time horizon divided in a finite number of time intervals of a predefined granularity, and events only happening at the boundaries of these time periods. Such a discrete time representation reduces the size of the mathematical model and improves its computational efficiency (Méndez et al., 2006). Nevertheless, solving these combinatorial problems optimally remains problematic. As in pure scheduling applications (Elkamel et al., 1997; Blömer & Günther, 1998; Blömer & Gunther, 2000; Chibeles-Martins et al., 2010, 2011; Harjunkoski & Bauer, 2017), we will develop a heuristic. The complete description of our MTO BPD problem, and the mathematical model can be found in section 3, the heuristic is described in section 4.

3 Problem description

Most BPD problems determine the number and size of production equipment units, needed to produce the required product quantities over a strategic planning horizon, at minimal (capital) cost. The aim of this study is to incorporate, as a measure of responsiveness, a target DLT for order fulfilment and the capital cost of throughput storage tanks in the design model for a MTO batch plant.

3.1 Assumptions

For a MTO batch plant, the demand required over the planning horizon can be expressed as customer orders quantities. The target DLT is a strategic objective for the actual DLT of each customer order, to be achieved by the plant's operations management. Since logistics is beyond the scope of plant design, the DLT of a customer order takes into account the time between ordering and loading of the finished product, but leaves out the transportation to the customer. In short, as illustrated in Figure 1, our BPD model should install the necessary installations for production and storage at minimal capital cost, and schedule each customer order within the target DLT.

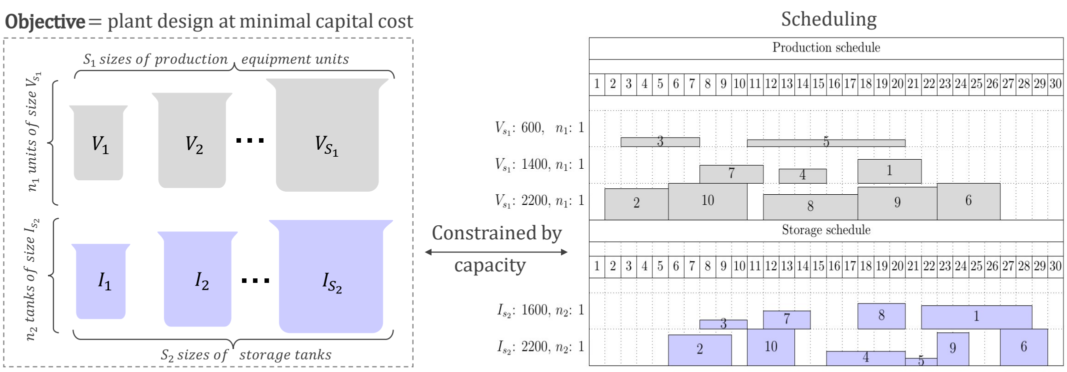

Figure 1: Visual representation of the batch plant design problem discussed in this paper

Several assumptions have been made concerning the design of our multiproduct MTO batch plant, the production process and the relation between batches and customer orders:

1. We only model one production stage. This can be interpreted as a single-stage production process, either as the bottleneck stage of the plant.

2. After production, a batch is immediately pushed to a (non-dedicated) storage tank and is stored in that (throughput) tank until loading.

3. Each batch must stay in the storage tanks at least during the time needed for quality control.

4. For both production as storage, multiple parallel installations with different discrete sizes are to be selected, unlike many multistage models where parallel equipment must have the same size (Loonkar & Robinson, 1970; Sparrow et al., 1975; Grossmann & Sargent, 1979; Voudouris & Grossmann, 1992).

5. Customer orders demand exactly one product. A customer order for multiple products is converted in to separate orders with identical due date.

6. Each customer order is produced in exactly one batch. Order splitting or order mixing is not allowed.

7. The maximum order size is limited to the maximum batch volume that can be processed by the plant equipment. The customers are aware of the minimum and maximum amount they may order.

8. Each product (and therefore each order) has a size factor that represents the volume needed to produce one unit mass, and a fixed and unit-independent batch processing time. For simplification, the sizing factor in our instances will be equal to one.

9. Production equipment is more expensive than storage tanks.

The simplifications introduced by assumption 1 and 8 allow us to focus on the responsiveness aspect, rather than complex production processes.

To include the target DLT in our BPD model, we assign to each customer order i an earliest start for production (Est_i) and a due date (Due_i) for loading. Est_i is based on the order date by the customer. Due_i is obtained by adding the target DLT to Est_i. In practice however, if the customer prefers a later loading date, Est_i is determined by subtracting the target DLT from the agreed due date Due_i. Indeed, in an MTO environment, producing too early would only block more storage tanks. The complete nomenclature of variables, indices and parameters can be found in Table 1. The process itself is illustrated in Figure 3.

3.2 Mathematical model

We opted for a discrete time dimension with time slots of granularity h. All events (earliest start, due date, start production, start storage, etc.) take place at the beginning of a time slot. For example, an order with due date t, is held in storage until the end of time slot $t-1$, and is out-of-factory at the beginning of time slot t.

3.2.1 Nomenclature

In Table 1 we define the necessary indices, parameters and variables.

Table 1: Nomenclature

Indices	
$i = 1, \ldots, O$	index identifying the order
$n_1 = 1, \ldots, N_1$	index of parallel production equipment (single stage process)
$n_2 = 1, \ldots, N_2$	index of parallel storage tanks
$s_1 = 1, \ldots, S_1$	index identifying the discrete size of a particular production equipment
$s_2 = 1, \ldots, S_2$	index identifying the discrete size of a particular storage tank
$t = 1, \ldots, H$	index identifying the begin of a timeslot
Parameters	
DLT	target delivery lead time
Due_i	due date (out-of-factory) of order i
Est_i	earliest start production of order i
h	granularity
H	horizon, total available time
I_{s_2}	discrete size of a storage tank
N_1	maximal number of production equipment
N_2	maximal number of storage tanks
V_{s_1}	discrete size of a production equipment
Q_i	total amount (mass) of product in order i
α_1, β_1	cost parameters for production equipment
α_2, β_2	cost parameters for storage tanks
η	quality control time (mandatory storage time)
$\rho_{1,i}$	size factor for product of order i during production
$\rho_{2,i}$	size factor for product of order i during storage
τ_i	batch processing time for product of order i
Variables	
Binary:	
$u_{n_1 s_1}$	equals 1 if n_1 production equipment of size V_{s_1} are installed, else 0
$w_{n_2 s_2}$	equals 1 if n_2 storage tanks of size I_{s_2} are installed, else 0
$x_{in_1 s_1 t}$	equals 1 if order i starts on production equipment n_1 of size V_{s_1} on time t with $t \in [Est_i, Due_i - \tau_i - \eta]$, else 0
$z_{in_2 s_2 t}$	equals 1 if order i is stored on storage tank n_2 of size I_{s_2} on time with $t \in [Est_i + \tau_i, Due_i - 1]$, else 0

Additionally, the following notations are introduced enabling to limit the range of the indices and reducing the number of variables considered by the MILP solver:

- $Due_M = \max_{i \in \{1,\ldots,O\}} (Due_i)$ Latest Duedate
- $Est_m = \min_{i \in \{1,\ldots,O\}} (Est_i)$ Earliest EarliestStartProduction
- $Lst_M = \max_{i \in \{1,\ldots,O\}} (Due_i - \eta)$ Latest LatestEndProduction
- $Ist_m = \min_{i \in \{1,\ldots,O\}} (Est_i + \tau_i)$ Earliest EarliestStartStorage
- $U_t = \{i | t \in [Est_i, Due_i - \tau_i - \eta]\}$ All possible timeslots in production
  $\forall t = Est_m, \ldots, Lst_M - \eta$
- $W_t = \{i | t \in [Est_i + \tau_i, Due_i - 1]\}$ All possible timeslots in storage
  $\forall t = Ist_m, \ldots, Due_M - 1$

Finally, as explained in section 3.1, the earliest start time of an order equals the due date minus the DLT. Although different target DLTs could be used for different product families, in our model, the value of the target DLT, is identical for all customer orders.

$$Est_i = Due_i - DLT \qquad \forall i = 1, \ldots, O \tag{1}$$

3.2.2 Objective function

Since all equipment has a discrete set of possible sizes, the volume dependent capital cost can be expressed as follows:

$$\text{Capital cost for production equipment of size } V_{s_1} = \alpha_1 V_{s_1}^{\beta_1} \tag{2}$$

$$\text{Capital cost for storage tank of size } I_{s_2} = \alpha_2 I_{s_2}^{\beta_2} \tag{3}$$

where α_1 and β_1 are cost factors for production equipment, α_2 and β_2 for storage tanks. The objective to minimise is the sum over all sizes of the n_1 installed production equipment of size V_{s_1} and n_2 installed storage tanks of size I_{s_2}:

$$min\left(\sum_{n_1=1}^{N_1} \sum_{s_1=1}^{S_1} \alpha_1 V_{s_1}^{\beta_1} n_1 u_{n_1 s_1} + \sum_{n_2=1}^{N_2} \sum_{s_2=1}^{S_2} \alpha_2 I_{s_2}^{\beta_2} n_2 w_{n_2 s_2} \right) \tag{4}$$

3.2.3 Design Constraints

Only one particular amount n_1 can be selected for production equipment of size V_{s_1}.

$$\sum_{n_1=1}^{N_1} u_{n_1 s_1} \leqslant 1 \qquad \forall s_1 = 1, \ldots, S_1$$

Only one particular amount n_2 can be selected for a storage tank of size I_{s_2}.

$$\sum_{n_2=1}^{N_2} w_{n_2 s_2} \leqslant 1 \qquad \forall s_2 = 1, \ldots, S_2 \tag{5}$$

No more than N_1 production equipment can be installed in total.

$$\sum_{n_1=1}^{N_1} \sum_{s_1=1}^{S_1} n_1 u_{n_1 s_1} \leqslant N_1 \tag{6}$$

No more than N_2 storage tanks can be installed in total.

$$\sum_{n_2=1}^{N_2} \sum_{s_2=1}^{S_2} n_2 w_{n_2 s_2} \leqslant N_2 \tag{7}$$

Every order i can only be assigned to one production equipment n_1 of size V_{s_1} and can only start at one single time t (of its DLT).

$$\sum_{n_1=1}^{N_1} \sum_{s_1=1}^{S_1} \sum_{t=Est_i}^{Due_i-\tau_i-\eta} x_{in_1s_1t} = 1 \qquad \forall i = 1, \ldots, O \tag{8}$$

Every order i can not be stored simultaneously in more than one of the installed storage tanks n_2 of size I_{s_2}, and such for every time t (of its DLT).

$$\sum_{n_2=1}^{N_2} \sum_{s_2=1}^{S_2} z_{in_2s_2t} \leqslant 1 \qquad \begin{array}{l} \forall i = 1, \ldots, O; \\ \forall t \in [Est_i + \tau_i, Due_i - 1] \end{array} \tag{9}$$

For every time t of the horizon, maximum one order can start on every production equipment n_1 of size V_{s_1}.

$$\sum_{i \in U_t} x_{in_1s_1t} \leqslant 1 \qquad \begin{array}{l} \forall n_1 = 1, \ldots, N_1; \\ \forall s_1 = 1, \ldots, S_1; \\ \forall t \in [Est_m, d_M - \eta] \end{array} \tag{10}$$

For every time t of the horizon, maximum one order can be stored on every storage tank n_2 of size I_{s_2}.

$$\sum_{i \in W_t} z_{in_2s_2t} \leqslant 1 \qquad \begin{array}{l} \forall n_2 = 1, \ldots, N_2; \\ \forall s_2 = 1, \ldots, S_2; \\ \forall t \in [Est_m, Due_M - 1] \end{array} \tag{11}$$

Every order i can only be started on production equipment n_1 of size V_{s_1} (at time t) if at least n_1 units of size V_{s_1} are installed.

$$\sum_{n_1=1}^{N_1} n_1 x_{in_1s_1t} \leqslant \sum_{n_1=1}^{N_1} n_1 u_{n_1s_1} \qquad \begin{array}{l} \forall i = 1, \ldots, O; \\ \forall s_1 = 1, \ldots, S_1; \\ \forall t \in [Est_i, Due_i - \tau_i - \eta] \end{array} \tag{12}$$

Every order i can only be stored on storage tank n_2 of size I_{s_2} (at time t) if at least n_2 tanks of size I_{s_2} are installed.

$$\sum_{n_2=1}^{N_2} n_2 z_{in_2s_2t} \leqslant \sum_{n_2=1}^{N_2} n_2 w_{n_2s_2} \qquad \begin{array}{l}\forall i = 1,\ldots,O;\\ \forall s_2 = 1,\ldots,S_2;\\ \forall t \in [Est_i + \tau_i, Due_i - 1]\end{array} \tag{13}$$

If order i is started on production equipment n_1 of size V_{s_1} at time t, then the volume of that equipment should at least be as large as the volume $Q_i\rho_{1,i}$ needed for order i.

$$Q_i\rho_{1,i} \leqslant \sum_{n_1=1}^{N_1}\sum_{s_1=1}^{S_1}\sum_{t=Est_i}^{Due_i-\tau_i-\eta} V_{s_1}x_{in_1s_1t} \qquad \forall i = 1,\ldots,O \tag{14}$$

If order i is assigned to storage tank n_2 of size I_{s_2} at time t, then the volume of the storage tank should at least be as large as the volume $Q_i\rho_{2,i}$ needed to store order i.

$$\sum_{n_2=1}^{N_2} Q_i\rho_{2,i}z_{in_2s_2t} \leqslant I_{s_2} \qquad \begin{array}{l}\forall i = 1,\ldots,O;\\ \forall s_2 = 1,\ldots,S_2;\\ \forall t \in [Est_i + \tau_i, Due_i - 1]\end{array} \tag{15}$$

3.2.4 Scheduling (timing) Constraints

Note that the scheduling of orders is considered as a constraint satisfaction problem to ensure that all orders can be produced within their DLT, also called capacity check. No typical scheduling objective, such as minimum makespan, profit maximisation or minimum delay or earliness is defined (Méndez et al., 2006).

For each production equipment n_1 of size V_{s_1}, the total duration needed to produce and store all orders cannot exceed the horizon H.

$$\sum_{i=1}^{O}\sum_{t=Est_i}^{Due_i-\tau_i-\eta} \tau_i x_{in_1s_1t} \leqslant H \qquad \begin{array}{l}\forall n_1 = 1,\ldots,N_1;\\ \forall s_1 = 1,\ldots,S_1\end{array} \tag{16}$$

Every order i has to be stored right after its production is finished (at $t + \tau_i$).

$$\sum_{n_1=1}^{N_1}\sum_{s_1=1}^{S_1} x_{in_1s_1t} \leqslant \sum_{n_2=1}^{N_2}\sum_{s_2=1}^{S_2} z_{in_2s_2(t+\tau_i)} \qquad \begin{array}{l}\forall i = 1,\ldots,O;\\ \forall t \in [Est_i, Due_i\\ -\tau_i - max(\eta,1)]\end{array} \tag{17}$$

When the production of order i starts at time t ($x_{in_1s_1t} = 1$), the l.h.s of the eq. (18) becomes 0, forcing the r.h.s (for all time slots between $Est_i + \tau_i$ and $t + \tau_i - 1$ during which the order is in production) to be 0 as well. This constraint forces every order i not to be stored before its production is finished (i.e. after $t + \tau_i - 1$).

$$(1 - \sum_{n_1=1}^{N_1}\sum_{s_1=1}^{S_1} x_{in_1s_1t})(t - Est_i) \geqslant \sum_{n_2=1}^{N_2}\sum_{s_2=1}^{S_2}\sum_{\ell=Est_i+\tau_i}^{t+\tau_i-1} z_{in_2s_2\ell} \qquad \begin{array}{l}\forall i = 1,\ldots,O;\\ \forall t \in [Est_i + 1, Due_i\\ -\tau_i - \eta]\end{array} \tag{18}$$

For every order i, when stored at time t, then it must be stored on the same storage tank n_2 of size I_{s_2} between t and Due_i (the latest on $Due_i - 1$).

$$z_{in_2s_2t} \leqslant z_{in_2s_2(t+1)} \qquad \begin{array}{l} \forall i = 1, \ldots, O; \\ \forall n_2 = 1, \ldots, N_2; \\ \forall s_2 = 1, \ldots, S_2; \\ \forall t \in [Est_i + \tau_i, Due_i - 2] \end{array} \tag{19}$$

For every order i, when produced on equipment n_1 of size V_{s_1} at time t, the production of another order i' (on the same equipment unit n_1 of size V_{s_1}) cannot start before the order i is finished.

$$\tau_i(1 - x_{in_1s_1t}) \geqslant \sum_{\ell=t}^{t+\tau_i-1} \sum_{\substack{i' \in U_\ell \\ i' \neq i}} x_{i'n_1s_1\ell} \qquad \begin{array}{l} \forall i = 1, \ldots, O; \\ \forall n_1 = 1, \ldots, N_1; \\ \forall s_1 = 1, \ldots, S_1; \\ \forall t \in [Est_i, Due_i - \tau_i - \eta] \end{array} \tag{20}$$

4 Heuristic

Despite our efforts to optimise the mathematical model for performance reasons, Table 3 in section 5 shows that it is difficult for the Gurobi MILP-solver to find optimal (or even feasible) solutions for instances with more than 30 or 40 orders, within a given time limit of 12 hours. Especially for larger target DLTs, few optimal solutions were found. Therefore a heuristic solver has been developed.

Essentially, our heuristic uses a decomposition approach. An outer loops generates different designs, while a heuristic checks whether that design is capable to schedule all orders between their earliest start time and their due date. The design with the lowest capital cost, that can withstand this capacity check, will be the best solution. It should be noted that, in this context, a 'design' stands for a configuration of production equipment and storage tanks, i.e. a number of different types of installations of different sizes. The two main elements of the heuristic are explained in detail in the subsections 4.1 and 4.2.

4.1 Elicitation over designs

The loop eliciting over designs, illustrated by the flowchart in Figure 2, is described as follows:

- The loop starts from *MaxDesign*, i.e. the configuration with the maximum number of production equipment and storage tanks, all of maximal size. These maxima are predefined.
- First, the feasibility of *MaxDesign* is tested. If the capacity check passes, this MaxDesign is assigned to *BestDesign*, i.e. the design with the *LowestCapitalCost* so far. If not, the heuristic ends immediately.
- Then, an outer loop runs over decreasing *LargeDesign*s, starting from *MaxDesign* and decrementing one by one the number of production equipment (of the

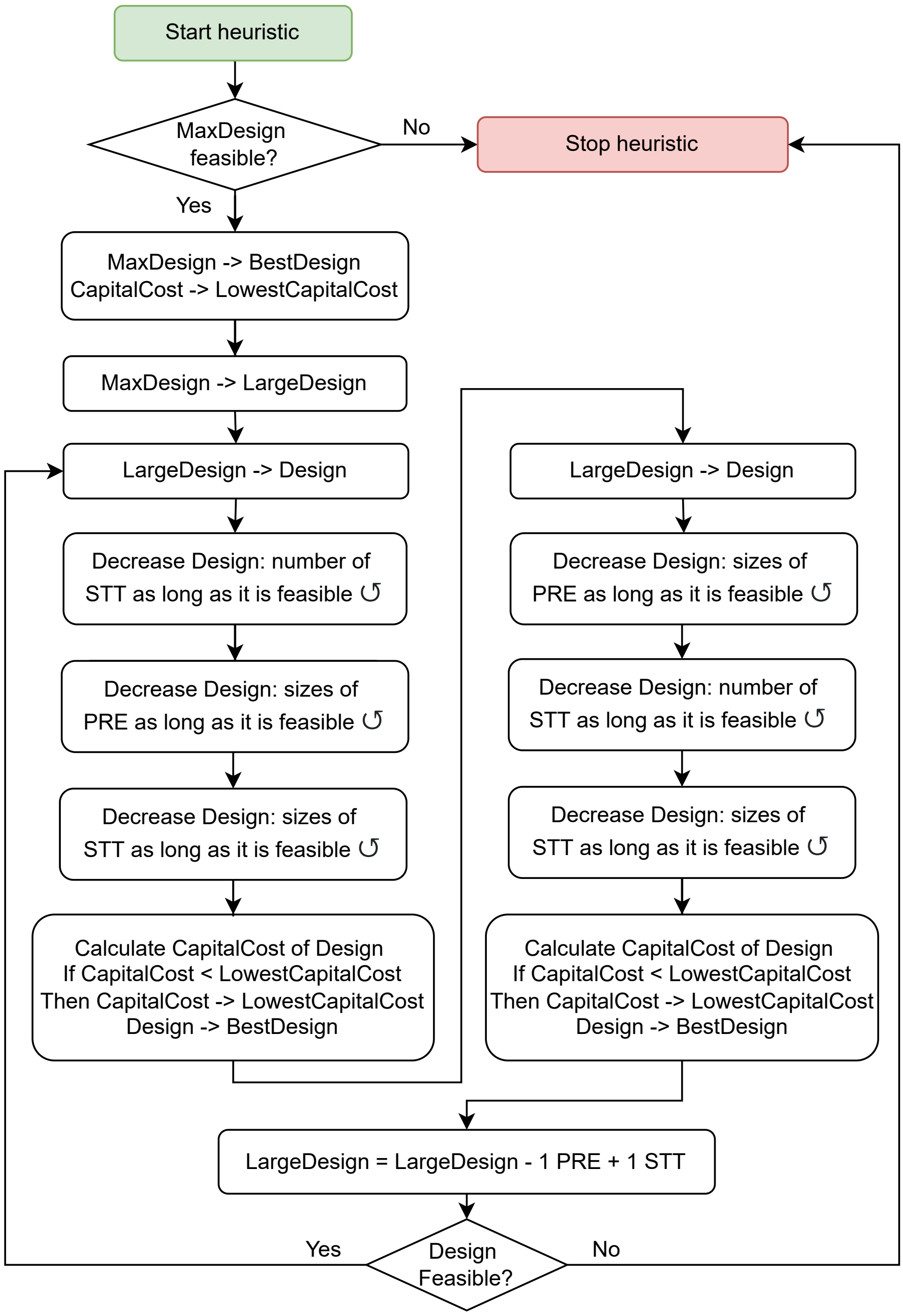

Figure 2: Flowchart: elicitation over designs
(PRE = production equipment; STT = storage tanks)

maximal size), until *LargeDesign* no longer passes the capacity check. However, for each removed production equipment, a storage tank of maximum size is added, keeping the total number of installations for each *LargeDesign* constant. In fact, exchanging a production equipment for a storage tank results in a lower net capital cost due to the assumption that production equipment is more expensive than storage tanks.

- Within the outer loop, i.e. for each *LargeDesign*, a search for a cheaper *Design* is performed, keeping the number of production equipment fixed. In a first sequence, the number of storage tanks (of maximum size) is reduced, then the size of the production equipment and lastly, the sizes of storage tanks are reduced, every time until the capacity check fails. If the capital cost of the smallest feasible *Design* found, is lower than *LowestCapitalCost*, this design is saved as *BestDesign* and the *LowestCapitalCost* is adapted. In a second sequence, starting again from the last *LargeDesign*, the order of reducing equipment is changed: first the sizes of the production equipment, then number and size of the storage tanks. Again, each reduction step is continued until capacity check fails. The last feasible *Design* is saved as *BestDesign* if its capital cost is lower than *LowestCapitalCost*.

It should be noted that, since our MTO plant produces each customer order in one batch, the maximum and minimum size needed for both production equipment and storage tanks are determined by the largest and smallest volume requested by a customer order. Therefore, our problem instances will ensure that the set of customer orders contains all relevant order sizes. Also, the minimum number of storage tanks required, will strongly depend on the number of customer orders with a simultaneous due date.

4.2 Capacity check

For the capacity check, a greedy heuristic has been developed, attempting to schedule all customer orders within their target DLT, on the production equipment and storage tanks installed in the design under test. Since this check is treated as a constraint satisfaction problem, there is no typical scheduling objective such as minimum make-span or minimum lateness. The goal is to schedule as many customer orders as possible. The capacity check is successful when all orders are scheduled.

As explained earlier, each customer order has to be processed in one batch (single stage and with a product dependent processing time), after which it immediately is pushed to a storage tank. As shown in Figure 3, the order must stay in this tank at least for the fixed time for quality control, and remain there until its loading date (due date). Therefore, the orders must preferably be scheduled as late as possible to avoid early occupation of the tanks. Consequently, our greedy heuristic will schedule backwards, placing the tasks from the end of the planning horizon to the beginning. Systematically, the remaining unscheduled order with the latest due date (or in a second run, with the latest earliest start storage) is selected, and placed as late as possible on the production equipment, entering as late as possible in the storage tanks.

Similarly to the mathematical model, our greedy heuristic uses the following attributes of order i:

- Q_i: order amount, $\rho_{1,i}$ and $\rho_{2,i}$: sizefactors
- τ_i: batch processing time, η: quality control time
- Due_i: due date = loading date = end of DLT for order i
- Est_i: earliest start production = Due_i - DLT
- Ist_i: earliest start storage = $Est_i + \tau_i$
- $Start_i$: scheduled start in production (comparable with x_{inst})

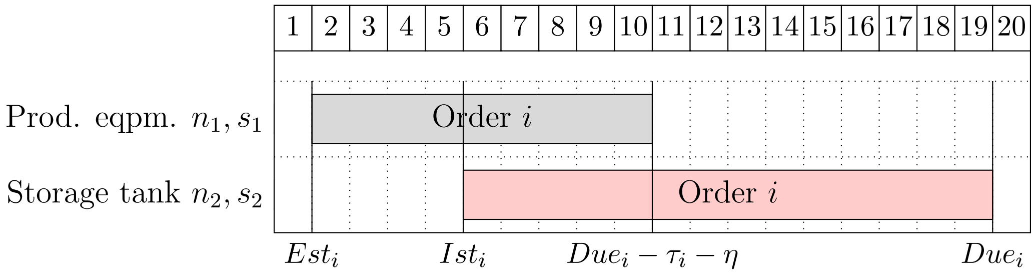

Figure 3: A visual representation of the limitations on the range of production and storage variables indices ($Est_i = 2, \tau_i = 4, \eta = 5, Due_i = 20$)

The heuristic, illustrated by the flowchart in Figure 4 is described below. To recap, the orders are scheduled as late as possible and different order selection sequences are tried.

- First, the orders are sorted on descending Due_i, next descending τ_i. This sorting determines the (deterministic) sequence in which the customers orders are selected to schedule. In this case, the latest orders with longest process time will be scheduled first.
- Next, for each selected order i, all production equipment large enough to process $Q_i\rho_{1,i}$ and able to start the order between Est_i and Due_i - η is listed. The order is assigned to the production equipment n_1 of size V_{s_1} that can process the order as late as possible, choosing for $Start_i$ the latest possible time slot. Then, the smallest possible storage tank able to store $Q_i\rho_{1,2}$ for at least the duration η between $Start_i + \tau_i$ until Due_i, is chosen. If more than one storage tank is available, the one with the smallest time gap with the previously stored order is assigned. If no more tank is free, order i can not be scheduled. No backtracking is performed, since choosing an earlier production start will never free a storage tank, on the contrary. If all customers orders are scheduled both on production equipment and storage tanks, the design under consideration is feasible, otherwise not.

- However, for the special case that all customer orders can be scheduled on production equipment but for some orders no storage tanks are available, a different storage assignment strategy is tried. While keeping the production schedule of the orders as before, the largest orders are now first assigned to a storage tank, avoiding small orders to obstruct large-sized storage tanks. All orders are sorted on descending $Q_i \rho_{2,i}$, next descending Due_i. If the new storage assignment succeeds, the schedule is feasible, otherwise not.

- If both previous scheduling attempts fail, the heuristic starts from the beginning once more, now by sorting the customer orders on descending Ist_i, i.e., taking the processing time into account. Indeed, for orders with the same due date, it could be better to schedule first the one with longest processing time, because it is more constraint by its target DLT. In case of equal Ist_i, the order with latest Due_i is scheduled first. The assignment to production and storage equipment works identically as described above. Again, if all orders are scheduled, the design under consideration is feasible, if all orders are scheduled on production equipment but not on storage tanks, the assignment to storage tanks is changed again by placing first the orders with largest order $Q_i \rho_{1,i}$.

5 Findings

In this section, the effect of the target DLT on the design and its capital cost is analyzed. To this end, several problem instances will be used and solved up to optimality when possible. If not, a suboptimal solution will be provided by either the MILP and/or heuristic described in the previous section. In a first experiment we compare the results of our heuristic with those obtained by the exact solver. This leads us to the conclusion that for larger-sized (i.e. real-world) problems the heuristic outperforms the MILP solver both on CPU-time and quality of the solution. Secondly, we use the heuristic to run an experiment in which we analyze the dependence of the capital cost and design on the target DLT, providing some insight into the cot of responsiveness of the constructed designs.

5.1 Input data

In order to study the presence of an effect of the target DLT on the design, a distinction is made between fixed and variable parameters. Indeed, some of the parameters (i.e. the discrete set of sizes and cost factors for production equipment and storage tanks, the maximum number of both types of equipment, the time needed for quality control, the time granularity of the schedule and the size factors of the ordered products) will be kept fixed over all problem instances. The values used here are inspired by those presented in the BPD problem literature (Biegler et al., 1997; Verbiest et al., 2017) as well as industrial practice, except for the size factors which are all set equal to 1. Since the BPD problem under consideration is a single stage problem, one may incorporate the size factors as a scaling of the order size. Hence, their presence

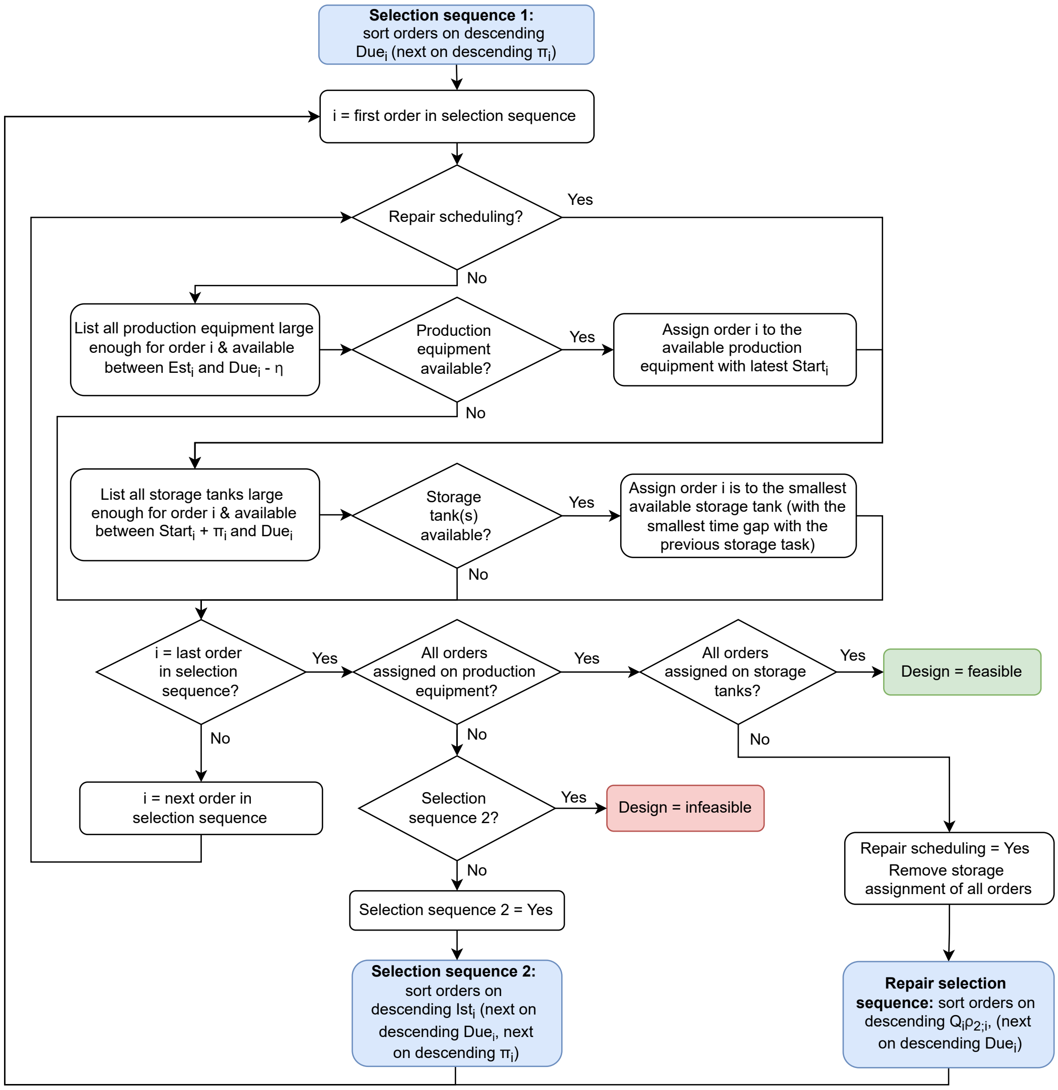

Figure 4: Flowchart: capacity check

merely serves as a change of units and does not contribute to the complexity of the optimisation problem.

Alternatively, the parameters such as the number of orders, the length of the planning horizon and the total amount to produce by the plant may vary among the problem instances. In order to make a distinction between small-sized and larger-sized problems their values are respectively selected from different value sets. The former are mainly used to compare the results of our heuristic with those of a MILP solver, while the latter will be used to study the effect of the target DLT on the design and since most of them cannot be solved by the MILP solver within a given limited amount of time.

In addition, the processing times, order quantities and due dates are parameters which are randomly generated for every order of a so-called order set. The quantity of each customer order is selected from a uniform distribution between the minimum and maximum quantity in such a manner that their sum is equal to the parameter "total amount to produce", up to a deviation of 1%. The minimum quantity of an order is selected to allow for the stirrers to still run and is set to half the size of the smallest tank. The maximum quantity corresponds to the largest production equipment and storage tank size, as a result from the assumption that all customer orders are produced in one batch. Each order set is built in such a manner that it consists of at least one order requiring the largest equipment or tank size for its quantity. Next, the processing time of each order is selected from a uniform distribution between 3 and 10 hours. The due dates of the orders are also selected from a uniform distribution between the maximum target DLT and the length of the horizon. The maximum target DLT of 50 hours assures that subtracting the target DLT from the due date, results in an earliest start time that falls not before the first time slot of the horizon. The minimum target DLT is 12 hours, as the DLT should at least cover the processing time (whose maximum value is 10 hours) and the mandatory storage time of 2 hours. An overview of the parameters values used is shown in Table 2. All used problem instances are available upon demand.

Table 2: Input data

Fixed parameters
$h = 1$ hour; $\eta = 2h$; maximum $DLT = 50h$
$N_1 = 15$; $N_2 = 45$
V_{s_1} and I_{s_2} (in ℓ) $= \{400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200\}$
$\forall i : \rho_{1,i} = \rho_{2,i} = 1\ell/\text{kg}$
$\alpha_1 = 200$; $\alpha_2 = 150$; $\beta_1 = 0.45$; $\beta_2 = 0.20$
Variable parameters
Small-sized problems:
$O = \{30, 40\}$
$H = \{100 \text{ hours}, 130 \text{ hours}\}$
Total amount to produce $= \{35000 \text{ kg}; 45000 \text{ kg}\}$
Larger-sized problems:
$O = \{200, 250, 300\}$
$H = \{7 \text{ days}(168 \text{ hours}), 10 \text{ days}(240 \text{ hours}), 14 \text{ days}(336 \text{ hours})\}$
Total amount to produce $= \{250000 \text{ kg}; 300000 \text{ kg}; 350000 \text{ kg}\}$
Order set parameters
$\forall i : \tau_i =$ between 3 and 10 hours
$\forall i : Q_i =$ between 200 kg and 2200 kg

In case of the larger-sized problems, for each of the 27 variable parameter combinations, 19 order sets are generated. Within each set, the customer orders have different processing times, order quantities and due dates. This results in a total of 513 order sets. Similarly, in case of the small-sized problems, 152 order sets were generated.

5.2 MILP solver versus heuristic

To compare the results found by the MILP solver and the heuristic solver, Table 3 depicts the capital cost and CPU time for 11 different parameter combinations. The results for each of these, considering a single order set, are presented, both for small-sized problems (first 6 rows) and larger-sized problems (last 4 rows) (see description in Table 2). All results were obtained using an Intel Xeon E5-2680v4 (Broadwell generation) CPU, 2.4 GHz and 128 GB of RAM per computing node. The time limit for each instance was 12 hours.

Table 3: Comparison between the results from the MILP model and the heuristic

Horizon - Orders - Total amount	**Target DLT (in h)**	**MILP capital cost (in m.u.)**	**MILP CPU time (in s)**	**MILP optimality gap (in %)**	**HEURISTIC capital cost (in m.u.)**	**HEURISTIC CPU time (in s)**	**GAP heuristic /MILP (in %)**
100 - 30 - 35 000 order set 15	DLT 15h	28 752	9 727	0.00	29 925	1.68	4.08
	DLT 20h	24 802	43 200	7.26	25 266	2.31	1.87
	DLT 25h	24 416	43 200	46.76	24 883	2.60	1.91
	DLT 30h	24 845	43 200	50.05	24 883	2.09	0.15
	DLT 35h	22 590	43 200	43.92	23 162	2.33	2.53
100 - 30 - 45 000 order set 31	DLT 15h	26 959	2 214	0.00	26 959	1.65	0.00
	DLT 20h	22 094	11 251	0.00	22 834	1.95	3.35
	DLT 25h	22 118	43 200	30.85	22 834	1.95	3.24
	DLT 30h	22 118	43 200	50.34	22 834	1.95	3.24
	DLT 35h	22 417	43 200	51.62	22 834	1.95	1.86
100 - 40 - 45 000 order set 73	DLT 15h	31 103	13 893	0.00	31 150	3.15	0.15
	DLT 20h	26 040	43 200	30.43	29 364	2.97	12.76
	DLT 25h	26 582	43 200	52.29	27 628	3.19	3.93
	DLT 30h	26 129	43 200	44.78	27 341	3.14	4.64
	DLT 35h	27 328	43 200	50.81	27 040	4.06	-1.05
130 - 30 - 45 000 order set 100	DLT 15h	25 694	2 769	0.00	25 741	1.98	0.18
	DLT 20h	21 059	3 246	0.00	22 033	1.87	4.63
	DLT 25h	20 680	43 200	13.99	21 771	1.94	5.28
	DLT 30h	20 612	43 200	23.97	21 771	2.05	5.62
	DLT 35h	20 612	43 200	38.47	21 771	2.06	5.62
130 - 40 - 35 000 order set 126	DLT 15h	21 910	9 935	0.00	22 569	3.69	3.01
	DLT 20h	18 468	43 200	25.78	19 803	3.63	7.23
	DLT 25h	18 485	43 200	32.68	18 923	4.62	2.37
	DLT 30h	18 358	43 200	37.94	18 816	3.68	2.49
	DLT 35h	18 346	43 200	40.17	18 816	3.75	2.56
130 - 40 - 45 000 order set 150	DLT 15h	34 567	2 785	0.00	34 567	3.03	0.00
	DLT 20h	25 227	19 617	0.00	25 767	3.71	2.14
	DLT 25h	24 962	43 200	42.48	24 955	3.27	-0.02
	DLT 30h	21 344	43 200	37.86	22 222	3.80	4.11
	DLT 35h	20 716	43 200	38.36	21 490	3.86	3.74
168 - 200 - 350 000 order set 198	DLT 15h	unknown	43 200	-	83 856	16.49	-
	DLT 20h	unknown	43 200	-	78 534	30.49	-
	DLT 25h	unknown	43 200	-	78 061	38.44	-
	DLT 30h	107 560	43 200	99.29	77 890	46.66	-27.58
	DLT 35h	unknown	43 200	-	77 890	54.99	-
168 - 300 - 350 000 order set 310	DLT 15h	infeasible	-	-	infeasible	-	-
	DLT 20h	infeasible	-	-	infeasible	-	-
	DLT 25h	unknown	43 200	-	106 396	34.36	-
	DLT 30h	unknown	43 200	-	105 968	45.43	-
	DLT 35h	unknown	43 200	-	104 738	43.57	-
240 - 250 - 300 000 order set 415	DLT 15h	63 232	43 200	80.63	62 822	41.15	-0.65
	DLT 20h	unknown	43 200	-	60 617	80.35	-
	DLT 25h	unknown	43 200	-	60 617	83.32	-
	DLT 30h	unknown	43 200	-	59 645	89.89	-
	DLT 35h	unknown	43 200	-	59 372	90.22	-
336 - 200 - 250 000 order set 495	DLT 15h	38 942	43 200	49.86	44 343	54.54	13.87
	DLT 20h	39 921	43 200	59.04	38 437	61.78	-3.72
	DLT 25h	61 529	43 200	86.46	36 718	73.19	-40.32
	DLT 30h	unknown	43 200	-	36 032	61.27	-
	DLT 35h	unknown	43 200	-	36 032	61.27	-
336 - 300 - 350 000 order set 657	DLT 15h	unknown	43 200	-	55 099	102.51	-
	DLT 20h	unknown	43 200	-	53 453	107.33	-
	DLT 25h	unknown	43 200	-	52 436	109.27	-
	DLT 30h	unknown	43 200	-	52 070	143.72	-
	DLT 35h	unknown	43 200	-	52 070	143.72	-

A considerable difference in CPU time between the MILP solver and the heuristic solver can be noticed. For small-sized problems, the MILP solver is able to find the optimal solution for some of the instances or can provide a feasible solution within the given time limit of 12 hours. In the latter case , the trend is that an increasing optimality gap as well as the corresponding best solution is provided by the exact solver for increasing target DLTs . For each of these problem instances the heuristic is able to provide a solution within a few seconds. As can be noticed from the last column in Table 3, the relative gap between the capital cost of both best solutions, provided resp. by the heuristic on such a short notice and the exact solver, are relatively low (on average 3.054%). Some of the gaps are negative, occuring in those situations for which the heuristic found a better solution than the MILP-solver when running for the fixed time limit.

For larger-sized problem instances, the heuristic is able to find solutions within a few minutes, whereas the MILP solver is most often not even able to find a feasible

solution within a given time limit of 12 hours. As the size of the instances of the BPD problems to solve become larger (i.e. more realistic), the MILP solver struggles even more to find feasible solutions. In case the MILP solver was unable to find a feasible solution within the given time frame, the solution for this problem instance is reported as "unknown", therefore no optimality gap or gap with the heuristic could be calculated. For some problem instances, such as those with parameter values '168 - 300 - 350 000' and target DLT 15h or 20h, no feasible solution does exist.
From this experiment we conclude that for small-sized problems the heuristic is able to provide solutions which are almost as good as the MILP solver with a time limit of 12 hours and in a few cases even better. In addition, for larger-sized problems, our heuristic is able to calculate a solution for all problem instances, where the exact solver is struggling to provide a feasible solution in a reasonable amount of time. Moreover, a plant design that is not optimal (but near optimal), offers some slack for the actually placed customer orders. Indeed, it is important to not forget when optimizing a design that the used set of orders, is a representative example and that the real customer orders' processing times, due dates or quantities may deviate slightly from this representative order set. Therefore in the following, the heuristic will be used to optimize larger-sized problem instances so as to study the effect of the target DLT on the design and capital costs.

5.3 Results

In order to draw conclusions about the optimal batch plant design and responsiveness, the results over all larger-sized problem instances are consolidated. To this end, the designs with the minimum, median and maximum capital cost across the 19 related order sets are selected for each of the 27 parameter combinations and each considered value of the target DLT.

Hence, as a generic example, Figure 5 shows the influence of the target DLT on the capital cost of the optimal design for 19 order sets comprising 200 orders, a total amount of 300000 kg and a horizon of 7 days. The graph plots the minimum, median and maximum capital cost found across the 19 related order sets, for an increasing target DLT. The results are only shown starting from a target DLT for which a feasible solution for all order sets could be found, which is 13 hours for this example.
As expected, the graph in Figure 5 shows that for shorter target DLTs the capital cost of the optimal designs are higher, which represents the *cost of responsiveness*. Indeed, for a shorter target DLT, the time window for production and storage of an order is shorter, resulting in less combinations/options for scheduling and a need to install new installations or replace them by larger sized equipment. However, as will be discussed further on, the effect on the total installed volume is less straightforward. In fact, when production equipment is added or increased in size, less storage tanks are needed or can be decreased in size. It should be noted that from a certain target DLT on the minimal design is found and the capital cost remains the same even if the target DLT would be increased.

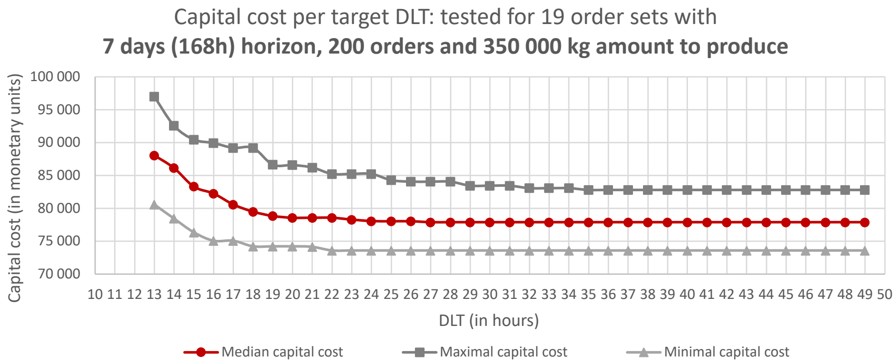

Figure 5: Minimum, median and maximum capital cost per target DLT of the 19 order sets with a 7 days (168h) horizon, 200 orders and a total amount to produce of 350000 kg

In Figure 6, the influence of the target DLT is studied in more detail. The total installed volume of this order set, as well as the number and sizes of the production equipment and storage tanks are shown for an increasing target DLT. For this, a particular order set amongst those represented in Figure 5 is selected, namely the order set whose capital cost per DLT is the nearest to the median capital cost per DLT (calculated over all the related order sets).

We observe that for a short target DLT, more production equipment and less storage tanks are needed. Moreover, the bottom part of the Figure 6 shows that, with a decreasing DLT, the cost of installed production equipment increases but the cost of installed storage tanks decreases in a nonlinear manner. In fact, there is a trade-off between production equipment and storage tanks: when production equipment is added, less storage tanks are needed, as orders are produced later and need to be kept in storage for a shorter period. The net effect on the total capital cost is still an increase, a result which can be explained by the (realistic) choice in our parameter settings. Indeed, the production equipment are assumed to be more expensive than the storage tanks. These conclusions are valid for all 513 order sets.

Again in Figure 6, one may observe that for multiple consecutive target DLTs, the total volume of all installations seems to remain more or less the same for all target DLTs, except for a small jump at a target DLT of 17 hours. In this case, 11 production equipment and 17 storage tanks are installed, whereas for a target DLT of 16 hours 12 production equipment but only 14 storage tanks are needed. Despite the decrease in the total installed volume, the influence on the design costs is still an increase.

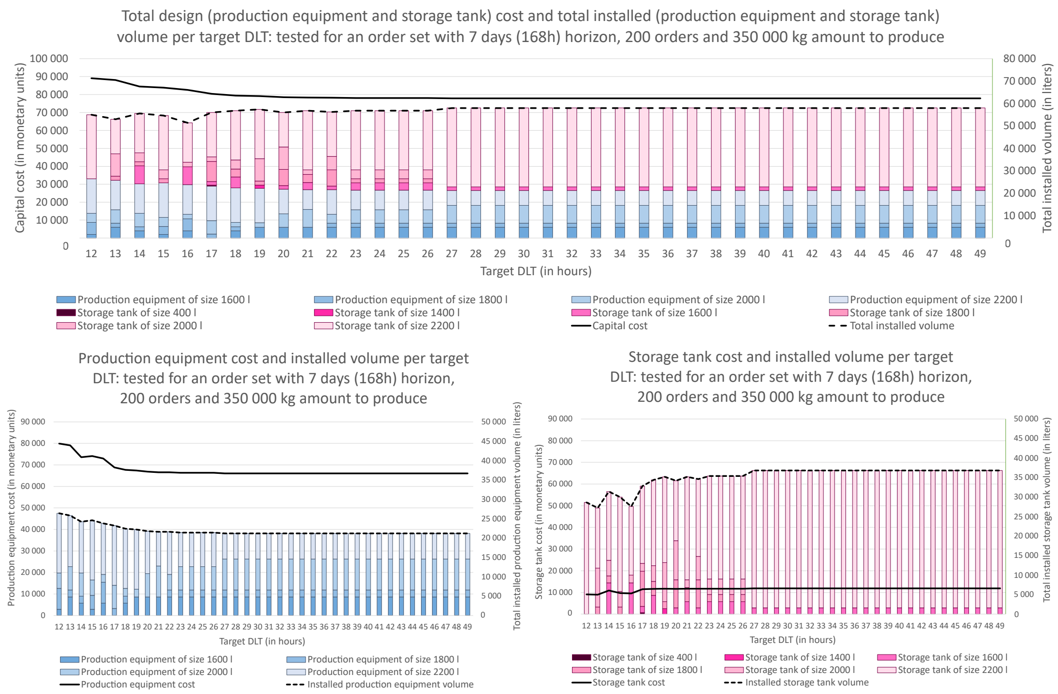

Figure 6: Above: Optimal capital cost and total installed volume of production equipment and storage tanks per target DLT for an order set comprising 200 orders, a total amount of 350 000 kg and an horizon of 7 days (168h) (order set 168) Below: cost and installed volume for production equipment and storage tanks separately

In Table 4, the results as shown in Figure 6 are listed amongst others. This table depicts the capital cost, installed volume, sizes of production equipment and storage tanks and the proportion of production equipment cost in the capital cost per target DLT. The results are shown for 7 different parameter combinations. For each parameter combination, again the order set is selected whose capital cost is the nearest to the median capital cost (calculated over all order sets). It can be noticed that the capital cost and the proportion of production equipment cost in the capital cost increase with a decreasing target DLT. Both observations result from the need for more production equipment and the cost difference between production equipment and storage tanks. Likewise, the total volume of production equipment increases and the total volume of storage tanks decreases with an increasing target DLT. In the last two columns, respectively the number of installed production equipment and storage tanks for each discrete size are listed per problem instance. It can be concluded that decreasing the DLT from 30 hours to 15 hours, results in an increase of the proportion of production equipment cost in the capital cost of 3.59% to 13.84%. Also, with a shorter target DLT, more and larger-sized production equipment are installed whereas the opposite can be noticed for storage tanks.

Table 4: Results for 7 order sets and DLT: capital cost, proportion of production equipment cost in capital cost, total volume of production equipment and storage tanks and number of installed production equipment and storage tanks for each discrete size

*Discrete set of production equipment and storage tank sizes = (400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200)

Horizon - orders - total amount	**Target DLT (in h)**	**Capital cost (in m.u.)**	**Proportion production equipment capital cost (in %)**	**Total volume production equipment (in l)**	**Total volume storage Tanks (in l)**	**Installed production equipment: resp. amounts of tanks per discrete size***	**Installed storage tanks: resp. amounts of tanks per discrete size***
168 - 200 - 350 000 order set 198	DLT 15h	83 856	88.39	24 600	30 000	(0,0,0,0,0,0,1,2,2,7)	(0,0,0,0,0,0,0,1,2,11)
	DLT 20h	78 534	85.14	21 800	34 200	(0,0,0,0,0,0,3,0,3,5)	(0,0,0,0,0,0,1,4,5,7)
	DLT 25h	78 061	84.95	21 400	35 400	(0,0,0,0,0,0,3,1,3,4)	(0,0,0,0,0,0,2,1,2,12)
	DLT 30h	77 890	84.80	21 200	36 800	(0,0,0,0,0,0,3,1,4,3)	(0,0,0,0,0,0,1,0,0,16)
	DLT 35h	77 890	84.80	21 200	36 800	(0,0,0,0,0,0,3,1,4,3)	(0,0,0,0,0,0,1,0,0,16)
168 - 250 - 300 000 order set 246	DLT 15h	94 558	90.11	26 000	25 600	(0,0,1,0,2,3,1,0,3,5)	(0,1,0,1,0,0,3,1,1,7)
	DLT 20h	90 168	82.87	21 600	37 000	(0,1,2,1,2,0,1,1,3,3)	(0,2,2,3,2,1,0,7,3,4)
	DLT 25h	90 168	82.87	21 600	37 000	(0,1,2,1,2,0,1,1,3,3)	(0,2,2,3,2,1,0,7,3,4)
	DLT 30h	90 168	82.87	21 600	37 000	(0,1,2,1,2,0,1,1,3,3)	(0,2,2,3,2,1,0,7,3,4)
	DLT 35h	90 168	82.87	21 600	37 000	(0,1,2,1,2,0,1,1,3,3)	(0,2,2,3,2,1,0,7,3,4)
240 - 200 - 250 000 order set 325	DLT 15h	57 504	90.69	16 200	14 600	(0,0,0,0,2,1,0,1,2,3)	(0,0,0,1,1,0,1,0,1,4)
	DLT 20h	51 194	86.93	13 400	18 200	(0,0,1,1,1,0,0,0,3,2)	(0,0,0,1,1,2,0,0,0,6)
	DLT 25h	48 602	79.91	11 600	24 200	(0,0,1,0,1,1,0,1,1,2)	(0,1,0,2,2,1,1,3,1,4)
	DLT 30h	48 071	79.48	11 200	25 000	(0,0,1,0,2,0,0,2,0,2)	(0,0,0,2,2,1,3,2,1,4)
	DLT 35h	48 071	79.48	11 200	25 000	(0,0,1,0,2,0,0,2,0,2)	(0,0,0,2,2,1,3,2,1,4)
240- 250 - 300 000 order set 405	DLT 15h	63 822	86.78	16 800	20 800	(0,1,1,1,0,0,1,0,2,4)	(0,0,1,3,2,1,0,0,0,6)
	DLT 20h	61 219	88.09	15 800	19 200	(0,1,1,1,0,1,1,1,1,3)	(0,0,0,2,1,1,1,0,1,5)
	DLT 25h	60 680	82.54	15 000	28 000	(0,0,1,1,0,1,1,2,0,3)	(0,1,0,2,0,2,0,4,0,7)
	DLT 30h	60 680	82.54	15 000	28 000	(0,0,1,1,0,1,1,2,0,3)	(0,1,0,2,0,2,0,4,0,7)
	DLT 35h	60 680	82.54	15 000	28 000	(0,0,1,1,0,1,1,2,0,3)	(0,1,0,2,0,2,0,4,0,7)
336 - 200 - 350 000 order set 533	DLT 15h	45 335	87.95	12 400	15 800	(0,1,0,0,0,1,0,1,1,3)	(0,0,0,0,0,1,0,2,1,4)
	DLT 20h	41 665	85.11	11 200	18 600	(0,0,0,0,0,1,1,1,1,2)	(0,0,0,0,0,1,0,0,2,6)
	DLT 25h	38 514	78.54	9 800	24 600	(0,0,0,0,0,0,1,1,1,2)	(0,0,0,0,0,0,2,0,3,7)
	DLT 30h	38 514	78.54	9 800	24 600	(0,0,0,0,0,0,1,1,1,2)	(0,0,0,0,0,0,2,0,3,7)
	DLT 35h	38 514	78.54	9 800	24 600	(0,0,0,0,0,0,1,1,1,2)	(0,0,0,0,0,0,2,0,3,7)
336 - 250 - 250 000 order set 559	DLT 15h	45 937	86.66	12 200	17 600	(0,0,1,0,0,1,0,2,1,2)	(0,0,0,0,1,0,2,0,0,6)
	DLT 20h	43 196	85.78	10 600	17 800	(0,0,2,0,1,1,0,0,1,2)	(0,0,0,0,1,0,1,1,0,6)
	DLT 25h	41 094	77.19	9 000	19 800	(0,0,1,1,1,0,0,1,1,1)	(0,0,4,2,3,1,1,2,0,2)
	DLT 30h	40 983	76.67	8 800	21 600	(0,0,1,1,1,0,1,0,1,1)	(0,0,1,3,4,1,1,2,1,2)
	DLT 35h	40 983	76.67	8 800	21 600	(0,0,1,1,1,0,1,0,1,1)	(0,0,1,3,4,1,1,2,1,2)
336 - 300 - 350 000 order set 650	DLT 15h	55 164	87.76	14 200	19 400	(0,1,1,1,0,1,0,0,3,2)	(0,1,0,0,1,0,0,0,0,8)
	DLT 20h	50 645	82.27	11 800	21 600	(0,1,1,1,1,0,0,1,1,2)	(0,2,1,2,0,1,0,2,3,3)
	DLT 25h	50 377	82.11	11 600	22 200	(0,1,1,1,1,0,1,0,1,2)	(0,2,2,1,0,0,0,3,1,5)
	DLT 30h	50 039	73.92	10 600	33 000	(0,1,0,1,1,1,0,0,1,2)	(0,2,1,2,1,0,0,4,7,3)
	DLT 35h	50 039	73.92	10 600	33 000	(0,1,0,1,1,1,0,0,1,2)	(0,2,1,2,1,0,0,4,7,3)

Table 5: Minimum capital cost and cost of responsiveness for 8 order sets with different parameter sets

Horizon - orders - total amount	Minimum capital cost (in m.u.)	Cost of responsiveness (8h) (in m.u.)	Cost of responsiveness (12h) (in m.u.)	Cost of responsiveness (16h) (in m.u.)	Cost of responsiveness (24h) (in m.u.)	Cost of responsiveness (32h) (in m.u.)
168 - 200 - 250 000 order set 170	75 247 (from DLT 45h)	621 (0.83 %)	612 (0.83 %)	3 132 (4.16 %)	4 724 (6.28 %)	12 761 (16.96 %)
168 - 250 - 300 000 order set 247	91 642 (from DLT 43h)	163 (0.18 %)	276 (0.30 %)	1 252 (1.37 %)	3 156 (3.44 %)	infeasible
168 - 300 - 350 000 order set 320	103 147 (from DLT 48h)	888 (0.86 %)	913 (0.89 %)	3 367 (3.26 %)	12 814 (12.42 %)	infeasible
240 - 200 - 250 000 order set 329	45 307 (from DLT 47h)	105 (0.23 %)	105 (0.23 %)	105 (0.23 %)	373 (0.82 %)	5 120 (11.30 %)
240 - 250 - 300 000 order set 415	58 370 (from DLT 44h)	1 001 (1.72 %)	1 275 (2.18 %)	2 247 (3.85 %)	2 247 (3.85 %)	13 646 (23.38 %)
336 - 200 - 250 000 order set 512	37 732 (from DLT 42h)	641 (1.70 %)	929 (2.46 %)	2 635 (6.98 %)	3 500 (9.28 %)	infeasible
336 - 250 - 300 000 order set 580	44 050 (from DLT 37h)	588 (1.34 %)	588 (1.34 %)	588 (1.34 %)	16 233 (36.85 %)	infeasible
336 - 300 - 350 000 order set 648	51 701 (from DLT 45h)	541 (1.05 %)	541 (1.05 %)	541 (1.05 %)	3 547 (6.86 %)	20 874 (40.37 %)

In Table 5, the minimum capital cost, as well as the cost of responsiveness is shown for 8 order sets with different values for the variable parameters. The minimum capital cost is reached from a certain target DLT, after which increasing it has no impact on the plant design, neither on the capital cost. The table lists the cost of increasing the plant's responsiveness, i.e. decreasing the DLT with 8, 12, 16, 24 or 32 hours. For every order set, we start from the DLT for which the minimal design is found. As an example, for the order set 320, where 300 orders are to be produced with a total amount of 350000 kg within a horizon of 168 hours (7 days), decreasing the DLT with 24 hours (1 day) implies decreasing the DLT from 48 to 24 hours. The difference in capital cost, and therefore the cost of this increase in responsiveness, is 12814 monetary units (or 12.42% of the minimum capital cost). When one would aim to decrease the target DLT with 32 hours, no design can be found. For such a decrease, the target DLT would be 16 hours. However, for this target DLT, no feasible design was found.
Another remarkable result is that for a plant with parameters '336-300-350 000' (order set 648), whose management wishes to decrease the target DLT with 32 hours, a capital cost increase of 40.37% is incurred. From this experiment, it can be concluded that the cost of responsiveness, when decreasing the target DLT with 8 hours, varies between 0.18% and 1.72% of the minimum capital cost. Decreasing the target DLT causes a capital cost to increase. Indeed, for a decrease of 12, 16, 24 and 32 hours, an increase of the capital cost is incurred between 0.23% and 2.46%, 0.23% and 6.98%, 0.82% and 36.85%, and between 11.30% and 40.37% respectively.

The aforementioned results allow us to conclude that it is possible to monetarize the responsiveness (a strategic supply chain parameter) of a batch plant at design level by means of the concept "target DLT". The extra cost of responsiveness for a batch plant can be determined by analyzing the effect on capital cost when reducing the target DLT.

5.4 Consistency results

As a by-product of the previous experiment some expected relationships were rediscovered, hereby increasing the degree of consistency and validity of our experiment. These relationships are obtained when varying one of the variable parameters (see Table 2), keeping the other two parameters constant.

First, one may notice from Figure 7 that the longer the horizon, for an identical amount of orders and amount to produce, the lower the capital cost. This relation is however nonlinear. Since a longer horizon results in due dates being more scattered. Hence, less orders are due at the same time, resulting in less storage tanks simultaneously needed.

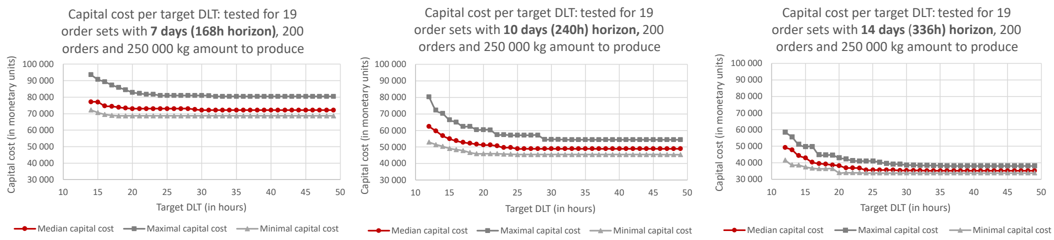

Figure 7: Capital cost per target DLT: difference in capital cost for different horizons for 200 orders to produce with a total amount of 250000 kg (left: 7 days, middle: 10 days, right: 14 days)

Secondly, when the amount of orders to be produced is increased, keeping the horizon and the total amount to produce constant, the number of due dates will increase. Consequently, the number of simultaneous productions will increase, resulting in the need of more production and storage tanks, hence a higher capital cost. Therefore, it can be stated that more orders to be produced in the same horizon and with an identical amount to produce, leads to a slightly higher capital cost. This relationship is however nonlinear in nature. Figure 8 illustrates this for the parameter combination corresponding to a total amount of 250000 kg to be produced in a horizon of 10 days. spread over 200, 250 or 300 orders.

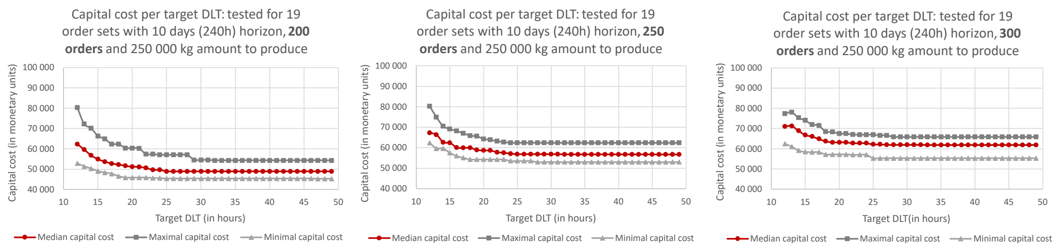

Figure 8: Capital cost per target DLT: difference in capital cost for more orders (left: 200 orders, middle: 250 orders, right: 300 orders)

Finally, when the total amount to be produced is higher, for the same horizon and amount of orders, the capital cost will be slightly higher. Also, this relation is nonlinear in nature, as illustrated in Figure 9 for a 300 orders to be produced in a horizon of 14 days.

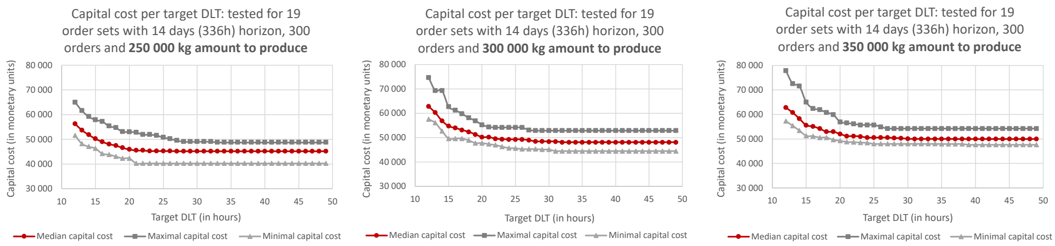

Figure 9: Capital cost per target DLT: difference in capital cost for a higher total amount to produce (left: 250000 kg, middle: 300000 kg, right: 350000 kg)

The fact that our results do not contradict these three relationships, although being rather trivial, strengthens our belief in the correctness of our previous findings on the use of a varying target DLT to determine the cost of responsiveness.

6 Conclusion

In this paper, the introduction of the target delivery lead time (DLT) in the strategic design of a make-to-order (MTO) multiproduct batch plant as well as the influence of the length of the target DLT is investigated. An exact model to define the optimal design is described, as well as a heuristic to obtain results for larger instances within an acceptable amount of time. A (discrete) time dimension, due dates, storage tanks and mandatory storage time (load time) are introduced in the mathematical model in order to compute the design for a plant operating with a certain target DLT. This has been tested for 513 order sets from which all can be concluded that the capital cost is higher when the target DLT is lower. With a lower target DLT, more production equipment but less storage tanks are needed, which results, because of the cost difference between production equipment and storage tanks, in a higher capital cost. The influence on the total installed volume is more ambiguous since a lower target DLT can result in a roughly equal volume although less storage tanks are installed. It is however certain that a lower target DLT results in a higher capital cost. From a certain DLT, a minimum design or capital cost is found and increasing the DLT would have no effect on the design or capital cost. To quantify the exact impact of a lower DLT on the capital cost, the cost of responsiveness is expressed as a percentage of the minimum capital cost. It can be concluded that decreasing the DLT with 8 hours results in a capital cost increase between 0.23 and 2.46% whereas decreasing the DLT with 24 hours (1 day) incurs a capital cost increase between 0.82 % and 36.85 %. When the exact cost of responsiveness is expressed in monetary units, management can weigh the cost of responsiveness with the profit of being more responsive.

As future work, further research is to be carried out to develop robust plants feasible for multiple order sets with the same (variable) parameters. Other ideas for additional research include introducing contaminations or product families. As this is researched for a make-to-order production environment specifically, it might be interesting to also determine the influence of the production lead time for other types of production environment.

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References

APICS. (2017). Quick reference guide. scor supply chain operations reference model.

Barbosa-Póvoa, A. P. (2007). A critical review on the design and retrofit of batch plants. *Computers & Chemical Engineering*, *31*(7), 833–855.

Barbosa-Póvoa, A., & Pantelides, C. (1997). Design of multipurpose plants using the resource-task network unified framework. *Computers & Chemical Engineering*, *21*, S703-S708. Retrieved from https://www.sciencedirect.com/science/article/pii/S0098135497875850 (Supplement to Computers and Chemical Engineering) doi: https://doi.org/10.1016/S0098-1354(97)87585-0

Bhatia, T., & Biegler, L. T. (1996). Dynamic optimization in the design and scheduling of multiproduct batch plants. *Industrial & Engineering Chemistry Research*, *35*(7), 2234–2246.

Biegler, L. T., Grossmann, I. E., & Westerberg, A. W. (1997). *Systematic methods for chemical process design.* Retrieved from https://www.osti.gov/biblio/293030

Birewar, D., & Grossmann, I. (1989). Incorporating scheduling in the optimal design of multiproduct batch plants. *Computers & Chemical Engineering*, *13*(1), 141-161. Retrieved from https://www.sciencedirect.com/science/article/pii/0098135489890143 (Computer Applications to Batch Chemical Processing) doi: https://doi.org/10.1016/0098-1354(89)89014-3

Blömer, F., & Gunther, H.-O. (2000). Lp-based heuristics for scheduling chemical batch processes. *International Journal of Production Research*, *38*(5), 1029–1051.

Blömer, F., & Günther, H.-O. (1998). Scheduling of a multi-product batch process in the chemical industry. *Computers in Industry*, *36*(3), 245-259. Retrieved from https://www.sciencedirect.com/science/article/pii/S016636159800075X doi: https://doi.org/10.1016/S0166-3615(98)00075-X

Burkard, R. E., Fortuna, T., & Hurkens, C. A. (2002). Makespan minimization for chemical batch processes using non-uniform time grids. *Comput-*

ers & Chemical Engineering, *26*(9), 1321-1332. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0098135402000972` doi: https://doi.org/10.1016/S0098-1354(02)00097-2

Chibeles-Martins, N., Pinto-Varela, T., Barbósa-Póvoa, A. P., & Novais, A. (2010). A meta-heuristics approach for the design and scheduling of multipurpose batch plants. In *Computer aided chemical engineering* (Vol. 28, pp. 1315–1320). Elsevier.

Chibeles-Martins, N., Pinto-Varela, T., Barbósa-Póvoa, A. P., & Novais, A. (2011). A simulated annealing approach for the biobjective design and scheduling of multipurpose batch plants. In *Computer aided chemical engineering* (Vol. 29, pp. 865–869). Elsevier.

Dietz, A., Azzaro-Pantel, C., Pibouleau, L., & Domenech, S. (2006). Multiobjective optimization for multiproduct batch plant design under economic and environmental considerations. *Computers & Chemical Engineering*, *30*(4), 599–613.

Elkamel, A., Zentner, M., Pekny, F., & Reklaitis, G. (1997). A decomposition heuristic for scheduling the general batch chemical plant. *Engineering Optimization+ A35*, *28*(4), 299–330.

Fumero, Y., Corsano, G., & Montagna, J. M. (2011). Detailed design of multiproduct batch plants considering production scheduling. *Industrial & engineering chemistry research*, *50*(10), 6146–6160. doi: https://doi.org/10.1021/ie1008376

Fumero, Y., Moreno, M. S., Corsano, G., & Montagna, J. M. (2016). A multiproduct batch plant design model incorporating production planning and scheduling decisions under a multiperiod scenario. *Applied Mathematical Modelling*, *40*(5-6), 3498–3515.

Grossmann, I. E., & Sargent, R. W. (1979). Optimum design of multipurpose chemical plants. *Industrial & Engineering Chemistry Process Design and Development*, *18*(2), 343–348. doi: https://doi.org/10.1021/i260070a031

Harjunkoski, I., & Bauer, R. (2017). Industrial scheduling solution based on flexible heuristics. *Computers & Chemical Engineering*, *106*, 883–891.

Hill, A., Cornelissens, T., & Sörensen, K. (2016). Efficient multi-product multi-bom batch scheduling for a petrochemical blending plant with a shared pipeline network. *Computers & Chemical Engineering*, *84*, 493-506. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0098135415003105` doi: https://doi.org/10.1016/j.compchemeng.2015.09.015

Ierapetritou, M., & Floudas, C. (1998). Effective continuous-time formulation for short-term scheduling. 1. multipurpose batch processes. *Industrial & engineering chemistry research*, *37*(11), 4341–4359. doi: https://doi.org/10.1021/ie970927g

Knopf, F. C., Okos, M. R., & Reklaitis, G. V. (1982). Optimal design of batch/semicontinuous processes. *Industrial & Engineering Chemistry Process Design and Development*, *21*(1), 79–86.

Kondili, E., Pantelides, C., & Sargent, R. (1993). A general algorithm for short-term scheduling of batch operations—i. milp formulation. *Computers & Chemical Engineering*, *17*(2), 211-227. Retrieved from `https://www.sciencedirect.com/`

science/article/pii/009813549380015F (An International Journal of Computer Applications in Chemical Enginnering) doi: https://doi.org/10.1016/0098-1354(93)80015-F

Lin, X., & Floudas, C. (2001). Design, synthesis and scheduling of multipurpose batch plants via an effective continuous-time formulation. *Computers & Chemical Engineering*, *25*(4), 665-674. Retrieved from https://www.sciencedirect.com/science/article/pii/S0098135401006639 doi: https://doi.org/10.1016/S0098-1354(01)00663-9

Loonkar, Y. R., & Robinson, J. D. (1970). Minimization of capital investment for batch processes. calculation of optimum equipment sizes. *Industrial & Engineering Chemistry Process Design and Development*, *9*(4), 625–629.

Méndez, C. A., Cerdá, J., Grossmann, I. E., Harjunkoski, I., & Fahl, M. (2006). State-of-the-art review of optimization methods for short-term scheduling of batch processes. *Computers & Chemical Engineering*, *30*(6), 913-946. Retrieved from https://www.sciencedirect.com/science/article/pii/S0098135406000287 doi: https://doi.org/10.1016/j.compchemeng.2006.02.008

Modi, A., & Karimi, I. (1989). Design of multiproduct batch processes with finite intermediate storage. *Computers & Chemical Engineering*, *13*(1), 127-139. Retrieved from https://www.sciencedirect.com/science/article/pii/0098135489890131 (Computer Applications to Batch Chemical Processing) doi: https://doi.org/10.1016/0098-1354(89)89013-1

Moreno, M. S., & Montagna, J. M. (2012). Multiperiod production planning and design of batch plants under uncertainty. *Computers & chemical engineering*, *40*, 181–190.

Moreno, M. S., Montagna, J. M., & Iribarren, O. A. (2007). Multiperiod optimization for the design and planning of multiproduct batch plants. *Computers & Chemical Engineering*, *31*(9), 1159-1173. Retrieved from https://www.sciencedirect.com/science/article/pii/S0098135406002559 doi: https://doi.org/10.1016/j.compchemeng.2006.10.003

Olhager, J. (2003). Strategic positioning of the order penetration point. *International journal of production economics*, *85*(3), 319–329.

Pantelides, C. C. (1994). Unified frameworks for optimal process planning and scheduling. In *Proceedings on the second conference on foundations of computer aided operations* (pp. 253–274).

Patel, A., Mah, R., & Karimi, I. (1991). Preliminary design of multiproduct noncontinuous plants using simulated annealing. *Computers & Chemical Engineering*, *15*(7), 451-469. Retrieved from https://www.sciencedirect.com/science/article/pii/009813549185025P doi: https://doi.org/10.1016/0098-1354(91)85025-P

Pinto, T., Barbósa-Póvoa, A. P. F., & Novais, A. Q. (2008). Design of multipurpose batch plants: A comparative analysis between the stn, m-stn, and rtn representations and formulations. *Industrial & Engineering Chemistry Research*, *47*(16), 6025–6044. doi: https://doi.org/10.1021/ie071281n

Pinto, T., Barbosa-Póvoa, A. P. F., & Novais, A. Q. (2005). Optimal design and retrofit of batch plants with a periodic mode of operation. *Computers & Chemical Engineering*, *29*(6), 1293-1303. Retrieved from https://www.sciencedirect.com/science/article/pii/S0098135405000177 (Selected Papers Presented at the 14th European Symposium on Computer Aided Process Engineering) doi: https://doi.org/10.1016/j.compchemeng.2005.02.001

Schilling, G., & Pantelides, C. (1999). Optimal periodic scheduling of multipurpose plants. *Computers & Chemical Engineering*, *23*(4), 635-655. Retrieved from https://www.sciencedirect.com/science/article/pii/S0098135498002993 doi: https://doi.org/10.1016/S0098-1354(98)00299-3

Shah, N., & Pantelides, C. C. (1992). Design of multipurpose batch plants with uncertain production requirements. *Industrial & Engineering Chemistry Research*, *31*(5), 1325–1337. doi: https://doi.org/10.1021/ie00005a013

Sparrow, R. E., Forder, G. J., & Rippin, D. W. (1975). The choice of equipment sizes for multiproduct batch plants. heuristics vs. branch and bound. *Industrial & Engineering Chemistry Process Design and Development*, *14*(3), 197–203.

Vaselenak, J. A., Grossmann, I. E., & Westerberg, A. W. (1987). An embedding formulation for the optimal scheduling and design of multipurpose batch plants. *Industrial & engineering chemistry research*, *26*(1), 139–148.

Verbiest, F., Cornelissens, T., & Springael, J. (2017). Design of a chemical batch plant with parallel production lines: Plant configuration and cost effectiveness. *Computers & Chemical Engineering*, *99*, 21-30. Retrieved from https://www.sciencedirect.com/science/article/pii/S0098135416304185 doi: https://doi.org/10.1016/j.compchemeng.2016.12.013

Verbiest, F., Cornelissens, T., & Springael, J. (2019). A matheuristic approach for the design of multiproduct batch plants with parallel production lines. *European Journal of Operational Research*, *273*(3), 933-947. Retrieved from https://www.sciencedirect.com/science/article/pii/S0377221718307586 doi: https://doi.org/10.1016/j.ejor.2018.09.012

Verbiest, F., Cornelissens, T., Springael, J., et al. (2021). *Multiperiod chemical batch plant design for a single product or mixed product campaign mode of operation.* University of Antwerp, Faculty of Business and Economics.

Verbiest, F., Pinto-Varela, T., Cornelissens, T., Springael, J., & Barbósa-Póvoa, A. (2019). Decomposition approaches for the design and scheduling of multiproduct multistage batch plants with parallel lines. *Computers & Chemical Engineering*, *127*, 111-126. Retrieved from https://www.sciencedirect.com/science/article/pii/S0098135418312894 doi: https://doi.org/10.1016/j.compchemeng.2019.05.001

Voudouris, V. T., & Grossmann, I. E. (1992). Mixed-integer linear programming reformulations for batch process design with discrete equipment sizes. *Industrial & engineering chemistry research*, *31*(5), 1315–1325. doi: https://doi.org/10.1021/ie00005a012

Xi-Gang, Y., & Zhong-Zhou, C. (1997). A hybrid global optimization method for design of batch chemical processes. *Computers & Chemical engineering*, *21*, S685–S690.