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RIGA TECHNICAL
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Dmitrijs Boreiko

METHODS AND ALGORITHMS FOR INCREASING ENERGY EFFICIENCY OF MANUFACTURING ENTERPRISES

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Electrical and Environmental Engineering

Institute of Power Engineering

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council ”RTU P-05” on November 3, 2022, at 12:00 the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12/1 Āzenes Street, Room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Dmitrijs Boreiko ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction, 4 chapters, Conclusions, 56 figures, 32 tables; the total number of pages is 116, including appendices. The Bibliography contains 63 titles.

CONTENTS

INTRODUCTION

THE TOPICALITY OF THE THESIS

The global, world-scale problem of diminishing climate change encompasses varied sub-problems related to the increasing of energy efficiency. From these sub-problems, various tasks of increasing the energy efficiency of industrial production can be singled out, since industrial enterprises consume about 40 % of the overall amount of energy produced and cause about 30 % of the greenhouse gas emissions of the European Union (EU). Therefore, in order to achieve the goals set as regards stopping climate change and to implement the long-term EU strategy aimed at climate neutrality, it is very important to decarbonise the EU power system and its energy end users, particularly industrial enterprises [1].

The efforts in decarbonisation will be based on the use of renewable energy sources (RES). Extensive and effective use of RES will only be possible by considerably improving the flexibility of the consumers of the power system.

More and more researchers address energy-efficient (EE) production planning (PP). The growing popularity of this direction of research goes hand in hand with the increase of energy consumption in the world, which, considering the scarcity of resources and the increasing prices of energy resources, is one of the drivers of these studies.

The concept of energy efficiency can be interpreted in two ways, depending on the goal to be set:

1. An energy-efficient plant is one which, with a smaller amount of energy consumed, ensures the same or better production of the set amount of products in an economically efficient way.
2. An energy-efficient plant is one which ensures the production of the set amount of products with lower energy costs.

Both of the above approaches are used at industrial enterprises. Still, in conjunction with wide use of RES and at the conditions of increasing electricity price fluctuations, it is the second approach that becomes the dominant one and will be used in this Thesis. It is this approach that makes it possible to use less energy at electricity price peak periods.

The solution of the energy efficiency problem can be aided by users that are flexible in terms of energy demand. The flexibility of the power system is its ability to addapt to the changeability and uncertainty of the load/generation balance.

In this Thesis, the author analyses the globally amassed experience regarding the issues of energy efficiency and demand response. Using this experience along with modern technologies, the author has developed a methodology that makes it possible to use the increasing of energy efficiency as well as demand response for large producers with the aim to diminish electricity costs and the amount of CO_2 emissions to the atmosphere. The complex approach includes such issues as optimisation of equipment use at the plant; optimisation of production cycles based on electricity prices; use of electricity storage in order to shift consumption in time, in conjunction with the above optimisation measures; integration of the plant's own "green" generation in conjunction with the above optimisation measures. All of these suggestions and measures have been virtually approbated at an enterprise in Riga, which took an interest in this study and furnished the information necessary for the research.

THE HYPOTHESIS, GOAL AND TASKS OF THE THESIS

The following **hypothesis** has been used in the Thesis:

It is possible to improve the energy efficiency of industrial enterprises by introducing production management based on the adaptation of the production processes to the changing prices and to the capacities of the renewable energy sources.

The main goal of the Thesis is to develop a methodology that makes it possible to increase energy efficiency and demand response to industrial producers of goods, diminishing the electricity costs and the emissions of CO_2 to the atmosphere.

The following main **tasks** have been solved to achieve this goal:

1. By using the example of a real-life plant and the data collected, the author conducted energy consumption analysis for the enterprise regarding the possibilities of formulating and solving optimisation problems for production equipment and production chains.
2. Based on the example of a real-life plant, the author developed production and energy consumption models, formulated an objective function, substantiated minimisation algorithms, synthesised software products and conducted optimisation of production cycles, considering the peculiarities of electricity price formation in Latvia.
3. The methodology has been deveoped for evaluating the effectiveness of using electricity storage; the storage can be used in conjunction with the above optimisation measures.
4. By using the example of a real-life plant, the author has developed a methodology for evaluating the effectiveness of using the producer's own green generation (in conjunction with the above optimisation measures).

5. By using the developed approach for increasing energy efficiency and for using demand response, as well as by using real-life data, the author has given recommendations to manufacturers in Latvia.

THE SCIENTIFIC NOVELTY OF THE THESIS

1. In the Thesis, analysis of the energy consumption of enterprises has been conducted and the possibility of optimising production equipment and production chains with the aim to increase energy efficiency was proven.
2. A mathematical model has been created for optimising production cycles in order to diminish electricity costs, considering the electricity prices in Latvia. Models of two types have been used; the effectiveness of the models has been proved.
3. The Thesis synthesises a mathematical model for selecting an electricity storage system and calculating its economic efficiency. The model has been approbated at a real-life plant.
4. A mathematical model has been created for selecting the plant's own green generation capacities (solar panels) and for calculating the economic efficiency of generation. The model has been approbated at a real-life plant.
5. A complex approach has been developed for ensuring the increasing of energy efficiency and the use of demand response for large industrial producers; recommendations for using the approach in Latvia are provided.

METHODS AND TOOLS USED

1. Systems of electricity consumption metering and monitoring.
2. Methods for evaluating economic efficiency.
3. Engineering problem solution software *Matlab*.
4. *Matlab* simulation environment Simulink, and libraries Symscape and SymPowerSystem.
5. Examination of the energy consumption of the production enterprise, data collection and utilisation.

PRACTICAL SIGNIFICANCE OF THE THESIS

The suggested approach, the created mathematic models and the synthesised and checked models can be used at production enterprises in Latvia and abroad. Using this approach in practice would diminish electricity costs, increase the competitiveness of production enterprises, foster the use of renewable energy sources and thus diminish the emissions of CO_2 to the atmosphere.

THE AUTHOR'S PERSONAL CONTRIBUTION TO THE RESEARCH

The foundation of the basic theses to be defended are the ideas created in close co-operation with Professor Antans Sauhats and teaching staff members Jevgeņijs Kozadajevs and Ļubova Petričenko. The checking of the ideas, the models, the synthesised software, the numerical experiments and their analysis as well as the recommendations for effective implementation belong personally to the author.

APPROBATION OF THE THESIS

The following articles on the researched subject have been published:

1. Boreiko, D., Kozadajevs, J., Zālītis, I., Dolgicers, A. Load Balancing Strategy for Power Networks in Critical Power Shortage Condition. From: 2017 5th IEEE Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), Latvia, Riga, November 24–25, 2017. Piscataway: IEEE, 2017, pp. 1–4. ISBN 978-1-5090-1201-5. e-ISBN 978-1-5386-4137-8.
2. Survilo, J., Boreiko, D., Zālītis, I., Kozadajevs, J. Primary Use of Renewable Energy Sources in Electric Power Industry. From: 2017 5th IEEE Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), Latvia, Riga, November 24–25, 2017. Piscataway: IEEE, 2017, pp. 1–6. ISBN 978-1-5386-4138-5. e-ISBN doi:10.1109/AIEEE.2017.8270531.
3. Boreiko, D., Kozadajevs, J., Sauhats, A. Implementing Energy Efficiency and Demand-Side Management in Glasswork Company. From: 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON): Proceedings, Latvia, Riga, October 12–14, 2017. Piscataway: IEEE, 2017, pp. 1–6. ISBN 978-1-5386-3847-7. e-ISBN 978-1-5386-3846-0.
4. Kozadajevs, J., Zālītis, I., Boreiko, D., Varfolomejeva, R. Detailed Modelling of a Battery Energy Storage System in an Energy-Intensive Enterprise. From: 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Italy, Palermo, June 12–15, 2018. Piscataway: IEEE, 2018, pp. 1–5. ISBN 978-1-5386-5187-2. e-ISBN 978-1-5386-5186-5.

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6. Sauhats, A., Kozadajevs, J., Dolgicers, A., Zālītis, I., Boreiko, D. Thermal Energy Storage for CHP in Power Market Conditions. From: 16th European Energy Market Conference (EEM 2019), Slovenia, Ljubljana, September 18−20, 2019. Piscataway: IEEE, 2019, pp. 1−4. ISBN 978-1-7281-1258-9. e-ISBN978-1-7281-257-2. ISSN2165-4077.e-ISSN2165-4093. Available: doi: 10.1109/EEM.2019.8916485.
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8. Petričenko, R., Boreiko, D. Adaptive Detection of Battery Energy Storage System Charge/Discharge Cycles Quantity. From: 2019 IEEE 7th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE 2019): Proceedings, Latvia, Liepaja, November 15−16, 2019. Piscataway: IEEE, 2019, pp. 118−121. ISBN 978-1-7281-5709-2. e-ISBN 978-1-7281-6730-5.
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11. Petričenko, Ļ., Kozadajevs, J., Petričenko, R., Ozgonenel, O., Boreiko, D., Dolgicers, A. Assessment of PV Integration in the Industrial and Residential Sector under

Energy Market Conditions. Latvian Journal of Physics and Technical Sciences, 2021, Vol. 58, No. 3, pp. 82−97. ISSN 0868-8257. Available: doi: 10.2478/lpts-2021–0018.

STRUCTURE AND SCOPE OF THE THESIS

This Doctoral Thesis has been written in Latvian, it contains an introduction, four chapters, conclusions and recommendations for further work as well as a bibliography. The total volume of the Thesis is 115 pages, containing 46 figures and 65 formulas. The bibliography contains 63 sources of information. The Introduction substantiates the topicality of the Thesis and formulates its goals. It looks at the problems solved in the Thesis, mentions conference presentations and publications approbating the results of the work as well as presents theses to be defended. *Chapter 1* contains a summary of scientific literature dedicated to the process of increasing the energy efficiency of various plants, to various types of demand response, as well as literature analysis and conclusions focusing on the selection of research directions and methods. *Chapter 2* is dedicated to the synthesis of models of the task of increasing energy efficiency, the formulation of the objective functions, the description of the limitations and the selection of the implementation of the optimisation procedures. *Chapter 3* provides a detailed hands-on description of the task of increasing the energy efficiency at a production enterprise and a list of the products to be manufactured, as well as a description of required energy. *Chapter 4* describes the methodology for economic substantiation of electric storage batteries and solar panels and provides detailed examples of applying them.

1. FORMULATION OF THE PROBLEM AND ANALYSIS OF LITERATURE

On the whole, research on the subject of energy-efficient production can be divided into two directions: (I) studies aimed at diminishing the energy consumption by implementing technological improvements in production processes [10, 11, 12] and (II) studies aimed at diminishing the energy consumption by adapting the organisational parameters of the production process, which we call energy-efficient production planning (EEPP).

By summarising the studies, the main directions of increasing the energy efficiency of production enterprises can be singled out (Fig. 1.1).

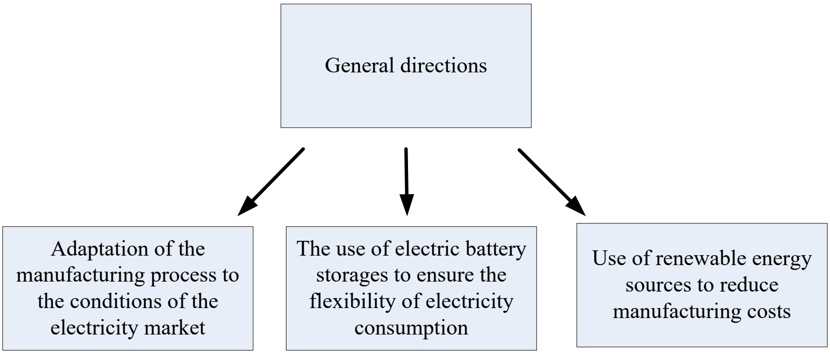

Fig. 1.1. The main directions of increasing energy efficiency.

The implementation structure of each direction is shown in Fig. 1.2.

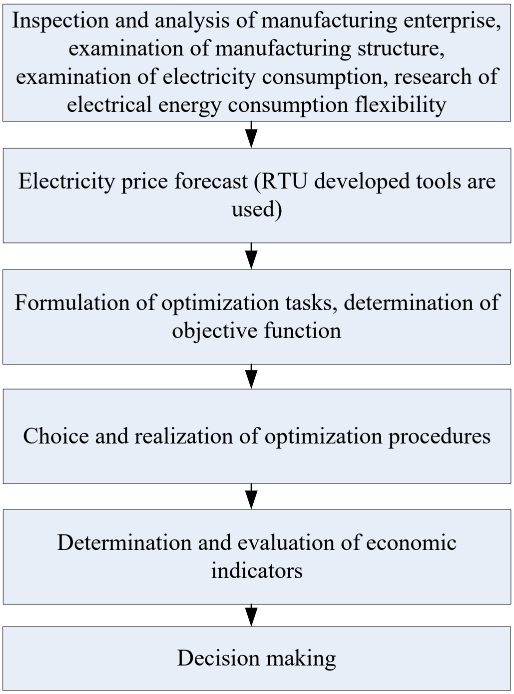

Fig. 1.2. The energy efficiency implementation structure for a manufacturing enterprise.

Summarising the above, the following can be concluded:

1. The planning of the equipment load schedule is a short-term planning problem which distributes work among equipment units and determines the sequence and time of work

to be done by a piece of equipment. If any type of work requires only one operation, or if a production system only consisting of one piece of equipment is studied, then the suggested sets and variables become simplified accordingly [22].

2. The continuously increasing energy consumption in manufacturing in conjunction with the drop in the use of non-renewable energy sources has made energy efficiency an important problem both for researchers and practitioners.
3. The increasing energy prices have led the industrial sector to rethink its attitude towards energy consumption, and society's increasing apprehension regarding environmental issues has made policy-makers to react by issuing corresponding directives.
4. The amount of research on energy-efficient production planning has considerably increased over the recent years, resulting in many publications integrating energy efficiency considerations into the existing production planning models. Still the present modelling approaches cannot yet be regarded as corresponding to the requirements which have undergone a rapid increase.

2. THE ELECTRICITY CONSUMPTION OPTIMISATION PROBLEM FOR AN ENTERPRISE

The increase in the electricity prices, the emergence of market mechanisms and the fluctuations of the electricity prices over a 24-hour period lead consumers to adapt to the market conditions and to organise their production in such way as to fulfil two main tasks:

1. To ensure compliance with the set production plan stipulating a certain amount of products to be made (in the general case, we mean products of several types).
2. To minimise the expenses in relation to the use of electricity.

The second task is meaningful if the enterprise can change production intensity over time and, consequently, the 24-hour consumption schedule.

Besides, limitations of three kinds have to be taken into account:

- limitation of the capacity of the production equipment;
- limitation of maximum permissible consumed capacities;
- technological limitations.

In order to increase the flexibility of production, it is possible to use additional technical systems (solutions) that ensure storage of energy. Such systems include technologies based on the use of storage devices, for example, storage batteries (Battery Energy Storage System, BESS). In addition, we use the following assumptions:

1. The consumer is situated in an electricity market area and acts in conditions when the price is known 24 hours ahead.
2. The consumer is not a participant of the market in a direct way. Payments for the energy consumed are made via an electricity trader, based on bilateral agreements.
3. The consumer's decision does not influence the electricity prices in the market.
4. The planning period is limited to a time period of one week ahead.

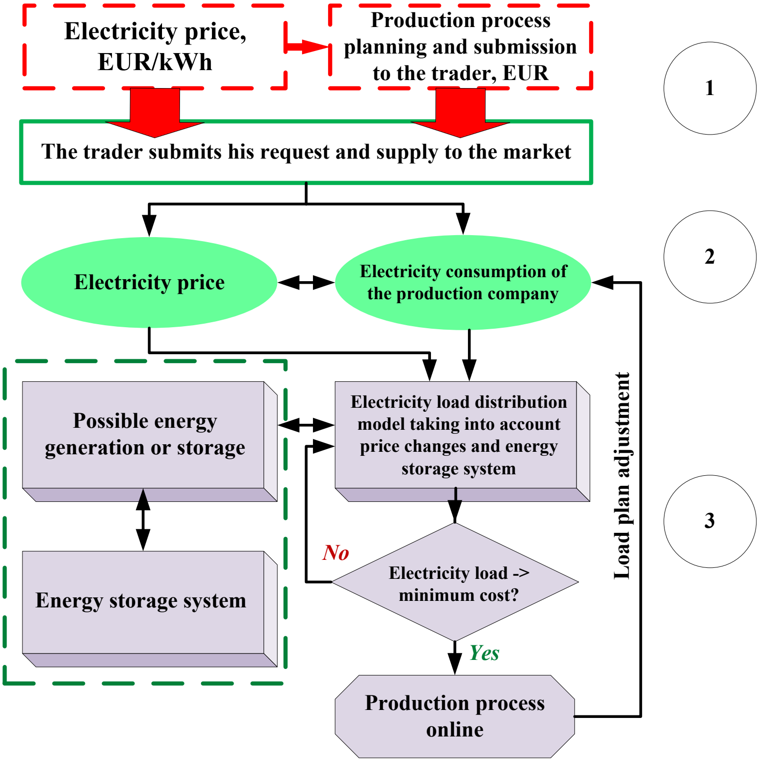

Fig. 2.1. The structure of the load planning algorithm for an industrial enterprise [42].

The energy supply optimisation algorithm for a production enterprise can in general terms be described by three sub-blocks (Fig. 3.2) which implement the following actions:

1) The production and planning operator submits to the trader its planned electricity consumption for a week ahead. Afterwards, when the trading at the exchange takes place and the results are known, the electricity trader, upon receiving the result, sends the production operator the prices for the day ahead.

2) The production enterprise, knowing the electricity prices, conducts optimisation for 24 hours ahead, distributing the load optimally, in such way as to diminish the expenses for the electricity consumed.

3) If there is a possibility for additional production or/and storage of electricity, then the optimisation model, after load distribution, adapts the additional generation/storage in such way as for the charging to take place at the lowest price without exceeding the limitations and for the discharging, or battery generation, to take place at the high-price hours, smoothing the expenses for the consumption.

2.1. Mathematical formulation of the problem

The literature review addresses writing dedicated to the formation of complex models, optimisation of production cycles and planning of production processes. It has to be stressed that in this paper, we do not set a task to develop a unique or unusually effective optimisation and planning method. Our aim is to combine various measures, such as increasing energy efficiency, increasing energy consumption, optimisation of energy consumption and production processes, introduction of storage technologies (demand response) and implementation of enterprises' own green generation in order to diminish the electricity expenses in the real-life enterprise we took as an example. Therefore, the Thesis provides an optimisation methodology that can be used in the most extensive way at various plants. This chapter looks at the mathematical formulation of the task for a virtual plant and various typical combinations of production chains (consecutive/parallel) for manufacturing certain products. For this approach to be as universal as possible, ten virtual scenarios for plants were optimised.

Let us assume that a plant manufactures I type products in the amount q_i, consequently: $q_1,\dots, q_I$.

The products are manufactured at hours $t = 1, \dots, T_{pl}$ (where T_{pl} stands for the duration of the planning period). Each product type q_i can be produced at any t-th hour; let us designate the i-th product type produced at hour t as $q_{t,i}$; in such case, the energy consumed for producing $q_{t,i}$ is $A_{t,i}$. The energy amount of each hour is purchased at price C_t.

The optimisation problem is to distribute the load of the plant over 24 hours in such way as to comply with the production plan and manufacture all the planned products without interrupting the production processes or exceeding the limitations regarding the permissible capacity and the working hours and ensuring the lowest total electricity prices. Considering that a number of production lines can operate at the plant both mutually linked and without links, there is a large number of alternatives of how to arrange the load of the lines over the 24-

hour period. Depending on the complexity of the problem, even with a small number of variables the number of combinations can be very large.

To implement the simulation of the enterprise's production, it is necessary to synthesise software whose aim is to optimise the electricity consumption based on market prices. During the development of the algorithm, it has to be taken into account that each consumer has special tariffs for the electricity used, which are met when paying the trader for the service used. The market prices are forecast or taken from the *Nord Pool* exchange day-ahead data and input to the software under development [43]. The second goal of the software is to optimise the operation of the electricity storage equipment – its charges and discharges over the 24-hour period. Thus, the task consists of two sub-modules, i.e. from the distribution of the electric load schedule and the modelling of the storage system. Then, for the overall problem, we can set a goal of minimising the electricity costs.

Minimisation of the cost function:

$$f(R) = \sum_{t=1}^{T}\left(C_t\left(A_{BC,t} - A_{BD,t}\right) + \sum_{i=1}^{I} C_t\, A_{t,i}\right) \rightarrow min\ , \tag{2.1}$$

where C_t is electricity price at the *t*-th hour, €/kWh; $A_{t,i}$ is electricity consumption for the *i*-th product at the *t*-th hour, kWh; $A_{BC,t}^{n}$ is the charging energy amount of the storage battery at the *t*-th hour, kWh; and $A_{BD,t}$ is the discharging energy amount of the storage battery at the *t*-th hour, kWh.

The limiting conditions of the problem are as follows:

1. The total hourly consumption for all the pieces of equipment must not exceed the maximum permissible value for the enterprise:

$$\sum_{i=1}^{I} A_{i,t} \leq A_{max}\ , \tag{2.2}$$

where A_{max} is the total maximum permissible hourly load, kWh. The condition (2.2) has to be met at all values of *t*.

2. The hourly consumption of each type of product (each piece of equipment) must not exceed the maximum permissible hourly consumption of the production line for this product:

$$A_{i,t} \leq A_{imax}, \tag{2.3}$$

where A_{imax} is the maximum permissible hourly load of the *i*-th type of product, kWh. The condition (2.3) has to be met at all values of *t*.

3. Organisational and technological limitations. When formulating the load schedule optimisation problem, not only is it necessary to consider the capacity limitations of the above-

described equipment, but at a real-life production enterprise, impact and limiting action is exerted by a variety of other factors, for example:

- compliance with the production plan, i.e. all the planned types of products have to be made;
- the work schedule of the workers, i.e. the number of workshifts has to be adapted;
- the schedule of raw material deliveries;
- the schedule of product deliveries has been co-ordinated with the customer;
- interruptions in the production process, for example, when a piece of equipment is being repaired or the intervention of a specialist is required for one or another piece of process equipment;
- the sequence and duration of the production operations is preset and unchangeable, for example, preparation and processing of raw materials, production of end products;
- the interdependence of the energy consumption by mutually linked production operations;
- the interdependence of the production of various product types (there are products that can be made together, or conversely, products that cannot be made together).

A detailed mathematical description of the above limitations can only be done for a certain enterprise. In a general case, based on the essence of the limitation under discussion, it is possible to conduct classification and mathematical description of these limitations.

4. Production plan compliance limitations.

Let us assume that the amounts of the planned products, q_1, q_2, …, q_I (kWh), are known. The specific energy consumption of each product, p_1, p_2, …, p_I (kWh/piece), is known. In this case, we can find the required amount of energy for each product:

$A_1 = q_1 \cdot p_1$; $A_2 = q_2 \cdot p_2$; …, $A_I = q_I \cdot p_I$.

These amounts of energy can be used in the planning period, thus:

$$\sum_{t=1}^{T_{pl}} A_{t,1} = A_1; \dots \sum_{t=1}^{T_{pl}} A_{t,I} = A_I . \qquad (2.4)$$

When performing the production operations in the set time period, in many cases it is necessary to ensure continuity to the process. This requirement brings about an additional limitation:

$$A_{t,i} \ \geq \ A_{i,min} , \qquad (2.5)$$

where $A_{i\,min}$ is the electricity consumption that ensures the minimum amount of production that is sufficient for the equipment to work without interruption, kWh.

The formulation of the problem mentioned in the title of this sub-section is simpler than the one described by formula (2.1), since the optimisation objective function can be described as follows:

$$f(A, T_{pl}) = \sum_{t=1}^{T_{pl}} C_t(A_{t,1} + A_{t,2} + \cdots + A_{t,I}) \rightarrow min\,. \qquad (2.6)$$

In the formation of the electricity consumer price, the necessary components are observed: the electricity price at the exchange (€/kWh), the variable component of the distribution tariff – ST_{main} (€/kWh), and the variable component of mandatory procurement – OIK_{main} (€/kWh).

$$C_{pat,t} = C_{el,t} + OIK_{main,t} + ST_{main,t} \qquad (2.9)$$

Upon comparing (2.6) with (2.1), it can be seen that the second objective function does not contain variables related to the operation of batteries, thus the number of variables diminishes and the task is simplified. It has to be noted that in the case if the capacity of the batteries in the problem (2.1) is assumed as zero, then this problem is transformed into (2.6).

2.2. Alternatives in technological and organisational limitations

As has been mentioned above, limitations exert a strong influence on the calculation of the minimisation function. Let us look at the essence of the main alternatives in various limitations:

1. Existence of workshifts. If the enterprise operates in one or two shifts, then the planning period can be reduced to eight or sixteen hours. The minimisation procedure is simplified. The existence of shifts does not change the essence of the battery charging problem, since the charging can be done automatically at any hour of day or night.
2. The production plan is strictly set with the number of products planned for production. The number of products is set and the specific energy consumption of each product is known. The production sequence and the production hours are set. The minimisation procedure is simplified. The optimisation can only be performed in the case when energy storage is used.
3. The production plan is set with the number of products planned for production. The number of products is set and the specific energy consumption of each product is known. The production sequence is set but the production hours can be chosen, shifting the start of production to a different time. The minimisation procedure is simplified.

4. Production of mutually linked products. A number of product types are produced but their production can only take place together; the production sequence in time is set for all the products.
5. Production of products that are not mutually linked. A number of product types are produced but their production can take place in any combination of product types and the production sequence in time can be freely chosen for all the products. This case can yield the largest savings, since the production is characterised by maximum flexibility.
6. Mixed production. In the general case, the above limitation alternatives can appear together. There may be linked and unrelated products and part of the plan is strictly set whereas the other part can be chosen freely.

Further, in light of the above, let us consolidate the above alternatives. Depending on the exact types of products, the technologies and equipment used, the production process can be organised in different ways:

1. In parallel. The products are produced simultaneously.
2. Consecutively. The products are produced one after another. Two sub-cases can be singled out:
   - 2.1. The production sequence can be chosen freely.
   - 2.2. A set production sequence. Limitations of this type may emerge, for example, based on product delivery conditions or after co-ordination with raw material delivery schedules.
3. Mixed. In this case, part of the products can be produced simultaneously whereas the other, consecutively.

2.3. Decomposition of optimisation problems

Load management depends on the possibility of regulating and storing electricity at hours when consumption or the energy price is low, and firstly using that energy at hours when the energy price is higher, thus ensuring equipment savings. The objective function is described by (2.1).

Already at $I = 3$, the number of variables exceeds one hundred. In real-life cases, this value can be measured in thousands. The objective function of the type of (2.1) is expressed in linear form. The task can be minimised by observing many limitations. If it were possible to describe all the limitations with linear equations or inequalities, then it would be possible to solve the optimisation problem by means of linear programming. In this case, the problem can be solved at very large numbers of optimisation variables.

2.4.Sorting (production according to priority)

The optimisation problem solved by means of linear programming distributes the electric load hour by hour but fails to consider the producer's potential wishes regarding the sequence of producing the products. Let us assume that the products have been arranged according to priority – the number of the product determines its priority; out of n types of products, it is firstly important to make products of the first type, then – of the second type, etc.

Priority distribution of the hourly capacity of all the product types can be conducted in the following main steps:

1. Calculate the number of hours SS1 which is required to produce the set amount of the first product type. It has to be taken into account that the total energy consumption at each hour has already been set (it has been taken from the results of the linear programming) and cannot be changed. Also, the potential capacity limitation of the technology of the first product has to be considered.
2. Shift the production of the first product from all the hours of the planning period in such way as to keep unchanged the energy consumption at each hour.
3. Calculate the energy remainder that is left for the production of the second product at the last of the SS1 hours.
4. Calculate the number of hours SS2, starting from the last SS1 hour.
5. Repeat the above steps for all the products.

The above procedure is implemented by using elementary arithmetical and logical operations and does not require large computer resources even at a large number of products.

2.5.Minimisation procedures

Minimisation of the objective functions (2.1) can be conducted by means of various methods, depending, first and foremost, on the types of limitations that follow from the exact production conditions in place and the available information.

Since the real-life data from the plants were not available, it is not possible to select a final method that could be safely used in all possible cases. In order to prepare for the optimisation of the plant under discussion, three main methods were selected:

1) enumeration;
2) random enumeration;
3) linear programming and enumeration.

The first two methods can be used in many non-linear cases. Their main limitation and drawback lies in the fact that sufficient computer resources are necessary, since the number of required iterations (attempts) can be huge.

The above methods have been implemented in MATLAB or C# programming language environment, analysed and verified, using assumptions to the effect that the production limitations are known. A more detailed description of the procedures and results and their analysis are provided further on in varied examples.

2.6.Data and assumptions used

We assume that the electricity prices for the day ahead are known, as are other components of the consumer price: the variable component of the distribution tariff and the variable component of mandatory procurement. This means that in the objective function (2.1), the price component is known.

- The calculation uses five types of products ($I = 5$).
- The planning period is 24 hours ($T_{pl} = 24$).
- The amount of each product type (q_i) that has to be produced during the planning period is changeable and the values used are given.
- The electricity prices (C_{el}) are known from 2 p.m. for the day ahead from the *Nord Pool* exchange. As a result, the day begins at 2 p.m.–3 p.m. and ends at 1 p.m–2 p.m.
- The distribution tariff is taken for three time zones (S8): the night zone and the weekend (0.030625 €/kWh), the peak hour zone (0.055902 €/kWh), and the day zone (0.039507 €/kWh) [49].
- The MPC payment is considered according to the existing normative acts as of January 1, 2019 (0.01783 €/kWh) [50].
- For each product type, the specific energy consumption (p) is set.
- The total maximum permissible hourly load (A_{max}) is 500 kWh/h.
- 11 scenarios are discussed.

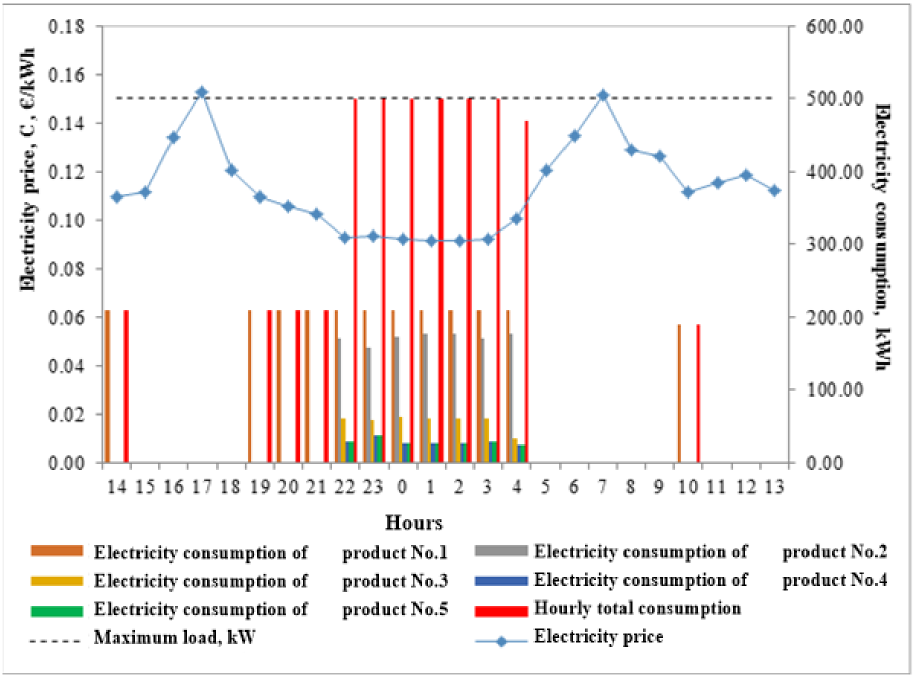

Fig. 2.2. Load distribution hour by hour.

The total planned production amount in the example is 9000 pcs. The total costs are also lower and amount to **434.69 €**.

The discussed model has been implemented in *MATLAB* environment. *Optimization Toolbox* (a linear programming function) is used.

In a case when five types of products are used and the software is implemented on a medium-capacity personal computer (Intel(R) Core(TM) i3-4160, processor frequency 3.6 GHz, memory 4 GB), the expense minimisation procedure takes less than twenty seconds.

2.7. An example of applying the enumeration method

Let us assume that all the products to be made belong to the same group (consecutive production), which means that the production of linked products takes place one after another and their product-to-product consumption hours will have exactly the ratio indicated by the operator. Consequently, the minimisation of the function will only depend on such limiting factors as the maximum permissible hourly load value as well as the work time.

If the limitation is violated, the software will fail to perform optimisation. If during the production period it is only planned to produce mutually linked products, the summary load of each hour is calculated as follows:

$$A_{t\Sigma} = \sum_{t}^{T} A_{ti} \ . \tag{2.10}$$

Table 2.1

Implementation Example

Group number	1	1	1	1	1
Group number	Product 1	Product 2	Product 3	Product 4	Product 5
	pcs.	pcs.	pcs.	pcs.	pcs.
Hour	q_1	q_2	q_3	q_4	q_5
1	25	0	80	45	0
2	25	0	80	45	0
3	25	0	80	45	0
4	0	30	0	45	0
5	0	30	0	45	0
6	0	30	0	0	100
7	0	30	0	0	100
8	0	30	0	0	100

From the graph in Fig. 2.3, it can easily be seen that the enumeration results in the selection of a relatively low load at the low-price hours (hours Nos. 10, 11, 12). This can be explained by the fact that the production sequence is strictly set. If this limitation can be lifted, then the production distribution hour by hour could become considerably more efficient.

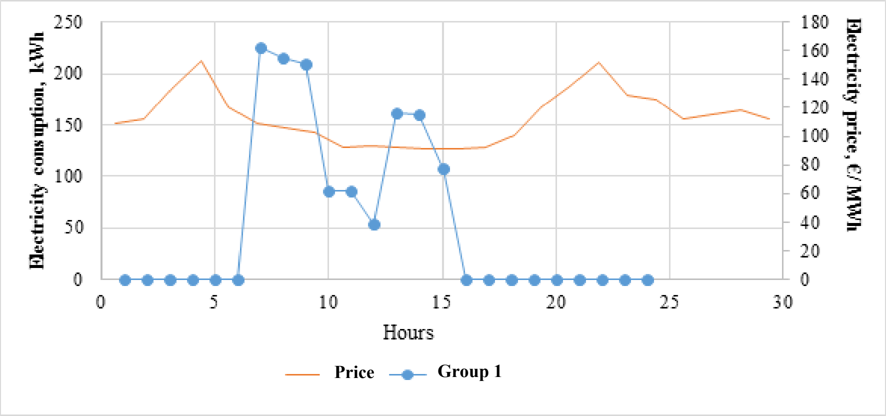

Fig. 2.3. Load distribution as a result of minimisation with the enumeration method.

2.8. Examples of applying the random enumeration method

The data input for this case is similar to that of the enumeration method. The difference is that here, all the products are not linked any more. The enumeration method above will become inefficient, since a very large number of various combinations have to be considered. The created software automatically “understands” when it is necessary to switch to the random enumeration method. A program module will start that will firstly combine all the mutually linked products (consecutive production) in columns by groups. What also remains here is the links between rows within one column (for example, consumption, which has been input as a process that lasts for four consecutive hours will not be divided into periods of one or two hours).

In such case, the problem is addressed by the Monte-Carlo method, by which the random enumeration procedure is implemented. For all the products (those combined into groups and those not combined), the first production hours will be randomly linked to certain hours; then, the program checks all the hours to establish whether the limit of permissible load (maximum consumption) is not exceeded; if not, then the objective function (2.1) is calculated, and if the result is better than the preceding iteration, then the matrix of consumptions as well as the total cost result is retained and the next iteration takes place. If in even one of the rows the load limitation has been violated, the next iteration takes place immediately.

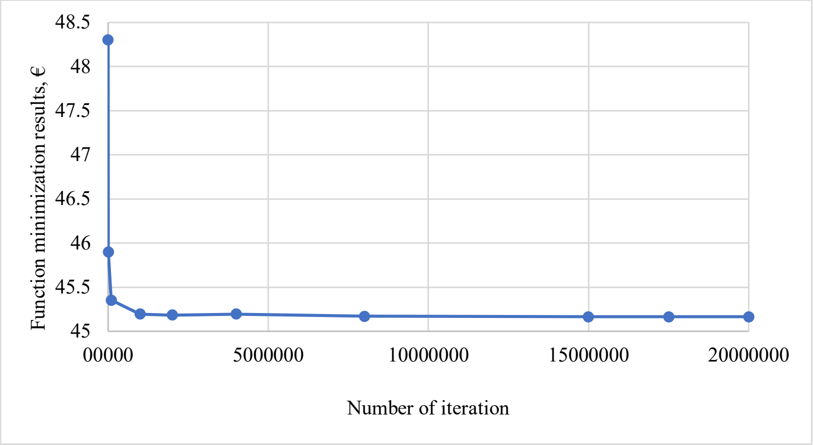

Fig. 2.4. Optimisation results with different numbers of iterations applied, using the Monte-Carlo method.

When applying the random enumeration procedure, the number of iterations is the decisive factor. The number of iterations influences both whether a correct result is achieved and the time within which that can be done. The calculation of the unknown specific electricity consumptions takes relatively little time. When using the Monte-Carlo method, one row of the problem takes up to 1.6 seconds. If the electricity consumption by the products is set, then no time at all is spent on calculating the specific loads. In order to determine the required number of iterations for performing the random enumeration procedure, several numerical experiments were conducted. Their results are shown in Fig. 2.4.

2.9. An example of the results

For one of the hours, the maximum capacity limitation was set at 100 kW and for the remaining hours – 200 kW, to make sure that the algorithm operates correctly. It can be seen that the 100 kW limitation in hour 7 compels the algorithm to find the next most advantageous solution; if there is no such limitation, hour 7 is used as much as possible (Figs. 2.5–2.6).

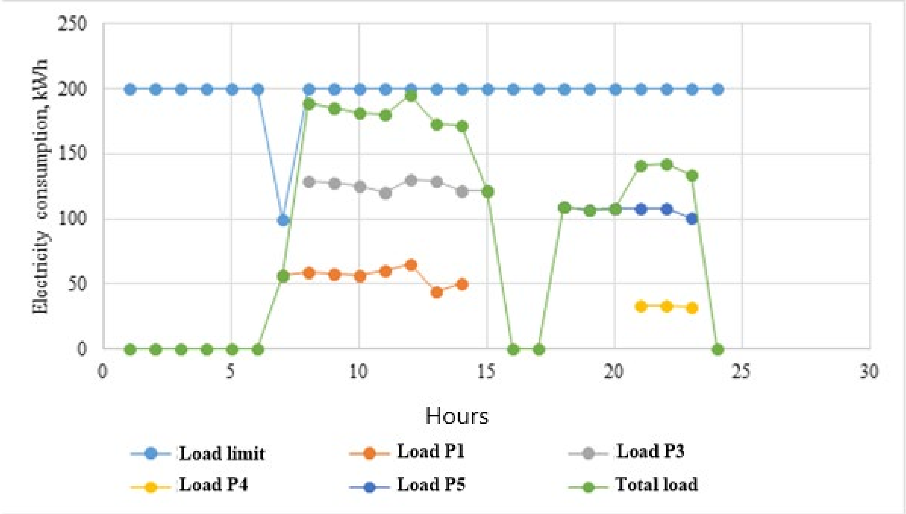

Fig. 2.5. Load distribution as a result of minimisation with the random enumeration method, using historical data and the Monte-Carlo method to determine the specific electricity consumption (Problem 2).

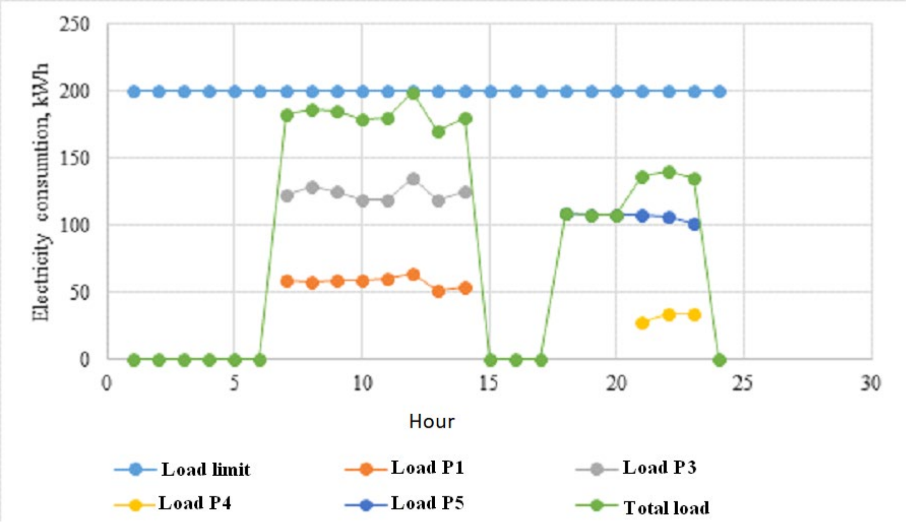

Fig. 2.6. Load distribution as a result of minimisation with the random enumeration method, using historical data and the Monte-Carlo method to determine the specific electricity consumption without the 100 kW limitation for maximum load.

2.10. An example: Comparison between the linear programming and random enumeration methods

Let us look at an example which cannot be solved by the enumeration method, is difficult to solve with the random enumeration method and can be easily solved by linear programming.

Let us assume that ten types of products are manufactured and parallel lines are used, which can operate simultaneously or at different times. The planned amount of products to be made is known: q_1, q_2, …, q_{10}. The specific energy consumption by each product is known: p_1, p_2,..., p_{10}. The capacity of each line is limited by the maximum possible amount of products that can be made, correspondingly: A_{1max}, A_{2max},..., A_{10max}. The energy prices for the day ahead are known: C_1, C_2, ..., C_{24}.

The data for a concrete example are shown in Table 2.2. The data have been selected in such way as to make the problem-solving result obvious.

Table 2.2

Input Data for the Example

q_i	q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9	q_{10}
pcs.	1000	950	900	850	800	750	700	650	600	550
p_i	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}
kWh/pc.	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{imax}	A_{1max}	A_{2max}	A_{3max}	A_{4max}	A_{5max}	A_{6max}	A_{7max}	A_{8max}	A_{9max}	A_{10max}
pcs.	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
C_i*	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Eur/MWh	50	55	60	65	70	75	80	85	90	95

*C_{11}, ..., C_{24} are equal and their value is 500; the permissible capacity of the enterprise is limited at 500 kW.

From the set limitations, we can see that in one hour, it is only possible to make one product. The energy costs will be minimal if the energy consumption is at its highest at the first hour and at its lowest at the tenth hour. In this way, the optimum production schedule coincides with the first row of the table. Here, the energy costs will be 54.13 EUR. The result can be easily achieved by means of linear programming. There is a completely different situation if the enumeration methods are used, since it is easy to calculate that the only one out of the possible 24^{10} alternatives has to be selected. The number of alternatives equals 63 403 380 965 376. Neither will the random enumeration method yield a guaranteed result.

Yet, to use it, let us change the optimisation problem and try to find a solution that **approaches** the optimum one.

Figure 2.7 shows the dependence of the evaluated energy costs on the number of attempts. It can be seen that the result approaches the value of 54.13 EUR, albeit not reaching it.

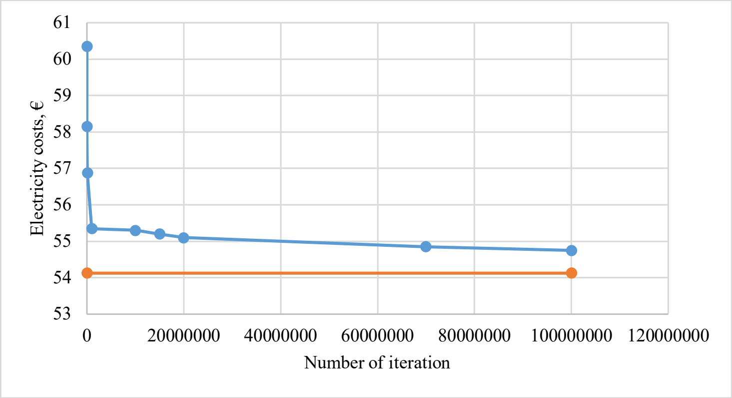

Fig. 2.7. Random enumeration approaches the result of linear programming.

2.11. Chapter conclusions

1. To ensure energy-efficient production planning for an industrial enterprise, it is necessary to synthesise software aimed at optimising the electricity consumption costs based on market prices. At the algorithm development stage, it has to be taken into account that every consumer has special tariffs for the electricity used; these are met when paying the trader for the service used. The market prices are forecast or taken from the database of the *Nord Pool* exchange.
2. Depending on exact types of products as well as on the technologies and equipment used, the production can be organised in different ways:
   - In parallel. The products are made simultaneously.
   - Consecutively. The products are made one after another. Two sub-cases can be singled out:
     - ➢ The product manufacturing sequence can be chosen freely.
     - ➢ The product manufacturing sequence is set. Limitations of this kind can arise, for example, from product delivery conditions or when adapting to raw material delivery schedules.

- In a mixed way. In this case, part of the products can be made simultaneously while the other part are made consecutively.

3. When optimising the energy consumption, the objective functions can be minimised by means of different methods, depending on the types of limitations that follow from the manufacturing conditions in place and the available information. Two main methods were selected:
   - random enumeration;
   - linear programming and enumeration.

   The above methods have been implemented in MATLAB or C# programming language environment, analysed and verified.
4. In a case when individual meters are not installed for each production line, an arrangement that would make it possible to form an exact distribution among the production amount, the product type and the energy consumption, historical production/consumption registration data can be used. The historical data have to contain the amount of product made by each piece of equipment per hour as well as the plant's total consumed electricity during the hour in question. The specific consumption of products can be determined by the Monte-Carlo method or the method of least squares. In all the considered cases, the distribution of the consumption hour by hour coincided for the Monte-Carlo method and the method of least squares.

3. AN EXAMPLE OF OPTIMISING THE ENERGY SUPPLY OF AN INDUSTRIAL ENTERPRISE

A glass-processing enterprise operating in Riga has expressed its interest in the present study and furnished us with the required information, which has served as the main reason for choosing this enterprise for further analysis. The provision of information about the enterprise in the Thesis has been approved by its owners. Part of the calculations that contains confidential information is not presented in the Thesis, showing only the result.

In order to describe the production processes in the glass-processing plant, let us look at the main production processes and the types of finished products as well as a description of the production processes stage by stage, which can be seen in Fig. 3.1. All in all, to fulfil orders in the amount of 350 m^2 of finished products, by 50 m^2 of each type, from 140 to 2296 minutes is needed, depending on the type of the finished products. The required technological processes and the time for manufacturing the end product are shown in Figs. 3.2–3.3.

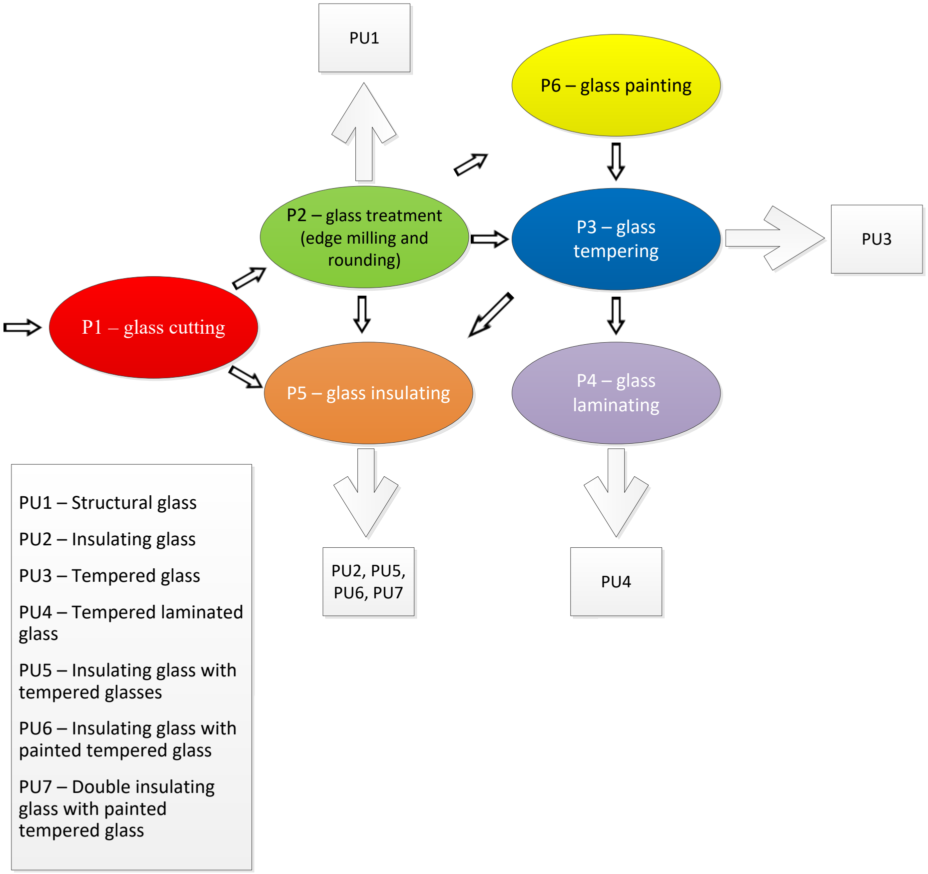

Fig. 3.1. A simplified depiction of the production flows at a glass-processing plant.

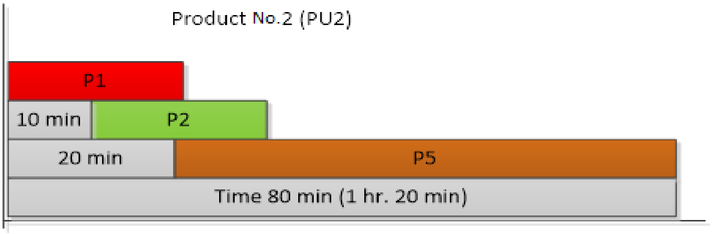

Fig. 3.2. PU2 – Insulating glass. Producing 50 m^2 of insulating glass requires 80 minutes.

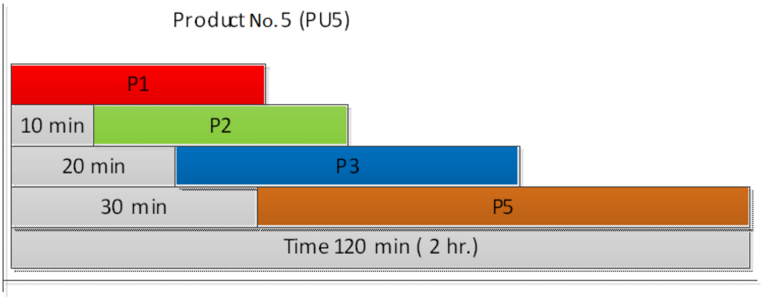

Fig. 3.3. PU5 — Insulating glass with tempered glasses. Producing 50 m^2 of insulating glass with tempered glasses requires 120 minutes.

3.1. Opportunities of increasing energy efficiency

In order to be able to conduct a detailed analysis of the energy consumption of the selected enterprise, it is necessary to install an electricity consumption monitoring system. Such a system was installed for each production line, which made it possible to analyse the electricity consumption in total, the electricity consumption of each individual production line and, as a result, to calculate the electricity consumption of each technological process and the amount of electricity used for each product type. Further, Fig. 3.4 shows the processed electricity consumption data for each production chain for October 2019.

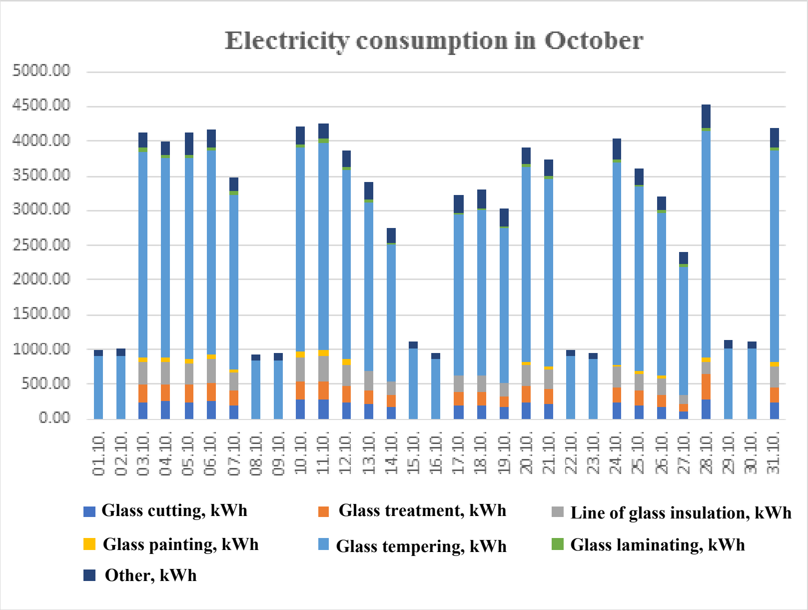

Fig. 3.4. The division of the electricity consumption in October.

Upon analysing the data in Table 3.4, which shows the electricity consumption for each individual technological process/production chain, it can be concluded that tempering is the most energy-intensive process and increasing its energy efficiency can produce the most substantial result. Analysis of the tempering cycle enables the conclusion that every day, a large amount of electricity is used to heat up the tempering furnace. That is, the furnace is switched off every day, it cools down so that a new operation cycle requires new heating up. There also are newer pieces of equipment which are foreseen for operation without being switched off, i.e. in the time periods between the tempering cycles (which in this case take place once a day) the furnace changes over to maintenance mode with a lower temperature. That is, the furnace does not cool down.

Table 3.4

Electricity Consumption for Each Individual Technological Process/Production Chain

	m^2	kWh	kWh/m^2	m^2/h	max consumption
P1 – glass cutting	15463.00	4666.60	0.34	90.00	30.32
P2 – glass processing	13056.00	4624.40	0.39	74.00	29.12
P3 – glass tempering	11334.00	64926.28	6.37	144.00	430.81
P4 – glass lamination	233.00	893.00	4.465	2.50	11.16
P5 – glass insulating	2334.00	5579.25	2.66	15.00	39.85
P6 – glass painting	223.00	919.80	4.60	4.599	11.4975

3.2. Optimisation of the electricity consumption of a glass-processing plant

For approbation, let us use the suggested optimisation for the above-described glass processing plant. The initial 24-hour schedule of electricity consumption is shown in Fig. 3.17. One of the days of October 2019 is taken as an example.

As can be seen from the graph in Fig. 3.17, the maximum of electricity consumption coincides in time with the price maximum. We use the above-described algorithms for the optimisation of the 24-hour schedule of plant operation. The process chains that are required for the optimisation algorithm are described in Fig. 3.1. Let us summarise the data.

All in all, there are six technological processes, one of which is tempering. Since tempering consumes much more energy than other production processes, the optimisation of the remaining five processes is shown in a separate graph. The plan for the day, the productivity of the lines as well as the electricity consumption of the production lines are all shown in Table 3.5.

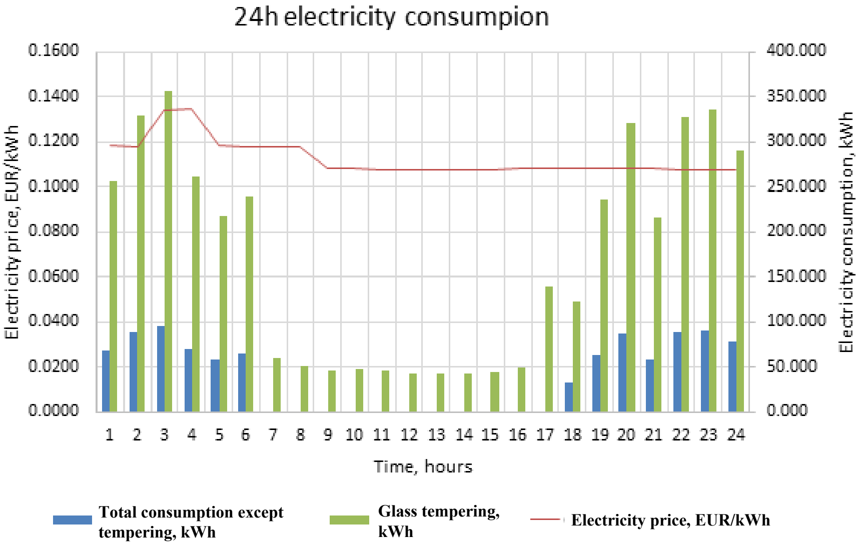

Fig. 3.17. Electricity consumption in a 24-hour period.

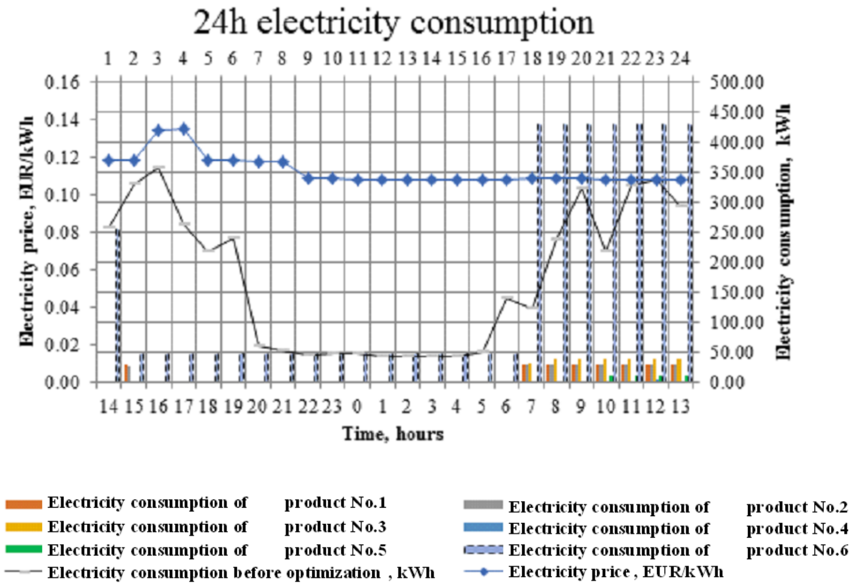

Fig. 3.19. Electricity consumption in a 24-hour period without the tempering process.

It has to be noted that in consecutive production chains, production processes that follow one another are started only if there is a product that has undergone the preceding stage. Therefore at this plant, cutting and afterwards processing always start first, or else a reserve of cut and processed glass is prepared at the end of the preceding working day. The optimisation result is shown in Fig. 3.18.

The working day concludes with pretreatment for the following day. In 2019, the electricity savings due to optimisation amount to 25,730 EUR.

3.3. Chapter conclusions

1. The example of the selected plant proves the possibility of increasing energy efficiency by shifting production operations to different times and using hours with lower electricity prices.
2. In 2019, the electricity cost savings due to optimisation could have been 25,730 EUR.

4. ELECTRICITY STORAGE AND SELF-GENERATION

One more solution that makes it possible to diminish the electricity costs (not the amount of electricity consumed but the costs, since the amount of electricity consumed increases slightly) is to use various electricity accumulators. The main idea here is that at the hours with the lowest electricity price, the accumulators are charged, whereas at the hours with the highest electricity price, the accumulated electricity is used, thus diminishing the consumption of expensive electricity. This means that the consumption graph smooths out and the consumption peaks at the "expensive" hours are shaved.

In the Thesis, we will consider the most widespread accumulator type – lithium-ion batteries.

For the research, an objective function is taken:

$$f_{obj,1}(W_{apl.bat}, P_{inv}, C_{biržas}, C_{ST,var}, t) \rightarrow max \, , \tag{4.1}$$

where t stands for the time value in hours.

The objective function (4.3.) can be rewritten as follows:

$$f_{obj,1} = C_{ietaup}^{d} = \sum_{t=1}^{24} (W_{ch}^{t} \cdot (C_{biržas}^{t} + C_{ST,var}^{t}) - W_{disch}^{t} \cdot (C_{biržas}^{t} + C_{ST,var}^{t}), \tag{4.2}$$

where C_{ietaup}^{d} stands for the daily savings from the operation of the battery, €;

W^{t}_{ch}, W^{t}_{disch} is the charging and discharging energy, respectively, at hour t, kWh/h; and d is the index of the day.

It has to be noted that this solution is a kind of two-level optimisation in which, after optimising the consumption of the plant, the next optimisation is used to select the operating mode for the storage battery. Because of the peculiarities of the production process, namely, the operation of the tempering furnace, the plant consumes electricity 24 hours a day, so it is useful to meet the consumption of the furnace by means of storage batteries at hours with maximum electricity price.

Taking into account the net present value calculations provided below, it can be concluded that at the present price of storage batteries and the present electricity price formation system, capital investments into a storage battery do not pay off. Therefore, the presence of a storage battery is considered as a future option. Figure 4.2 provides an example of optimisation, selecting a battery with a capacity of 100 kWh and a DoD of 80 %. The economic efficiency is discussed further, using the NPV criterion.

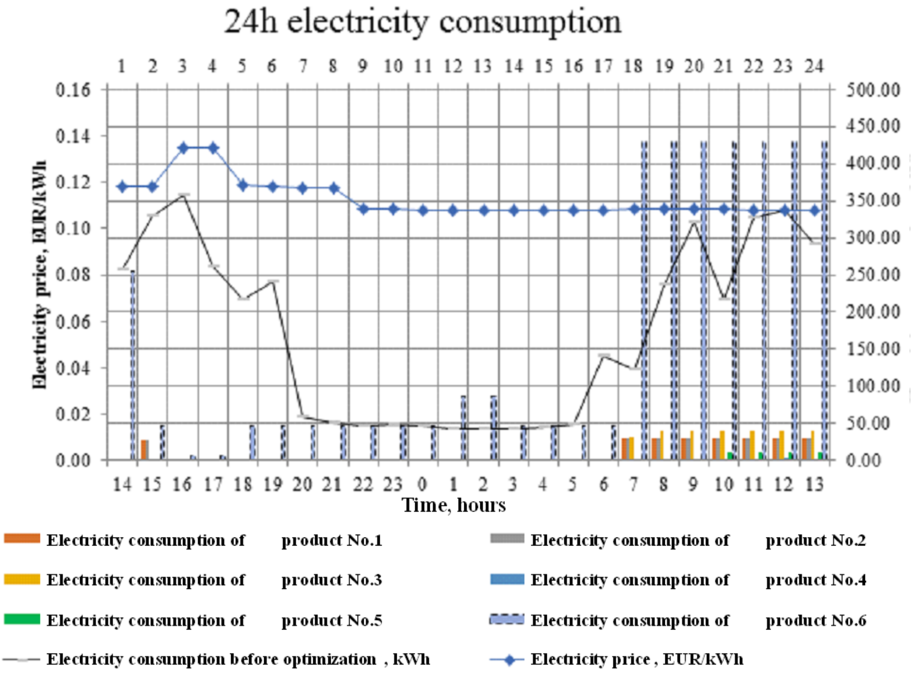

Fig. 4.2. The 24-hour electricity consumption when using storage batteries.

4.1. The economic efficiency of storage batteries, the NPV criterion

The cost and benefit analysis of using a battery is conducted on the basis of the optimised battery operation schedule. The benefit to the end users is defined as the difference between the energy costs if no battery is installed, C^{g}_{izm,nav_bat}, and the energy costs when a battery is used, $C^{g}_{izm,bat}$. Thus, the benefit over the whole year is as follows:

$$C^{g}_{ietaup} = C^{g}_{izm,nav\_bat} - C^{g}_{izm,bat}. \tag{4.3}$$

The total costs for the selected battery are as follows:

$$C_{bat\_izmaksas} = W_{apl.bat} \cdot \left(C_{bat} + C_{tansp} + C_{inst}\right) + C_{uztur} + C_{bat\_plaukts} + C_{ekspl}, \tag{4.4}$$

where

C_{bat} – the cost of the storage battery for 1 kWh, €/kWh;

C_{transp} – the cost of transporting the storage battery, €/kW;

C_{inst} – the cost of installing the storage battery, €/kWh;

C_{uztur} – the maintenance costs for the storage battery, €;

$C_{bat\_plaukts}$ – the cost of the shelf of the storage battery, €;

C_{ekspl} – the operating costs of the storage battery, €.

Last of all, the NPV for the whole planning period is calculated (25 years in this investigation of several cases):

- without taking a loan

$$NPV = -\left(C_{inv\_kop}\right) + \sum_{g=1}^{G} \frac{C_{ietaup}^{g}}{(1+i_{disk})^{g}}, \tag{4.5}$$

where i_{disk} is the discount rate, %;

- taking a loan

$$NPV = -\left(C_{inv\_kop}\right) + \sum_{g=1}^{G} \frac{C_{ietaup}^{g} - \left(\frac{C_{inv\_kop}}{G} + C_{atlik,g} \cdot i_{kred}\right)}{(1+i_{d})^{g}}, \tag{4.6}$$

where

$C_{atlik,g}$ – the loan balance at year *t*, €;

i_{kred} – the loan interest rate, %;

i_{d} – the discount rate, %.

It has to be taken into account that the total number of cycles for a lithium-ion battery is approximately 6000. This means that the service life of the battery will be about 16 years if one cycle per day is set and 8 years if two cycles per day are set.

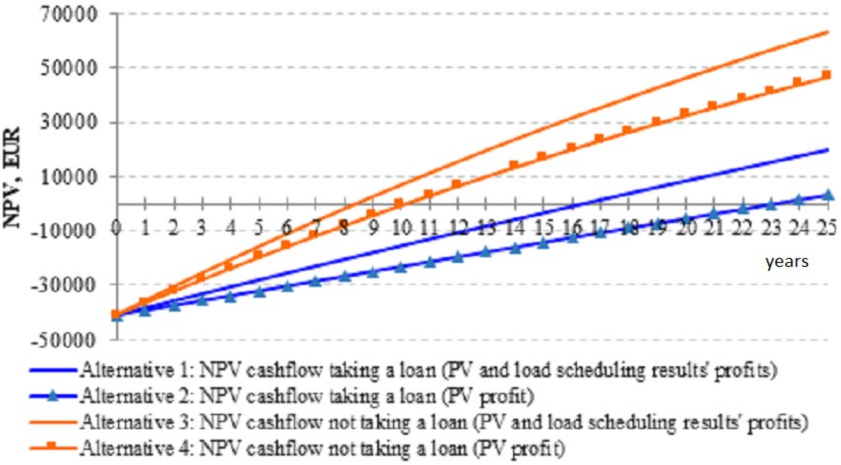

Fig. 4.3. NPV calculation for four cases.

4.2. Installation of the consumer's own renewable generation

The next step is to install the consumer's own generation from renewable energy sources.

In the Thesis, we assume that for a photovoltaic technology with a capacity of 33 kW, the purchasing and installation costs are approximately 41,000 € [60]. However, it can be expected that the prices of photovoltaic equipment will diminish in the near future, which can be seen from the real prices of high-capacity solar power plants. For example, in Pärnu, Estonia, the installation cost of 1 kW at a new 3.96 MW solar power plant is 883.83 € [61]. The choice of such type of capacity is predetermined by the opportunity to consider installation of photovoltaic equipment without storage batteries and with the condition that the consumption is 100 %, since it is less advantageous to submit the remainder of energy to the network and no payment for network services is required.

As shown in the previous chapter, investments into storage batteries do not pay off at present. Therefore, we will look at a combination of production optimisation and installation of solar panels. Since the capacity of the solar panels is less than the minimum consumption – the tempering furnace operates 24 hours per day – they did not influence the load distribution. On the other hand, the solar panels made it possible to make savings on account of electricity consumption. Let us discuss the payback of the investments into the installation of solar panels – the NPV. The NPV is calculated for four alternatives:

Alternative 1. A loan is taken and the total avoided costs are taken into account, (C_{AC_total}):

$$NPV(T_{plan}) = -p_{inv} + \sum_{y=1}^{T_{plan}} \frac{C_{AC\_total,y} - (\frac{p_{inv}}{T_{plan}} + p_{loan,y} \cdot i)}{(1+i_d)^y}, \tag{4.16}$$

where i_d is the discount rate; p_{inv} is the initial investments into photovoltaic equipment, €; $C_{AC\_total,y}$ is the consumer's total avoided costs (AC) at year y, €; $p_{loan,y}$ is the residual loan amount for year y, €; and i is the loan interest rate, %.

Alternative 2. A loan is taken and the avoided costs when installing photovoltaic equipment are taken into account, ($C_{AC_{PV}}$);

$$NPV(T_{plan}) = -p_{inv} + \sum_{y=1}^{T_{plan}} \frac{C_{AC_{PV},y} - \left(\frac{p_{inv}}{T_{plan}} + p_{loan,y} \cdot i\right)}{(1+i_d)^y}. \tag{4.17}$$

Alternative 3. No loan is taken and the total avoided costs are taken into account, (C_{AC_total}). If the consumer does not take a loan, then the upper part of formula (4.17), $\left(\frac{p_{inv}}{T_{plan}} + p_{loan,y} \cdot i\right)$, equals 0.

Alternative 4. No loan is taken and the avoided costs when installing photovoltaic equipment are taken into account, ($C_{AC_{PV}}$). If the consumer does not take a loan, then the upper part of formula (4.17), $\left(\frac{p_{inv}}{T_{plan}} + p_{loan,y} \cdot i\right)$, equals 0.

The total annual amount of energy generated by photovoltaic equipment with a capacity of 33 kW is 40,015.3 kWh.

It is worth noting that the whole amount of generated electricity is used for the self-consumption of the plant.

Taking into account the NPV calculations above, it can be concluded that the payback of the storage battery introduction project is currently not an attractive solution in terms of investment and requires subsidies from outside. Still, it is possible to consider such an option, since, if the initial price of storage batteries diminishes considerably and the electricity price increases, this solution can become more economically substantiated in the future.

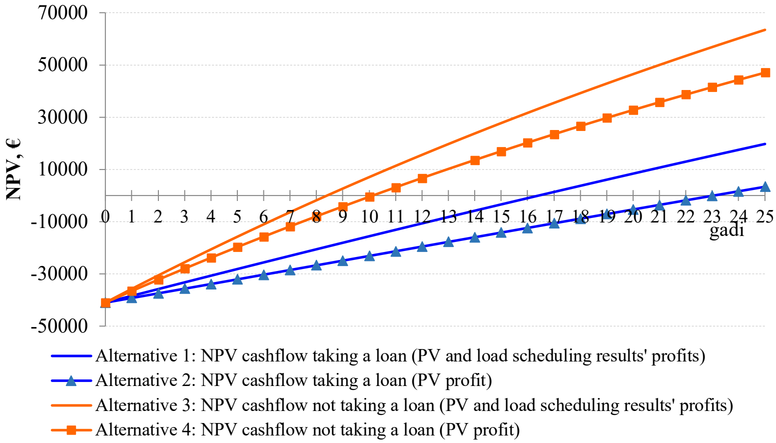

Fig. 4.6. NPV calculation.

The annual income of the plant from using photovoltaic equipment is 4509.52 €. This is the maximum amount that the user can obtain by adapting the energy consumption to its generation. In addition, the tentative NPV of using photovoltaic equipment shows a positive tendency. As can be seen, Alternative 3 corresponds to the most lucrative case when no loan is taken and the NPV is calculated by means of the total avoided costs. Here, the payback period is 8 years and the total NPV is 63,430.97 €. Alternative 2 has the poorest results: the payback period is 23 years and the NPV is only 3,346.96 €. As regards Alternatives 1 and 4, their payback periods are 16 and 10 years, respectively (Fig. 4.6).

CONCLUSIONS

The volume of research on the subject of energy-efficient production planning has considerably increased over the recent years, resulting in many publications in which energy-efficiency considerations are integrated into present production planning models. Still, the present modelling approaches cannot yet be recognised as compliant with the requirements that have rapidly increased.

Energy-efficient production planning of an industrial enterprise requires synthesis of software whose aim is to optimise the electricity consumption costs based on market prices. During the development of the algorithm, it has to be taken into account that each consumer has special tariffs for the electricity used, which are met when paying the trader for the service.

The market prices are forecast or taken from the database of the *Nord Pool* exchange. Electricity consumption in low price hours helps to decrease CO_2 emission to the atmosphere because the high price electricity is produced from fossil fuel.

Depending on the exact types of products, the technologies and equipment used, the production process can be organised in different ways:

- In parallel. The products are produced simultaneously.
- Consecutively. The products are produced one after another. Two sub-cases can be singled out:
  - The production sequence can be chosen freely.
  - The production sequence has been set. Limitations of this type may emerge, for example, based on product delivery conditions or after co-ordination with raw material delivery schedules.
- Mixed. In this case, part of the products can be produced simultaneously whereas the other part, consecutively.

When optimising the energy consumption, the minimisation of the objective functions can be performed by means of various methods depending on the types of limitations that follow from the production conditions in place and the available information.

Two main methods were selected:

- Random enumeration.
- Linear programming and enumeration.

The above methods have been implemented in MATLAB or C# programming language environment, analysed and verified.

In a case when individual meters are not installed for each production line, an arrangement that would make it possible to form an exact distribution among the production amount, the product type and the energy consumption, historical production/consumption registration data can be used. The historical data have to contain the amount of product made by each piece of equipment per hour as well as the plant's total consumed electricity during the hour in question. The specific consumption of products can be determined by the Monte-Carlo method or the method of least squares. In all the considered cases, the distribution of the consumption hour by hour coincided for the Monte-Carlo method and the method of least squares.

The example of the selected plant proves the possibility of increasing energy efficiency by shifting production operations to different times and using hours with lower electricity prices. In 2019, the electricity cost savings due to optimisation could have been 25,730 EUR.

The payback of the storage battery introduction project is currently not an attractive solution in terms of investment and requires subsidies from outside. Still, it is possible to consider such an option, since, if the initial price of storage batteries diminishes considerably and the electricity price increases, this solution can become more economically substantiated in the future.

The tentative NPV of using photovoltaic equipment shows a positive tendency. The most advantageous is the case when no loan is taken and the NPV is calculated by means of the total avoided costs. Here, the payback period is 8 years.

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