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Considering start-ups and shutdowns using an optimisation tool – Including a dairy production planning case study

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HIGHLIGHTS

- ▶ Four alternative ways to consider start-ups and shutdowns in production planning using MILP.
- ▶ Description of the constraints needed for these alternatives.
- ▶ Implementation of these alternatives in the energy system optimisation tool reMIND.
- ▶ Analyses of the alternatives in a simple dairy case study.

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ABSTRACT

There are many different aspects a production-planning model has to be able to handle to make a model adequate for the purpose. One aspect is the handling of start-ups and shutdowns for different processes. The production plan is likely to be changed when considering, for example, a cost connected to the start-up and/or shutdown of processes. Besides costs associated with start-ups and shutdowns, waste may be produced during the start-up and shutdown. However, there is also the possibility of carrying out soft start-ups and shutdowns or limiting the number of start-ups and shutdowns. Thus, start-ups and shutdowns have to be handled in an adequate way in models to produce reliable and accurate results. In optimisation tools, this may be dealt with by introducing certain constraints, including integers. In this paper, the implementation of alternative ways to consider start-ups and shutdowns are presented. This is done in the energy system optimisation tool reMIND, which deals with Mixed Integer Linear Programming (MILP) problems. The purpose of this paper is to show four alternatives to consider start-ups and shutdowns in optimisation models. This involves, in total, almost 50 constraints. Also, a simple dairy case study is included in the paper to visualise the effect of implementing the different alternatives to shutdowns.

1. Introduction

There are many different aspects to consider in the production-planning process, and there are different types of models that can be used to help with different situations. Simulation tools are widely used in industry as one part in the decision-making process. Decision support also includes risk management, economic calculations and optimisation. The decision support is a part of the decision-making process, which means helping people to make good decisions by understanding and analysing the effects of all of the alternatives [1]. Simulation modelling tools may be complemented by other modelling tools that enhance the support for decisions. Mardan and Klahr [2] have shown that an optimisation tool may be a very powerful complement to a simulation tool. By combining these tools this may increase the reliability of the results, but it also enhances the possibility of finding better solutions. An optimisation tool may be used to find the optimal result and a simulation tool may be used to find out whether it is possible to run the solution in reality [3].

To further increase the advantages of using a simulation tool and an optimisation tool in combination, it is necessary to consider start-ups and shutdowns in the optimisation tool. Many of the differences in the results from the two different tools occur because of a lack of modelling start-ups and shutdowns in the optimisation tool. Even without the use of both tools in combination there is a need for optimisation tools to consider start-ups and shutdowns, to make adequate production planning.

Many articles have been published on the optimisation of systems, where the costs associated with the starting up and/or shutting down of processes are considered, see for example [4–8].

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Nomenclature

c	a parameter: represents e.g. (1) a slope of a function [slope] and (2) a step in a function [step] (real)
C	a constant (real)
e	the proportion of the flow in the branches, in the previous and/or the following time step, that have to pass the branches in the actual time step (real)
g	continuous variable (real, help variable)
i	flow entering a node (integer)
I	total amount of flows entering a node (integer)
j	flow leaving a node (integer)
J	total amount of flows leaving a node (integer)
k	indicating a binary variable associated with flow(s) (integer)
lts	last time step (integer)
min	lower limit value (real)
o	objective function
pr	price (real)
r, $r1$, $r2$	indicating a help binary variable (integer)
R	total amount of start-ups ($R1$) or shutdowns ($R2$) (integer)
s	constant cost when the process is in operation (real)
S	cost of starting up or shutting down (real)
t	time step (integer)
T	total amount of time steps (integer)
tv	threshold value (real)
u	a large number (real) (determined in reMIND, set to 10^6 by default)
v	the number of a specific real variable (integer)
V	the total number of real variables in the problem (integer)
w	the number of a specific integer variable (integer)
W	the total number of integer variables (integer)
wf	indicating the waste flow (real)
WF	a fixed ($WF1$) or percentage ($WF2$) value indicating the amount of waste (real)
x	continuous variable, represents a flow of any kind (real)
y	integer variable (integer)
Y	binary variable (only attaining the values 0 or 1) (integer)
z	the number of a specific constraint (integer)
Z	total number of constraints (integer)

However, appropriate or detailed information of the type of constraints that are needed to be included in the model for representing a start-up and/or a shutdown process are missing. Furthermore, the papers consider just a start-up and/or a shutdown that is associated with a cost, and do not take into consideration any other alternatives, such as the production of waste (called "waste" in the subsequent text) when shutting down or starting up a process or a restriction in processes requirements that force the processes to start or stop slowly. In addition, neither production planning nor manufacturing industries are used as case studies in published articles when considering start-ups or shutdowns.

When looking at earlier systems that have been modelled using the energy systems optimisation tool reMIND [9], scrutinising other energy systems' optimisation tools and conducting an additional survey between companies, four different alternatives on start-ups and shutdowns have been found to be most relevant involving e.g. costs and wastes associated with start-ups and shutdowns.

The purpose of this paper is to show possible ways to model start-ups and shutdowns in optimisation models. Four alternatives have been included in this paper and the corresponding constraints for each alternative are presented. Also, a simple case study is included in the paper to show how important it is to consider start-ups and shutdowns in models for production planning in a dairy. To reduce the size of the paper, only shutdown examples are included, as both start-ups and shutdowns work in the same way.

2. Method

2.1. MILP in general

As the basis for the study, MILP is used. A MILP problem is defined, in general, according to Eqs. (1) and (2) [10]. The parameters, variables and subscripts found in the constraints below are explained the first time they appear in the text. A nomenclature is also included as help.

Objective:

$$\min \sum_{v=1}^{V}\sum_{w=1}^{W}(c_{1,v}x_v + c_{2,w}y_w) \tag{1}$$

subject to:

$$\sum_{v=1}^{V}\sum_{w=1}^{W}(c_{3,v,z}x_v + c_{4,w,z}y_w)\begin{Bmatrix}\leqslant\\ =\\ \geqslant\end{Bmatrix}c_z, \quad \forall z = 1,2,\ldots,Z \tag{2}$$

$$x \geqslant 0$$

where v and w are the numbers of a specific real and integer variable, respectively, and V and W are the total numbers of real and integer variables, respectively, in the problem. c is a parameter, while x represent continuous variables and y represent the integer variables. z is the number of a specific constraint while Z is the total number of constraints in the problem

In Eq. (1) variables are included that influence the system cost and for each variable the corresponding coefficient are included, representing the price per unit of the specific variable. A variable may e.g. be the amount of electricity that is needed to be purchased in the system that is modelled and the corresponding coefficient represents the electricity price. The variables are also included in the constraints. The constraints (included in the model by Eq. (2)) may be of any kind that restricts the allowed solution range. A constraint may for example represent a limitation of the maximum electricity that may be purchased.

2.2. reMIND in general

This study uses the energy system optimisation tool reMIND, which is based on the MIND method (Method for analysis of INDustrial energy systems) developed at Linköping University in Sweden [9,11]. The method has been developed for the optimisation of dynamic industrial energy systems, but other types of systems may be analysed as well. The dynamics of the modelled systems are considered by dividing time into time steps (TSs). The amount and length of the TSs depend on the purpose of the analysis and the system to be modelled. The structure of the system is modelled using branches and nodes. The branches represent different kinds of flow (e.g. materials and electricity) and the nodes represent different kinds of processes (e.g. separators and boilers). All limitations and relations in the system are included in a standardised file. The file is optimised using an optimisation solver. In