Decision support for planning techniques in energy efficiency projects

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Abstract

Factory operators can select from a multitude of measures to improve their energy efficiency. Despite the variety of planning techniques intended to help investigating the energy flows, little assistance is available for determining the most efficient approach to pursue in a specific project. This paper presents decision support procedures for making appropriate selections during planning, focusing on the selections of an energy model and a matching energy data acquisition method. They build on problem-independent decision models and systematize available alternatives. The models are solved independently by applying the Analytic Hierarchy Process that allows the integration and quantification of different criteria.

Keywords: Energy efficiency; Sustainable development; Decision-making; Analytic Hierarchy Process

1. Introduction

As the reliance on renewable energy increases and more electric vehicles need to be charged in Europe, energy prices become increasingly volatile. Production companies need to adapt their processes to compensate the effects by devising new ways to adjust their demand to the availability of energy. Hence, a great number of assessment and planning techniques have been developed to support the design and implementation of suitable energy efficiency measures (see e.g. [1,2]). The knowledge on past and future energy demands of processes, machines and production lines is a primary concern in that regard (see [3]). Yet, little assistance is available for selecting an appropriate way to model energy flows or acquiring the respective energy data. The selection of these, however, determines the effectiveness as well as the necessary expenses of any energy efficiency measure.

In that light, Stoldt and Putz presented a procedure model to guide the execution of simulation studies [4]. This paper builds on that work and introduces detailed decision support procedures to select a suitable approach to model energy flows as well as to enhance the efficiency of energy data acquisition. Both aspects are relevant to the procedure model but also to the application of other techniques intended for use in the planning of energy efficiency measures. Furthermore, both selections depend on each other. The decision support procedures rely on the well-established Analytic Hierarchy Process (AHP), which has been applied in a great number of case studies to solve a various decision problems (see [5]).

The following section discusses the state of the art of aspects to be considered when planning for energy efficiency. Section 3 introduces the basics of the AHP as well as the two developed decision support procedures. Afterwards, a brief trial is presented to exemplify their application.

2. Planning for energy efficiency

The requirements in the selection of an energy model and a suitable data acquisition method can be derived from typical energy efficiency measures as well as planning techniques used in their design and implementation. Accordingly, the state of the art on both aspects is discussed hereafter. Lastly, a brief introduction to data acquisition methods is presented.
2.1. Data requirements for planning efficiency measures

A wide array of approaches exists to improve energy efficiency of already established as well as newly planned factory systems. According to the systematization of Müller and Löffler six basic categories for efficiency measures can be identified [6]. These generalised measures can be applied in different settings and planning phases. The following Fig. 1 relates these categories to the typical planning phases found in production companies and factories.

While this categorization is not exhaustive and offers space for specification, fundamental data requirements are already identifiable and can be described for each planning phase. Planning actions that concern the overall production system are, on the one hand, characterized by more decision alternatives but, on the other hand, may lack available information because new equipment may not be accessible for data collection. Hence, historical and average consumption data (e.g. in datasheets) are often utilised. Depending on the specific task, load profiles of different machines may be required. This can induce the necessity for further information regarding the specific processes and different machine operating states.

In the product planning phase, estimated values for energy consumption in different process steps often suffice. Additional process data (e.g. material removal rate, material forming) and estimated load profiles can improve the assessment of different product designs. Mostly, the requirements for data accuracy over time and in general are rather lower than for other planning phases. A reason for this being that usually applied life cycle assessment methods require no analysis of the joint demand profiles of parallel processes over time. Moreover, the eventual production facilities are usually unknown in this phase and will only be defined later, which typically prompts for making more generalised assumptions.

Measures associated with the phase production planning and control focus on the optimization of existing machines and processes. Depending on the specific task, less detailed consumption indicators may suffice but very precise demand profiles may also be required. The actual requirements are usually defined by the planning technique employed. Since the system will already operate in this planning phase, more approaches for data gathering will be available and the data acquisition can be more detailed.

2.2. Data requirements of existing planning techniques

Planning techniques provide methodological assistance for specific or comparable planning problems in certain phases of this cycle. They are typically applied to structure a part or all of the problem solving cycle from systems engineering that consists of the following three phases [7]:

- Target definition: situation and/or system analysis; definition of targets and assessment criteria.
- Solution search: concept and/or system synthesis; concept and/or system analysis.
- Solution selection: concept and/or system assessment; selection of the optimal concept and/or system.

To plan for energy efficiency, a number of comprehensive frameworks were published in recent years (e.g. [6,8]). Müller and Löffler particularly stress the importance of energy consumption data and the consideration of different energy prices, suggesting the inclusion of “load profiles […] in technical documentation and life cycle documentations” [6]. This emphasises the analytical aspect of planning techniques developed for projects of this kind.

The most basic type of techniques is static modelling. An approach that has reached some popularity is a form of value stream mapping that includes energy or environmental considerations (e.g. [9]). But also the application of flow system theory has been used in this respect [10]. Life cycle costing (e.g. [11]) or eco-efficiency assessment of product systems [12] also belong in this category. They generally only require a small number of consumption indicators (e.g. idle and production demand) or simple load profiles offering only limited insight into the dynamics of the energy flows.

Another important category comprises techniques intended for use in energy-oriented production planning and control (PPC). An in-depth review of these works is found in [13]. Like the former static modelling, these approaches usually require fixed value consumption indicators. In contrast, they are not intended for the assessment of systems but aim to solve the PPC problems usually dealt with in operations research. Optimizers are a tool of choice in that, yet, given the complexity of the problems calculations need to be simplified. Accordingly, high resolution input data is often not required.

Simulation is a particularly interesting technique to plan energy efficiency measures on different levels. On very abstract levels, system dynamics modelling may suffice to evaluate the behaviour of a large system but more detailed investigations of production systems can be realised using discrete event simulation [14]. The major advantage of simulation is the possibility to investigate the system’s dynamic behaviour. Yet, the necessary effort for data collection, modelling and experimentation is considerable.

One way to cope with this issue is to decide on a suitable level of abstraction that minimises the efforts while allowing for the generation of the desired results. This is particularly important for the combined simulation of energy and material flows. Accordingly, different approaches for modelling the consumption (from simple consumption indicators to detailed profiles or functions) and provisioning of energy in simulation can be found in existing approaches (see [4]). They offer different accuracy and require input data in varying form [15].
Aside from the above simulation approaches that cover production systems or even full value chains, the simulation of subsystems (e.g. heating systems), machines and machine components is also a well-established planning technique (e.g. [16]). These require usually very detailed models of the energy consumption and input data (see [17]).

Summarising, many techniques to plan for energy efficiency can be found in the literature but also in practice. They differ considerably in the way they regard the consumption and provisioning of energy. Yet, most works only suggest a single energy model to be used. Carefully selecting an ideal energy model and data acquisition method promises to increase the planning efficiency by adapting accuracy and necessary efforts to the planning task at hand. These methods are introduced in the following.

2.3. Brief introduction on energy data acquisition methods

The efforts for data acquisition are, inter alia, determined by the selected method. The desired information as result of the acquisition process usually comprises power load data with or without references to machine parameters and process times in varying granularity. Although some energy models may be characterized by specific requirements, general categories for acquisition methods can be identified. Kouki et al., for instance, introduce life cycle inventory (LCI) databases, technical documentation, mathematical models and measurements as basic means for data acquisition [18].

The use of databases and documents allows quick access to energy and consumption related information of processes, materials and machines. This data may in some cases be sufficient for an estimated calculation or classification of consumers but often provides less detailed information.

Mathematical models are based on equations that comprise various energy related parameters with reference to the machines, tooling or product itself. Since these methods are mostly based on basic principles of physics, they often calculate a theoretical minimum energy that can be scaled to greater accuracy using empirical factors. The expenditures of using these models correspond with their complexity and, moreover, may depend on the required hard- and software.

Measurements are the most obvious option for acquiring case- and target-specific consumption data. Time and costs for energy data measurements vary significantly depending on the targeted system, necessary equipment and required knowledge. As a further categorization Posselt divides this group into spot, temporary (periodic) and stationary measurements. This categorization refers mainly to the duration of the actual measurements but is also linked to the equipment. Stationary measurements are typically conducted with integrated energy meters whereas temporary and spot measurements may be executed with a wide range of measuring systems and multimeters [19].

The selection of an appropriate data acquisition method is typically part of an overall acquisition strategy. Considering this, Posselt provides an overview of several measuring strategies described in literature (see [19]). Moreover several standards and guidelines describe energy efficiency assessment procedures for factories and provide guidance for energy data acquisition (see [20,21]). In general, they can be structured into phases like target definition, planning and decision, conducting and finally analysis and processing. Yet, selecting a method for energy data acquisition under efficiency considerations while minding the requirements of the energy model and the situational preconditions is a necessity.

3. Methodology

The previous section introduced an overview of energy data modelling and acquisition requirements for planning energy efficiency measures. Selecting an energy model and a matching data acquisition method suitable for the planning task at hand serves to improve the planning efficiency. The following subsections briefly introduce the general process of AHP as well as specific procedures for the afore-mentioned tasks. The specific procedures may be applied by themselves for any planning technique but are also an integral part of the initially mentioned procedure model for simulation studies (see [4]). Regardless, a project-specific list of processes and facilities to be measured is expected and assumed as fixed.

3.1. Overview of the Analytic Hierarchy Process

The fundamental idea of the AHP is the decomposition of an overall problem into its separate parts and the subsequent aggregation of the partial results for the entire decision [22]. The AHP is executed in five steps. Firstly, the problem is modelled as a hierarchy structure and, secondly, the elements (i.e. the decision criteria as well as the alternatives) are compared pairwise. In order to support and standardize the comparison, Saaty introduced a universal scale that ranges from 1 (equal importance) to 9 (absolute importance) and also includes the respective reciprocals (e.g. 1/9) for lesser importance [23]. Consequently, rationally measurable as well as intuitive factors or aspects with different units may be compared and included in the decision.

The third step aims to obtain a vector from the pairwise comparisons that measures the importance of each element regarding the next higher level. This calculation can be conducted with different approaches. Besides the eigenvalue method, Saaty introduces four approximation procedures that provide sufficient accuracy and can be used with simple spreadsheet programs as well as little effort [22].

In the fourth step, every matrix of pairwise comparisons needs to be tested since the number of elements may lead to inconsistencies. For this purpose, a consistency value is calculated to decide if the generated matrix is still permissible. If the matrix is not regarded as consistent the pairwise comparison should be repeated and refined.

Lastly, all alternatives of the matrix are evaluated regarding their fulfilment of the overall target. Starting from the second highest hierarchy level, this entails multiplying the weight vector for each matrix with the superior elements global weight. On the lowest level, i.e. for the alternatives, these global weights per decision criterion are summed up to calculate the overall weight. An alternative can be selected by considering the highest target conformity (e.g. min or max).
3.2. Energy model

An extensive literature review (see [4]) showed that six characteristic approaches to model energy consumption were used in previously documented simulation studies. These are also typically utilised in the application of other planning techniques. The following list provides an overview:

- Continuous/physical models
- Equivalents for consumption or emissions (e.g. CO₂ equivalent or aggregated primary energy use)
- Only operating state (i.e. substituting measurement of the time of an element spent in each operating state)
- Operating states with average consumption values
- Operating states with spline curves for consumption (i.e. time series with fixed values or piecewise functions)
- Operating states with artificial consumption models (i.e. functions that approximate consumption over time)

When aiming for increased efficiency in a planning process, the selection of an energy model is fundamentally a matter of effort associated with its application and the benefits it promises. The latter can be broadly distinguished in achievable accuracy and flexibility for experiments, i.e. the ability to be used in the assessment of alternative scenarios or solutions without spending additional effort to retain validity.

Fig. 2 depicts a hierarchical target system for the use in simulation studies. While the primary level should be applicable for most planning techniques, the secondary level may need to be adapted to the focus in the specific project and the techniques employed.

Each of the previously listed approaches to model energy has certain characteristics considering its accuracy. For instance, “operating states with average consumption values” does not allow for high resolution modelling of the energy flow behaviour of production equipment.

Hence, some of the alternatives may be eliminated based on their characteristics and the requirements of the planning project or planning technique. This is also the first step of the proposed methodology for selecting a suitable energy model. The elimination process should particularly consider the borders of the system to be analysed, the characteristics of elements to be included and the specific focus of investigation.

In a second step, priorities for the remaining alternatives (i.e. fundamental energy models) need to be calculated. This is ideally done using the previously introduced AHP. For this purpose, the target system depicted in Fig. 2 may be used as-is but may also be adapted to fit the user’s priorities more closely. The eventual result is a vector of overall weights for all considered alternatives that is used for the actual selection, usually prioritising the alternative with the highest value. In case two alternatives have (about) equally high overall weights, additional criteria (like familiarity with the modelling approaches) may be considered to make a well-founded decision after the AHP is completed. This procedure is also shown in [23] and emphasises the need for a critical review of the AHP results as they should not be understood as dogmatic but rather as an indicator to guide decisions.

![Estimated global weights of lowest level criteria](image_url)

To further simplify the application of the proposed methodology, weights for the criteria depicted in Fig. 2 were estimated using the AHP based on knowledge gained from the extensive literature study, discourses in expert groups and the authors’ simulation experience. Particularly, the weights for the subcriteria associated with effort were derived from shares of time typically required for different tasks in simulation studies (see [24]). All results are summarised in the lower part of Fig. 2. With these, pairwise comparisons only need to be made for the alternatives considering each of the criteria, e.g. supported with software tools or spreadsheet tables. Yet, project-specific weights may also be calculated.

3.3. Energy data acquisition method

The hereafter presented model for decision support (see Fig. 3) is based on the general heuristic decision procedure of Grünig and Kühn [25] and has been adapted to the specific context of energy data acquisition.

The initial trigger of the decision is the necessity of input information for a distinct energy model. In the first step, the problem analysis, the required data needs to be precisely defined and a consistent target definition for the selection of a suitable method found. Efficiency is a central target for the evaluation of all acquisition methods. It is generally defined as relation of output (value of the gathered information) and input (costs of energy data acquisition). Evaluating the output is a particularly challenging task in that regard.

The elaboration of alternatives is necessary to reduce complexity in an early stage and to provide an appropriate overview of options. Some conclusions can already be drawn at this point of the decision model. As mentioned in section 2, each of the methods above can be characterised by different advantages and disadvantages. Hence, the list of alternatives that results from this step is choice of actual options the decision-makers have.
In the third step, sub targets and criteria are chosen or defined. Typical requirements that should be taken into account for the definition are operability, completeness and avoidance of redundancies [26]. Furthermore, the amount and hierarchical levels of criteria should generally be limited to maintain applicability of the AHP (step 5) and the whole decision process. Input and output criteria should be arranged in independent hierarchy structures.

Since there is a broad variety of possible criteria, some typical examples can be categorized and highlighted. As already elaborated by Posselt, criteria for assessing the necessary inputs for an energy data acquisition method can be related to the phases of the Life Cycle Costing described in EN 60300-3-3:2004 [19]. Namely, all relevant cost factors can be attributed to the phases concept, development, purchasing, installation, operation and maintenance (i.e. use), as well as disposal. Especially costs for purchasing and installing necessary acquisition instruments may often be highly relevant. Yet, additional costs from license fees, production downtimes, etc. should not be underestimated.

In contrast, the output criteria are less clearly separable. The output, above all, comprises technical and energetic information (e.g. power, resolution, frequency) which can be compared quantitatively. Additionally, there are pieces of meta-information (e.g. process time, temperature, machine parameters) which contribute to the integration of energy data into its overall context. Finally, further effects (e.g. mode of data transfer) can be relevant in the assessment of alternatives.

If necessary, environmental influences can be evaluated in the fourth step depending on different energy transparency levels that are defined by Posselt [19]. For each of these levels there are several criteria proposed that could have higher relevance for the outcome of the decision. Therefore, their impact on the decision may be checked and quantified with an additional sensitivity analysis where the pairwise comparisons account for the definition are operationality, completeness and avoidance of redundancies [26]. Furthermore, the amount and hierarchical levels of criteria should generally be limited to maintain applicability of the AHP (step 5) and the whole decision process. Input and output criteria should be arranged in independent hierarchy structures.

In the final step of the overall methodology, the results of all preceding phases are combined by calculating and comparing the efficiency of the acquisition methods. It is suggested to calculate the output value by applying the AHP since these criteria usually have heterogenic characteristics and units or are not quantifiable. In contrast, there are two options for assessing the input criteria. If all costs are known and confirmed they can simply be calculated so that applying the AHP is not required. If costs can only be estimated or it is necessary to include weightings for different cost positions the AHP provides the methodological framework for the quantification.

It is important to note that the final efficiency values (quotient of output and input) for each method are only meaningful in a comparative evaluation. Summarising, the described procedure provides the means for decision support to allow for profound and structured decision-making even when several persons participate in the process. Its integration in an overall procedure for energy data acquisition is presented in [3], where further organisational aspects are discussed.

### 4. Trial application

The energy consumption of an individual machine, which allows the integration of different laser tools, was investigated to allow for the prognosis of energy demands in production. For this purpose, using the methodology presented in section 3.2, operating states with average consumption values were identified as an appropriate energy model. Prior to the study, no data acquisition had taken place and no information system offered the required energy data. Hence, only measurement methods were considered in the following selection process, particularly, spot, temporary and stationary measurements.

Since rapid movements of the machine’s axes suggested brief and high load peaks, a sufficiently fast sampling rate and a high resolution of the gathered data was required to provide sufficient information. Moreover, low error tolerance of the data acquisition method was necessary for precise results. Further considered output information were the connection for the subsequent data analysis (i.e. the data transfer and access) and the time reference in terms of the depiction of data. Identified cost factors comprised planning efforts and several aspects of the installation as well as the use phase. Besides price and implementation costs as the most important factors, energy consumption of the metering equipment and necessary wages for using the measuring system were regarded. The AHP was applied for both the output as well as the input factors since some cost positions could only be roughly estimated (see Fig. 4).

The division of the considered alternatives’ output values by the corresponding values of the input vector leads to the final efficiency evaluation. Results are shown in Table 1. Consequently, temporary measurements were identified as the most efficient alternative for the described trial.

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Output Vector</th>
<th>Input Vector</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot</td>
<td>0,090</td>
<td>0,106</td>
<td>0,849</td>
</tr>
<tr>
<td>Temporary</td>
<td>0,451</td>
<td>0,366</td>
<td>1,231</td>
</tr>
<tr>
<td>Stationary</td>
<td>0,459</td>
<td>0,528</td>
<td>0,870</td>
</tr>
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</table>
5. Conclusion and Outlook

As production companies aim to improve their energy efficiency, they can build on a variety of measures described in literature or realised in practice. To aid in the selection and planning of appropriate actions, a multitude of planning techniques, like simulation, were developed. These have different requirements for modelling energy flows and energy data acquisition. This paper aims to help companies in improving their sustainability by providing guidance in the planning process. It presents a methodology for multi-criteria decision-making to select an energy model and a data acquisition method when planning the implementation of an efficiency measure. The introduced procedures rely on the well-established Analytical Hierarchy Process (AHP). The developed procedures serve to heuristically identify alternatives and criteria, assess their suitability and make profound decisions, effectively aiding to increase energy efficiency in factories.

Much of the work that was the basis for the presented methodology concerned modelling electricity systems and acquiring data in these. Future research may investigate if additional specifications (e.g. in the selection of criteria) can be made for alternative energy carriers. Moreover, the implementation of the decision support models in IT systems for collaborative application of the methods can be valuable for practitioners as well as researchers.

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