

# Sequencing problems in designing energy efficient production systems

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## Sequencing problems in designing energy efficient production systems

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### Abstract

A sustainable development of world economy implies that industrial energy conservation is indispensable. Therefore, managerial aspects of industrial energy conservation need to be studied. In this article, a tool is described that enables to study the influence of sequential decision making on the design (choice of unit operations) and, consequently, on the specific energy consumption of a production system. Results show that by taking decisions sequentially, the energy conservation potential may be reduced drastically. Furthermore, it is demonstrated that with the described tool it is possible to select that combination of non-optimum unit operation that when combined with each other build an optimum production system from an energy point of view.

*Keywords:* Energy efficiency; Production systems; Sequencing problems; Design

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### 1. Introduction

Industrial energy conservation is indispensable in pursuing a sustainable development of world economy. The achievement of the required change in applied technology is a major challenge to industry. Decision support tools are required to assist decision makers in achieving such a change.

In energy conservation projects, the bare transformation system is often kept unimpaired, i.e. decision makers tend to sequentially add some energy conserving technique, rather than putting the energy consuming part of their production system for debate. Therefore, it is useful to study the influence of such a sequential decision-making process on the

specific energy consumption of a production system.

### 2. The structure of a general production system

Let a *production system* be the set of unit operations and their mutual relations, which are present at a specific location and which are directly or indirectly involved in the transformation of a specific set of raw materials into a set of commodities. In practice, a production system defined like this corresponds to a plant. Consequently, the *system boundary* of a production system is defined to be at plant-level. Within the system boundary, *subsystems* are identified. The decomposition into subsystems is based on the different processes acting upon the energy flows passing through the system. In the

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case of flow processes (i.e. continuous energy flows), three different types of processes can be discerned, corresponding to three subsystems:

- The *transformation subsystem* transforms the raw materials into the desired commodity by using energy.
- The *utility subsystem* makes energy available in the right quality and quantity.
- The *heat recovery subsystem* recovers residual heat.

This decomposition applies to most production systems. In the case of batch processes, an additional subsystem will be present: the *control subsystem*. This controls the starting and finishing times of the different batches.

Each subsystem is decomposed into elements. The elements of the transformation subsystem are the *production unit operations*. Each of these performs a specific task (e.g. mixing, separating, etc.) in transforming raw materials into commodities.

Thermal and electrical energy flows are dominant in most energy-intensive production systems. Therefore, *boilers and combined heat and power (CHP)-units* are the most important elements of the utility subsystem, although other devices may be present. In this study these are not included because generally their contribution to the energy conservation potential is negligible. In a *boiler*, fossil fuel is burned to generate heat at specific temperature levels. A *CHP-unit* generates both heat and electricity from fossil fuel.

The heat recovery subsystem recovers leaving energy flows by means of *heat exchangers* (passive elements) and *heat pumps* (active elements). An *active* element needs input of external energy to operate, a *passive* one does not. In this study only electrically driven heat pumps are taken into account.

### 3. The design of an optimum production system

In a production system that is optimum according to some objective, the production unit operations have to be attuned to each other and to the possibilities of designing the other two subsystems. This implies that, to design an optimum system, non-optimum elements may have to be selected in the subsystems. Consequently, it is insufficient to

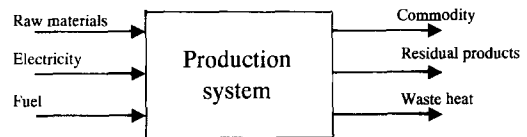


Fig. 1. The model of a general production system.

sequentially select optimum elements of each subsystem. The tool presented here enables to study the influence of sequential decision making on the design (choice of unit operations) and, consequently, on the specific energy consumption of a production system.

The design process starts by modelling the production system, its subsystems, their elements and their mutual relations. Since the tool is focused on industrial energy conservation, these relations are the mass and energy flows involved in the production of commodities. Only available energy flows are incorporated [1–3]. Mass and energy flows, although treated separately, may be physically combined in practice. To illustrate the applied modelling approach, the model of a general production system is shown in Fig. 1. According to the first law of thermodynamics, the total amount of energy entering a production system is conserved and equals the leaving energy. However, according to the second law of thermodynamics, the leaving *exergy* is decreased with respect to the entering *exergy* [1]. This can be visualised by means of the so-called energy characteristics of a (combination of) production unit operation(s). In these characteristics the entering or leaving power is shown as a function of the quality of the involved energy carriers [1].

### 4. The design strategies

Decisions on the optimum design of the three subsystems can be made in different sequences, the so-called *design strategies* [4]. Since the subsystems interact, the design and consequently the specific energy consumption of the total production system depend on the design strategy that is used.

The transformation subsystem actually transforms the raw materials into the desired commodity by using energy, and is therefore responsible for

the energy consumption. If a production system with a minimal specific energy consumption is pursued, the transformation subsystem should be incorporated in the first optimisation decision. To consider every possible sequence in which the three subsystems can be designed, six design strategies (DS1 ... DS6) are defined. These are presented in Table 1. Note that DS6 corresponds to an integral design approach. In a (re-)build situation, decisions are taken in a sequence corresponding to the ranks in this table. In a retrofit situation, DS1, DS2 and DS3 represent situations where the utility subsystem and heat recovery subsystem, attached to an already existing transformation system, are sequentially or simultaneously optimised. DS4 and DS5 represent situations where only the heat recovery subsystem respectively the utility subsystem are optimized. DS6 represents the situation where nothing is changed in the case of a retrofit.

To study the influence of sequential decision making by means of the design strategies, mathematical building blocks have been derived for each element in the subsystems [4–7]. Each building block is a model of the potential contribution of the respective elements on the specific energy consumption of the total production system. The building blocks can be combined into an objective function which can be optimised. Thus, the opti-

imum configuration of the elements that are included in the objective function, can be determined. By defining the optimising objective functions in a sequence corresponding to the design strategies, the influence of sequential decision making can be studied. Each optimisation fixes the configuration of a (combination of) subsystem(s), which is then used as input for the objective function of the next step in the sequence of decisions.

## 5. Demonstration problem

### 5.1. Retrofit situation

Consider a production system producing a commodity  $C$  by performing two tasks in its transformation subsystem. These are carried out by two production unit operations,  $puo_{11}$  and  $puo_{21}$  respectively. The data on the entering and leaving energy flows are presented in Table 2 ( $C_p$  is the heat flow rate,  $E_d$  is the demanded electrical power,  $H_d$  and  $H_s$  are respectively the demanded and supplied thermal power). The energy characteristics of these two production unit operations are presented in Fig. 2.

Before an energy conservation project is carried out in this system, insight is needed in the energy

Table 1  
The six design strategies

	DS1	DS2	DS3	DS4	DS5	DS6
Transformation subsystem	1st	1st	1st	1st	1st	1st
Utility subsystem	2nd	3rd	2nd	1st	2nd	1st
Het recovery subsystem	3rd	2nd	2nd	2nd	1st	1st

Table 2  
Data on the energy flows of the currently applied production unit operations

	Type	Energy flow	$C_p$ (kW/°C)	Temperature (°C)	Electrical power (kW)
$puo_{11}$	In	$E_{d11}$	—	—	400
	Out	$H_{s11}$	2.0	150	—
$puo_{21}$	In	$E_{d21}$	—	—	350
	Out	$H_{s21}$	5.0	70	—

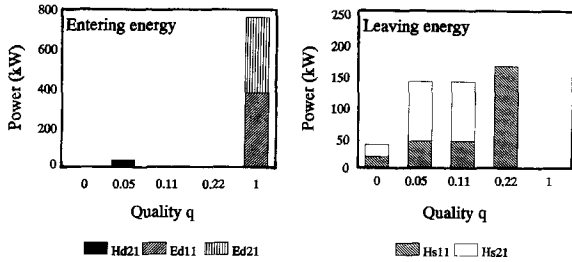


Fig. 2. The energy characteristics of the two production unit operations.

conservation potential. To estimate this potential, the degrees of freedom within the production system which can be used to realise a possible energy conservation potential, have to be traced. In this case a retrofit rather than a complete rebuild is preferred, keeping the transformation and the utility subsystems unimpaired. Hence, energy conservation can only be realised by the introduction of a heat recovery subsystem. The energy conservation potential is therefore completely determined by the heat recovery potential. This situation is represented by DS4.

Calculations reveal that in this case the heat recovery potential, resulting from the possible application of heat exchangers and heat pumps, equals 25 kW. This is only a relatively small energy conservation potential within this production system.

After realisation of this 25 kW decrease in energy use, the energy conservation potential of integration with a nearby production system is considered. In this system a commodity *D* is produced by one production unit operation. The data on the energy flows of this operation, including consumption of electricity, are not known to the management of the former production system. Only the heat requirement of 2000 kW, and the fact that it is generated by a boiler, is known. It is not known at which temperature level the heat is required. Therefore, a heat recovery subsystem between the two production systems is out of the question. This situation is represented by design strategy DS5 (retrofit situation). The energy conservation potential results from the possibility of (re-) designing a joint utility subsystem.

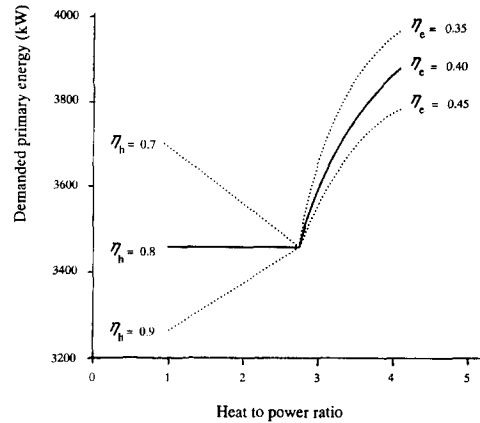


Fig. 3. The results of the optimisation.

Fig. 3 presents the primary energy demand of the optimised combination of production systems as a function of the heat to power ratio. The optimum has been calculated for heat efficiency of a boiler  $\eta_h = 0.8$  and electricity efficiency of a power station  $\eta_e = 0.4$ . The ratio of the heat efficiency  $\eta_{ch}$  and electricity efficiency  $\eta_{ce}$  of a CHP-unit equals the heat to power ratio of that CHP-unit. The minimum energy demand is obtained at the trajectory where the produced heat is the active constraint in the optimisation. Since the primary energy demand depends strongly on  $\eta_h$  and  $\eta_e$ , a sensitivity analysis with respect to these parameters is useful. Some results of this analysis are indicated by dashed lines. For  $\eta_h \leq \eta_{ch} + \eta_{ce}$ , a minimum is reached at the heat to power ratio at which the CHP-unit covers both the demand for heat and electricity. If  $\eta_h \geq \eta_{ch} + \eta_{ce}$ , the minimum is reached at the lowest possible heat to power ratio. Note that only  $\eta_e$  influences the primary energy demand in the domain where the heat production is the limiting constraint to the application of the CHP-unit. In the domain where the electricity production is the constraint, only  $\eta_h$  is relevant to the energy demand. By introduction of a CHP-unit the occupation level of the boiler decreases. Also less electricity has to be purchased from the grid. In Fig. 4, both quantities are presented as a function of the heat to power ratio of the CHP-unit, assuming that the boiler has a maximum capacity of 2000 kW.

## 5.2. Rebuild situation

To investigate the energy conservation potential of a complete rebuild of the production system that has been discussed in the previous subsection, alternative production unit operations have to be identified. Let a production unit operation  $puo_{22}$  exist which is an alternative to production unit operation  $puo_{21}$ . The data on the energy flows of  $puo_{22}$  are presented in Table 3. The question arises as to whether the introduction of this alternative results in energy conservation. To solve this problem the

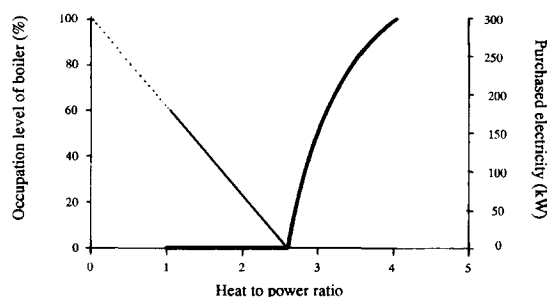


Fig. 4. Consequences of the introduction of a CHP-unit.

Table 3  
Data on the energy flows of the alternative production unit operation

	Type	Energy flow	$C_p$ (kW/°C)	Temperature (°C)	Electrical power (kW)
$puo_{22}$	In	$H_{d_{22}}$	5	180	—
	Out	$H_{s_{22}}$	10	60	—

Table 4  
The results of the optimisation according to the six design strategies (\*: selected; —: not selected)

	DS1	DS2	DS3	DS4	DS5	DS6
Task 1, $puo_{11}$	*	*	*	*	*	*
Task 2, $puo_{21}$	*	*	*	—	—	—
Task 2, $puo_{22}$	—	—	—	*	*	*
Boiler (kW)	0	0	0	0	0	0
CHP-unit (kWe)	9.1	0	0	363.60	35.75	90.91
$\eta_{ch}/\eta_{ce}$	2.2	—	—	2.2	2.2	2.2
Transferred thermal power (kW)	0.0	20.0	20.0	0.0	721.3	600.0
Purchased electrical power (kWe)	740.1	750.0	750.0	36.4	446.0	351.8
Demanded primary energy (kW)	1889	1875	1875	1545	1258	1243

six design strategies from Table 1 should be studied.

With the energy characteristics of  $puo_{22}$  known, optimisation according to DS1 through DS3 reveals that the two originally applied production unit operations have to be preferred. However, application of DS4 through DS6 reveals that  $puo_{22}$  has to be selected to perform the second task. The results of the optimisation are presented in Table 4.

In this table it is demonstrated that each design strategy results in a different design of the three subsystems and, consequently, of the production system. Note that the optimum production system, resulting from DS6, contains those two production unit operations that, when considered apart, require the most energy. The differences in the results for each design strategy can be explained as follows: in DS1 through DS3, the possibilities for energy conservation are limited by early selection of the production unit operations. According to DS1 and DS4, a CHP-unit is installed before heat recovery is considered. Although this reduces the amount of purchased electricity, it also diminishes the energy conservation potential of an eventual heat recovery subsystem. In this case study there is no difference

between the results of DS2 and DS3, because no electrically driven heat pumps have to be applied to realise the energy conservation potential of the heat recovery subsystem. The impact of heat pumps is illustrated by the results of DS5 and DS6.

## 6. Results and conclusions

A modelling method of a general industrial production system has been described. Three subsystems have been defined and six design sequences have been identified to obtain an optimum solution from an energy point of view. These design strategies can be applied in both retrofit and rebuild situations. Furthermore, a mathematical tool that is used to carry out optimisation calculations is discussed.

Rebuild and retrofit situations have been elaborated by means of a demonstration problem. The solutions resulting from the different design strategies have been compared and evaluated. They show whether, from an energy point of view, it is more worthwhile to retrofit a plant, or to rebuild it using thermodynamically more compatible production unit operations. Furthermore, the results illustrate that with the described mathematical for-

mulation it is possible to select those non-optimum production unit operations that when combined with each other and the elements of the heat recovery utility subsystem, result in the optimum production system.

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