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Increasing solar energy utilisation by rescheduling operations with heat and electricity demand

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The efficient management of renewables to reduce utilisation of energy sources with high impact on the environment (e.g. fossil fuels) is a widely studied research topic. The core of the complexity for this kind of planning and operational problems is the variety and variation on both the supply and demand side. In a typical case study both high and low temperature heat, and electricity demands are present and they vary through the time. This study applies mathematical programming for the rescheduling of the operations in order to minimise the utility consumption. It reduces the impact on the environment by exploiting an inherent flexibility of the processes on the demand side. Some operations can be shifted in time if the site has enough of a certain resource in stock. An example is the milling of wheat at a storehouse (production of flour) or the washing of laundry at a hotel (clean towels).
A flexible operation can be rescheduled; however, the size of the stock implies a limitation for the shifting in time. The optimal solution of the operational level can depend on the design parameters. A retrofit sensitivity analysis has been done, where the optimal schedule was identified for different design conditions.

1. Introduction

The basis of Batch Process Integration were introduced by Kemp and Deakin (1989), and further developed by Klemeš et al. (1994). One of the models called Time Slice Model (TSM), proposed a Heat Integration of batch processes in each Time Slice separately. It was extended by Varbanov and Klemeš (2011) for analysing Total Sites with the integration of renewables. An overview of recent Process Integration works considering both batch and continuous processes can be found in elsewhere, see e.g. Friedler (2009, 2010).
To obtain sustainable processes the utilisation of s solar energy, should be integrated as efficiently as possible (Pereira, 2009). The integration of solar energy is, however, a complex problem due to fluctuations of availability of solar energy and the process demands (Atkins, 2010). A number of different process units and various temperature levels of demand also contribute to the complexity of the problem. In addition, even the capture of solar thermal energy can be performed at different temperature levels. To deal with problem two main approaches are possible:
Dynamic models, which are complex, and obtaining a solution cannot be guaranteed. A multi-period model involving a series of steady-state time intervals for the modelling horizon.
This work applies the second approach, i.e., the Heat Integration is performed in each period separately.

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This work integrates as high amount of solar thermal energy to processes as possible with varying demand. For this purpose an MILP model has been developed to minimise the fossil fuel consumption and electricity usage by rescheduling the process demands. This will simultaneously increase the amount integrated solar thermal energy.

2. Methodology

The processes' utility system has significant impact on the process sustainability. The hierarchy, which seems appropriate to cover heat demand in the descending order (Perry et al, 2008; Varbanov and Klemeš, 2011)

i. Maximise the heat recovery by applying the Heat Integration methods (Klemeš et al, 2010)
ii. Maximise the integration of renewable energy sources having usually less impact on the environment and
iii. As a last option use utilities, with constant availability in time. They are usually produced by fossil fuels and having generally a higher impact on environment.

The major focus is on point (ii) of this hierarchy, i.e., the integration of solar energy. The aim is to minimise the fossil fuel consumption, which is achieved by more efficient integration of solar thermal energy. The advantages of utilising solar thermal energy as soon as possible are twofold (IEA, 2007):

i. Increased amount of the integrated solar thermal heat and
ii. The storage capacity can be reduced, when utilising the same amount of heat.

A utility with constant availability should be used as a backup (e.g., fossil fuel, gas, biomass). The scheme of the system is presented in Figure 1. It consists of a solar collector from where the heat is transferred to the storage. The water from this storage can be used for the washing of towels and plates, where additional heating with electricity may be required. The water of the storage tank can also be pumped to the boiler, where the water is kept on a constant temperature by using gas if needed. The water in the boiler is used for fixed demands, e.g. showering. Both storages can be filled with tap water, when needed.

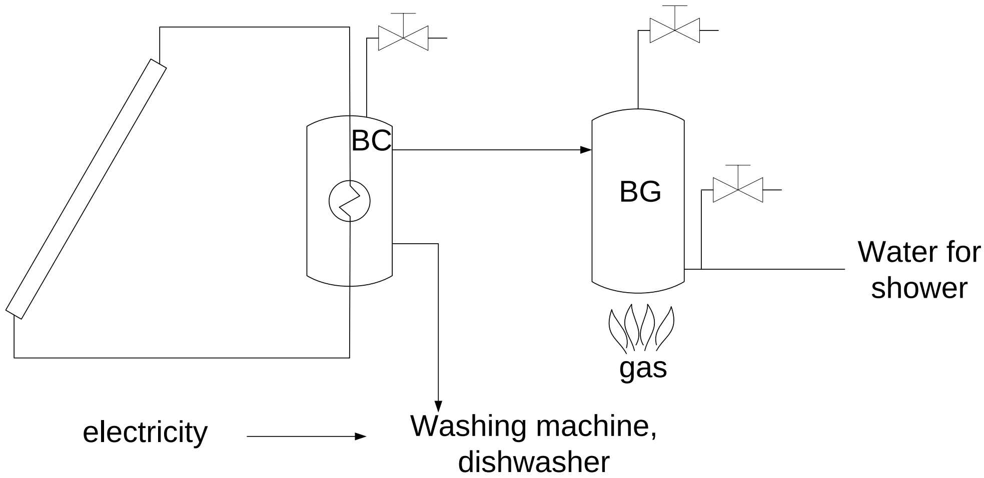

Figure 1: Scheme of the process system

The mathematical programming model

A mathematical programming based formulation has been developed to find the optimal schedule of the shiftable processes, The model is based on a discrete time representation, where the time horizon is divided into uniform length time slices, denoted by $TS=\{1,2\ldots,n_{TS}\}$, where n_{TS} is the number of considered intervals. This set is indexed by t, and the length of each time slice is t^{TS}.

The fix demands are given in set FD, each $d \in FD$ corresponds to exactly one time slice, and defines an amount of water, that is taken from the boiler.

Demand types that can be shifted are given in set *VD*. Note that this is not the set of demands, only the set of different type of items, e.g., towels, plates. It is assumed, that there is a stock of each type $d \in VD$, denoted by $stock_d^{VD}$. An item can be in three different states: *unused*, when it is clean, and ready to be given to the customers, if it is needed; *inuse*, when it is at the customer being used; and *used*, when it is returned from the customer, but still not ready to give it to another one. To each of these states, a continuous variable is assigned at each Time Slice (TS). The demands for this type of items are given by two set of parameters: $need_{d,t}^{VD}$ and $return_{d,t}^{VD}$, that represents the need for unused items at the beginning of TS *t*, and the amount of returned items at the end of the TSs. Simple mass balance constraints can express the connection between the aforementioned variables and parameters, however, a restoring/cleaning operation can be performed at any (TS), and as such, the *used* items can be converted into *unused* ones. Eqs.1-6 describes the mass balances and the effect of this operation:

$$unused_{d,t+1}^{VD} \leq unused_{d,t}^{VD} - need_{d,t}^{VD} + rec_{d,t}^{VD} \quad (1)$$

$$inuse_{d,t+1}^{VD} = inuse_{d,t}^{VD} + need_{d,t}^{VD} - return_{d,t}^{VD} \quad (2)$$

$$unused_{d,t}^{VD} + inuse_{d,t}^{VD} + used_{d,t}^{VD} = stock_d^{VD} \quad (3)$$

$$rec_{d,t}^{VD} \leq clean_{d,t}^{VD} \cdot m_d^{VD} \quad (4)$$

$$rec_{d,t}^{VD} \leq used_{d,t}^{VD} \quad (5)$$

$$unused_{d,t}^{VD} \leq need_{d,t}^{VD} \quad (6)$$

where $rec_{d,t}^{VD}$ is the amount of restored items, and binary variable $clean_{d,t}^{VD}$ denotes, whether a cleaning operation takes place at TS *t* for demand type *d*. Parameter m_d^{VD} denotes the capacity of the dishwasher, or washing machine, etc.

Another set of mass balance constraints describe the water exchanges at the beginning of each TS:

$$m_t^{BC-BG} + m_t^{TW-BG} = \sum_{d \in FD, t_d^{FD}=t} m_d^{FD} \quad (7)$$

$$m_t^{TW-BG} \geq \sum_{d \in FD, t_d^{FD}=t} m_d^{FD} \quad (8)$$

$$m^{VD} \cdot clean_{d,t}^{VD} = m_{t,d}^{BC-VD} + m_{t,d}^{TW-VD} \quad (9)$$

$$m_t^{TW-BC} = m_t^{BC-BG} + \sum_{d \in VD} m_{t,d}^{BC-VD} \quad (10)$$

After the fix demands are satisfied, the boiler has to be heated up to its goal temperature. This energy demand is fulfilled by burning m_t^{BG} kg of natural gas:

$$m_t^{BG} \cdot \eta^{GC} \cdot L^G \geq \left[(T^{BG} - T_t^{BC}) \cdot m_t^{BC-BG} + (T^{BG} - T^{TW}) \cdot m_t^{TW-BG} \right] \cdot c^W \quad (11)$$

In a similar fashion, if a cleaning operation takes place at TS *t*, the water needs to be heated up by using electrical energy.

$$W_{t,d}^{VD} \cdot \eta_d^E \geq \left[(T_d^{VD} - T_t^{BC}) \cdot m_{t,d}^{BC-VD} + (T_d^{VD} - T^{TW}) \cdot m_{t,d}^{TW-VD} \right] \cdot c^W \quad (12)$$

The temperature of the water in the storage at the beginning of each TS is denoted by T_t^{BC}. After some of the water is removed to be used at cleaning operations or filling the boiler, the rest of the storage is filled with tap water. The temperature after this exchange is $T_t'^{,BC}$ can be calculated by Eq. 13:

$$T_t'^{,BC} = \frac{\left[(m^{BC} - (m_t^{BC-BG} + \sum_{d \in VD} m_d^{BC-VD}) \right] \cdot T_t^{BC}}{m^{BC}} + \frac{\left[(m^{BC} - (m_t^{BC-BG} + \sum_{d \in VD} m_d^{BC-VD}) \right] \cdot T^{TW}}{m^{BC}} \quad (13)$$

As this equation includes nonlinear terms, either an MINLP solver, or a discretisation for the temperature of the water in the storage can be considered. We applied the latter approach with flexible discretisation accuracy.

In the rest of the TS this water is heated up by the solar collector. The following equation expresses the captured heat:

$$Q_t^C = \left(T_{t+1}^{BC} - T_t'^{,BC}\right) \cdot m^C \cdot c^W \tag{14}$$

The amount of captured heat, Q_t^C depends on the solar irradiation, G, area of the solar collectors, A and their efficiency, η_t^c (Atkins, 2010)

$$Q_t^C = G \cdot A \cdot \eta_t^c \tag{15}$$

The efficiency of the solar collector is a continuous variable, that depends on the optical efficiency of the collector, η^o , the ambient temperature, T_t^A , the difference between the inlet and outlet temperature of the water and the solar collector thermal loss coefficients, a^{C1} and a^{C2} .

$$\eta_t^c = \eta^o - \frac{a^{C1} \cdot (\frac{T_t^{C,OUT} - T_t^{C,IN}}{2} - T_t^A) + a^{C2} \cdot (\frac{T_t^{C,OUT} - T_t^{C,IN}}{2} - T_t^A)^2}{G} \tag{16}$$

Inlet and outlet temperatures are aggregated values for the time slice based on $T_t'^{,BC}$, and T_{t+1}^{BC} . Since the coefficient a^{C2} is negligible compared to a^{C1}, the quadratic part of the formula is omitted to maintain linearity.

3. Illustrative Case study

A hotel with towel and dish washing processes and hot water demand, for showering is used as an illustrative case study. The washing processes are considered as shiftable processes in time. These processes can be postponed, at the expense of higher number of items, until there are enough clean / unused items.

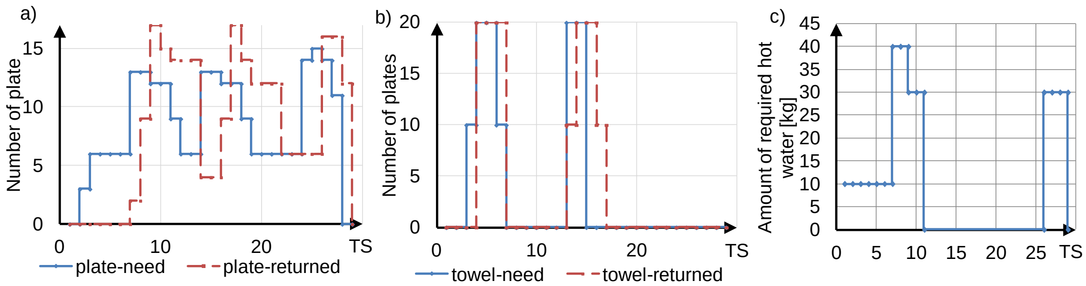

Figure 2: a) Requirement and return rates for plates Plate b) Requirement and return rates for towels c) Hot water requirement

The showering process is a fixed demand, as the guests of the hotels cannot be ordered to take a shower following certain schedule. The differences between the daily cost are shown in Figure 3 for the following four scenarios:

(i) No solar thermal energy is integrated to process, only tap water is used to fill the boiler and the washing machines.

(ii) Heuristic approach, where a cleaning operation is performed immediately, if the washing machine can be completely filled.

(iii) Optimal scheduling with the available plates and towels.

(iv) Optimal scheduling in a retrofit case with increased amount of items.

The maximal amount of *used* items at the end of time horizon is limited to be lower capacity of the washing machines for each scenario for a fair comparison.

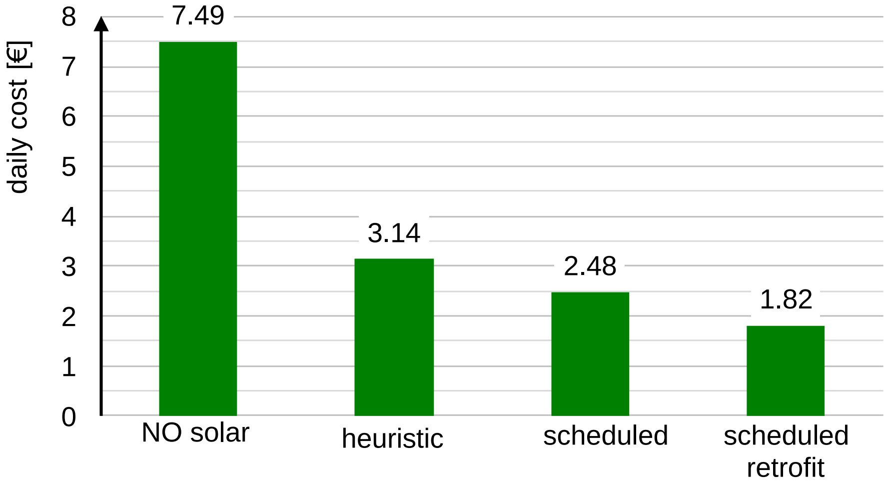

Figure 3: daily cost of different scenarios

A sensitivity analysis is performed by increasing number of each item in order to evaluate the influence of the number of plates and towels The best solution is obtained when the number of towels is increased by 50 (Figure 4, arrow). Additional increasing of the stocks is not beneficial as the improvement on the solution is very minor. Even in the case when 250 plates and 200 towels are available there is no significant gain in comparison when 100 plates and 150 towels are available, the improvement remains below 3%.

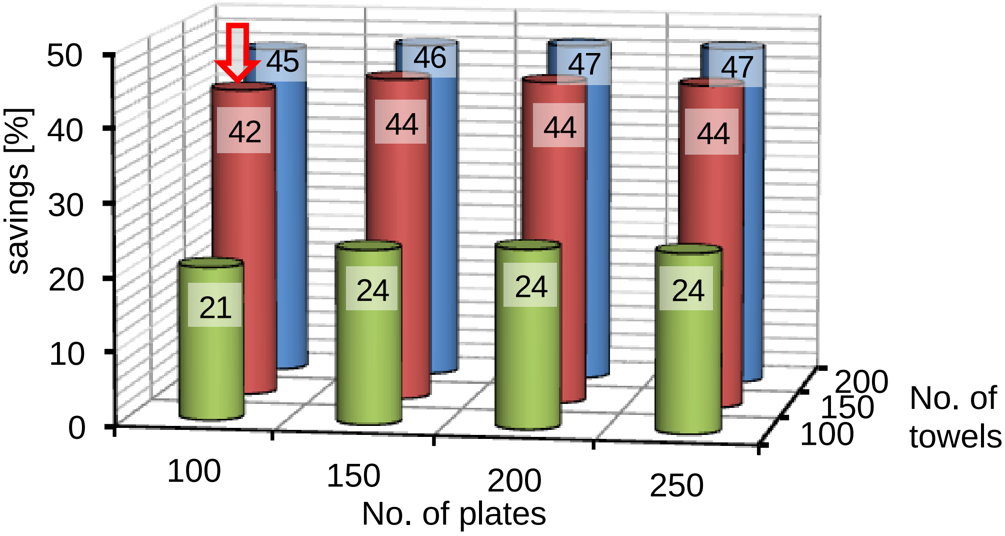

Figure 4: Influence of the number of items on the solution

4. Conclusions

The minimisation of utility consumption by re-scheduling some movable processes with heat demand is presented. In the illustrative case study the decrease of the utility consumption can be up to 47%, which indicates, it is worth to explore scheduling. Especially, when there is a huge number of processes movable in time. The retrofit analysis of the case study has shown that further investment into the size of the stocks may also be beneficial in terms of energy usage.

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