

# Energy-Oriented Life Cycle Costing – An Approach for the Economic Evaluation of Energy Efficiency Measures in Factory Planning

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## **Abstract**

Energy efficiency gets increasingly important as ecological and political objective of industrial companies. In order to achieve this objective, several procedures and guidelines have been developed in the field of factory planning intending to raise energy efficiency by technical, organisational and structural measures. However, the potential of these measures is not fully utilized at present. To a great extent, this is caused by deficits within the economic evaluation of energy-efficient planning solutions, which lead to misjudging their economic efficiency. To meet these deficits, a life cycle costing approach for the economic evaluation of energy efficiency measures was developed. This approach is based on the dynamic methods of investment appraisal, especially the net present value method, as well as on a broad comprehension of the term “energy costs”. The approach and its applicability are presented theoretically as well as by a case example in the area of intralogistics with special emphasis on the requirements of factory planning.

## **Keywords:**

Life Cycle Costing, factory planning, energy efficiency

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## 1 Introduction

Increasing energy prices, policy conditions and environmental awareness lead to a growing importance of energy efficiency as an objective of industrial companies. Factory planning plays a significant role for the long-term achievement of this objective. Factory planning projects can be distinguished regarding the extent to which energy efficiency is integrated: There are projects that replace single existing machines by energy-efficient alternatives or that raise energy efficiency by a more systemic point of view [1]. A systemic consideration often leads to better effects and should therefore be aspired, but the effort is very high. Regarding energy efficiency as decisive criterion for new machines can therefore be a reasonable starting point for companies to incorporate energy efficiency in their strategies. However, tools and methods for the holistic and long-term economic evaluation are needed in both cases to enable the achievement of these objectives.

At present, often a deficit between the political or company-related goals and the actual energy consumption exists because of insufficiently realised energy efficiency measures. Among other reasons, this is due to the fact that economic efficiency is often misjudged in practice. The two central obstacles that lead to this situation are explained in the following [2].

The investment needed by energy-efficient alternatives in the acquisition phase is often higher than that of well-tried planning solutions. But they lead to cost savings in the utilization phase due to lower energy consumption. Since investment decisions are often based only on acquisition costs, the trade-offs between these costs and energy costs are not considered adequately over the life cycle. A survey among approx. 1500 companies of the manufacturing industry revealed that only 14 % of the enterprises use life cycle approaches to evaluate investments [3]. This survey also showed that applying life cycle tools is significantly related to the use of energy-saving technologies.

Another cause is the separation of planning and financial responsibility between company departments (e.g. production and supply engineering). The effects on energy consumption and costs are often not regarded on a factory level, but only in the respective departments.

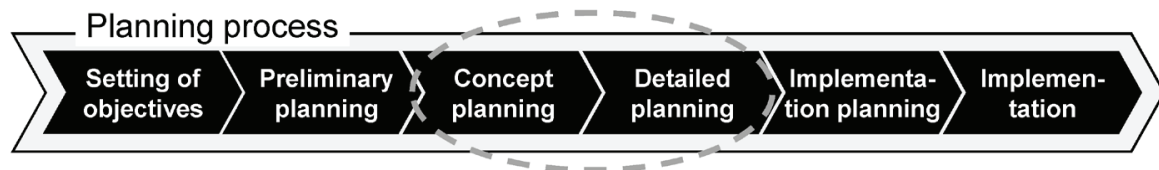
The method “Energy-oriented Life Cycle Costing”, which is presented in this paper, meets these deficits – with a focus on the first one – on the basis of a life cycle approach in consideration of the special requirements of energy efficiency.

## 2 Economic Appraisal of Planning Solutions

### 2.1 Appraisal Methods Used in Factory Planning

Factory planning is basically concerned with the development of sustainable solutions for constructing and running a plant. Specific planning problems that arise in this context range from the integration of new production technologies and the re-configuration of production areas to the new development of whole factories. In all cases, such planning problems are characterized by high complexity because of the diversity of objects and influencing factors that have to be considered.

To handle the complexity and to coordinate and systematically accomplish the various planning tasks, subdividing the planning process into consecutive phases has proven its worth. For this purpose, literature provides diverse procedure models, which differ in the number and names of the planning phases (for different procedure models, see [4-7]). In general, as exemplarily shown in Figure 1, the process of factory planning covers creative phases for the main design and configuration of the factory system as well as activities to support its implementation.



**Figure 1:** Procedure Model of Factory Planning (according to [5])

Typically, different alternatives for the factory's specification and layout are developed during this process. These alternatives have to be assessed and enhanced within each planning phase with respect to the requirements that have to be fulfilled by the planned factory or parts of it. Requirements relevant in factory planning are: flexibility, product/process quality, employee-orientation, economic efficiency or energy efficiency, etc. [7]. To pay attention to all of them and to consider the differences in their measurement appropriately, the evaluation and comparison of alternatives is usually based on both monetary and non-monetary appraisal methods:

- Within the *monetary appraisal*, the advantage of a particular planning solution is determined by means of a financial target measure. Since decisions in the context of factory planning are in most cases associated with long-term investment, especially the methods of investment appraisal and their specific financial target measures (e.g. profit, costs, net present value) are applied [6]. In many planning projects, these target measures represent limiting factors and therefore can be seen as the fundamental criteria for the decision to continue, change or cancel a particular project.

- In contrast, the *non-monetary appraisal* provides a basis to take into account the multitude of qualitative (e.g. flexibility, transparency) and other quantitative criteria (e.g. capacity, product quality). Typically, these criteria are not expressed in monetary terms but crucial in factory planning as well. Since some of these criteria usually conflict with each other, it is hardly possible to achieve all of them to the desired level. Therefore, the non-monetary appraisal has to be considered as a multiple-criteria decision making problem, which can be solved with corresponding methods, such as utility value analysis or the analytic hierarchy process [8-10].

As mentioned above, the assessment of planning solutions – monetary and non-monetary – takes place several times during the planning process. This is especially important to stepwise review the conformity of planning solutions to the planning objectives and to justify the elimination of some alternatives. Elimination gets necessary, since the general restrictions of a planning project (e.g. financial, organizational and temporal) hardly allow pursuing all imaginable alternatives in detail. Particularly in the phases of concept and detailed planning (see Figure 1), one preferred alternative, which is to be planned in detail and finally realized in the subsequent planning phases, has to be selected [4, 5, 7].

## 2.2 Integration of Life Cycle-Oriented Approaches

In the literature of factory planning, discussions about life cycle-oriented approaches mainly arise with respect to the monetary appraisal and in particular focus on the concept of life cycle costing (LCC) [4, 6, 11]. This concept intends to reveal the overall costs caused by a specific object during its life cycle – including its initial development or acquisition, its utilization and its elimination [12, 13]. Hence, it enables the consideration of trade-offs between the costs (and revenues) of different life cycle stages, which among others plays an important role in the appraisal of energy efficiency measures. Such measures typically lead to cost savings that first and foremost are generated due to a decrease in energy consumption in the utilization phase of an object and consequently require long-term cost considerations for taking their effects into account correctly.

For that reason, the life cycle costs become exceedingly relevant as a decisive criterion within the proper economic appraisal of energy efficiency measures. The concept in general also contributes to understand the origin of costs and to justify possibly higher acquisition costs of an object in favour of the identification of factory systems, which are advantageous in their overall costs. Despite these potentials, a suitable life cycle costing approach, which tends to meet the demands of (energy efficiency-oriented) factory planning, hardly exists to date. In most cases, only the pertinence of life cycle costing appraisals and the stages of the factory life cycle are emphasized and described within the literature of factory planning. In addition, the

different life cycles that have to be considered due to the multitude of objects within a factory are occasionally pointed out, but not discussed in detail (e.g. concerning their interactions) [4, 14, 15].

Therefore, a conceptual framework for the systematic appraisal of a factory's life cycle costs in terms of a procedure model is to be presented in section 3.2. The application of this procedure model in principle is not restricted to a particular planning phase, but the accuracy of its results is certainly improved by the gradual increase of (cost) information during the planning process. At the beginning of this process, typically just a vague conception of planning solutions and objects exists, so that costs and investment volume can only be determined approximately. In contrast, more detailed cost calculations can be achieved in the phase of implementation planning (see Figure 1) based on detailed layouts, specified production facilities and buildings and corresponding offers [4-7].

So, the methodical elaboration of the procedure model has to be adapted to the structure of information retrieval and decision making in factory planning projects to enhance its applicability. For this purpose, the general process of factory planning can be taken as a starting point since it allows drawing conclusions about:

- the (energy-related) data base that is available in each planning phase to determine the (energy-related) life cycle costs and
- the interactions and dependencies between different planning objects and the stepwise decisions to specify them (e.g. dimension, technical parameter), which influence the configuration of the factory system and thus, the (energy-related) life cycle costs.

Besides the methodical requirements, which can be deduced from the process of factory planning itself, further implications for the development of a life cycle costing approach specified to (energy efficiency-oriented) factory planning can be found in general life cycle costing models as outlined in the following.

### **3 Approach for Energy-Oriented Life Cycle Costing in Factory Planning**

#### **3.1 Implications from General Life Cycle Costing Models**

Over time, a multitude of life cycle costing models has been developed – especially in managerial literature. These models primarily differ with regard to the degree of specification, the user, the subject matter, the methodology of appraisal as well as the type and scope of target measures. Besides, the concept of life cycle costing

overlaps with the various approaches for total cost of ownership (TCO) [16, 17].<sup>1</sup> In general, the developed models refer to specific types of objects and can mainly be classified into models for products (and services) and models for non-consumable resources (e.g. technologies, processes, systems, software). In addition, further approaches regarding the life cycle of organizations or branches exist [21].

Beyond that, life cycle costing is discussed not only in scientific literature, but also in engineering standards [22-24]. From a more practical point of view, these engineering standards outline some fundamentals of life cycle costing and give further advice for its application in practice. Since the engineering standards focus on the life cycle costs of products and production facilities, their models can also be categorized as mentioned above.

Although these models are neither specified to factory planning nor to energy efficiency<sup>2</sup>, they provide more or less detailed information about:

- the different life cycle stages of several objects which are also relevant in factory planning (e.g. production facilities or products)
- distinctive characteristics and the development of financial target measures related to specific objects and life cycle stages
- relevant cost categories for specific objects and life cycle stages (cost breakdown structure) and
- basic methods and algorithms to calculate specific cost categories.

Therefore, the general life cycle costing models form a basis for modelling the life cycles of the various objects which have to be configured during the process of factory planning. Furthermore, several requirements concerning the development of a comprehensive life cycle costing approach in the context of (energy efficiency-oriented) factory planning can be deduced from these models. In this regard, the approach should comprise:

- basic structures and characteristics of the factory's life cycle and the life cycles of other objects, which occur within the factory's life cycle (and have an influence on energy efficiency and energy-related costs)
- suggestions to systematically capture all the planning objects, their (energy-related) life cycle costs and interactions

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<sup>1</sup> By now, discussions about the relation of life cycle costing and total cost of ownership are still controversial. So, there is no unanimous opinion whether LCC denotes a subset of TCO or vice versa [17]. Occasionally, both terms are even used synonymously [18]. For an analysis of different TCO approaches and their methodical elaboration see [19]. Since the (energy-related) life cycle costs of a factory are regarded from a user's perspective in this paper, they are interpreted as equal to the TCO [see also 20].

<sup>2</sup> Most models include the energy costs as one relevant cost category, but their specific calculation still remains disregarded.



- classifications of (energy-related) costs and influencing factors
- methods to calculate the (energy-related) life cycle costs of a factory (possibly integrating the methods already used in factory planning)
- methods to estimate the (energy-related) life cycle costs of a factory and to incorporate the related uncertainty.

## 3.2 Procedure Model to Determine the Energy-Related Life Cycle Costs

### 3.2.1 Preliminary considerations

The procedure model presented in this paper is intended to support the systematic appraisal of a factory's energy-related life cycle costs. But before this is to be explained in detail, the basic understanding of the energy-related life cycle costs should be clarified.

In general, all costs accrued by the acquisition of energy (carriers) to cover the demand of energy are referred to as "energy costs". So, the energy costs represent a financial target measure to assess the energy consumption based on the amount of final energy acquired. However, in factory planning projects, the economic appraisal of energy efficiency measures should take into account not only the energy consumption but also the related effects on the internal energy supply system (e.g. lower dimension of facilities for energy transformation and distribution). Therefore, the term "energy-related costs" is used in this paper rather than the term "energy costs". Following [25], this is to express, that besides the costs for the acquisition of energy, the costs for its internal transport, transformation, storage and re-utilization are considered as well.

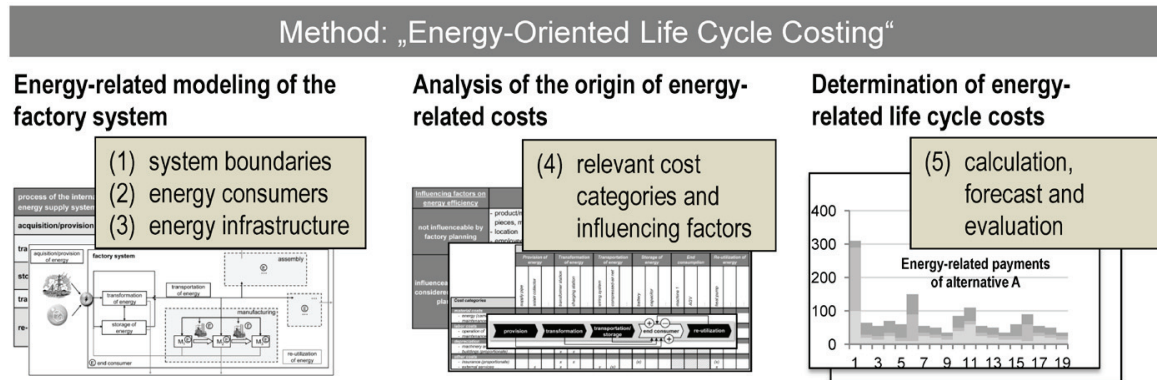
To determine these costs, the procedure model illustrated in Figure 2 was developed. The basic steps of this procedure will be explained in the following and refer to the:<sup>3</sup>

- (1) Definition of System Boundaries
- (2) Determination of Energy Consumers and Energy Demand
- (3) Analysis of Energy Infrastructure
- (4) Identification of Relevant Cost Categories

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<sup>3</sup> Please note, that in principle this procedure model is similar to the generic one presented in [20], where different levels of models to determine the overall life cycle costs of a factory are described. Particularly focussing on the origin of energy-related life cycle costs, the explanations given in this paper take a closer look at a specific category of sub models of the generic model in [20]. For a more detailed description of the development of sub models and their interactions see [20] as well as [26].

## (5) Calculation of Energy-Related Life Cycle Costs and Evaluation of Alternatives.



**Figure 2:** Overview of the Procedure Model of “Energy-Oriented Life Cycle Costing”

### 3.2.2 Definition of System Boundaries

The purpose of this initial step is to specify the scope of planning and the subject matter. To structure the factory system in an appropriate manner and to systematically cover all the objects that have to be planned, factory planning literature provides diverse approaches, such as the hierarchical and the peripheral order, which are used most commonly. Based on the super- and subordination of systems and system elements, the hierarchical order subdivides the manufacturing plant into divisions, sections, workstation groups and single workstations. The peripheral order defines the subsystems of a factory by their functional relation (directly connected or not) to the manufacturing program and/or the main processes (manufacturing and assembly) [27]. So, with the help of these structuring approaches it is possible to define the system boundaries precisely according to the parts of the factory that have to be considered in the particular planning case and the specific objects whose (energy-related) life cycle costs probably are affected.

What should be kept in mind when defining the system boundaries is, that these have to be similar for all alternatives in order to ensure the comparability of the subsequently calculated (energy-related) life cycle costs. Furthermore, to narrow the effort for cost estimation when comparing several alternatives, the scope should preferably contain the objects or elements whose costs actually differ.

### 3.2.3 Determination of Energy Consumers and Energy Demand

The determination of energy consumers and their energy demand is one essential basis to estimate the energy-related life cycle costs. In this paper, the term “energy consumer” refers to all technical elements within a factory that can be understood as end consumers using energy solely to generate products and services related to the actual purpose of production and the final goods. Besides the operating facilities



of production areas, this also includes logistic equipment (e.g. conveyors) as well as building services (e.g. lighting).

In order to determine the energy-related life cycle costs of these end consumers, an estimation of their energy demand is required. In this regard, operating time and conditions – expected according to the manufacturing program – and resulting load profiles form a starting point to estimate the energy demand approximately.

### 3.2.4 Analysis of Energy Infrastructure

Within this step, each facility of the energy supply system (for provision, transportation, transformation, storage and re-utilization of energy) that is required for the operation of a particular energy consumer (determined according to section 3.2.3), has to be identified and analyzed. On the one hand, this is to estimate the total amount of energy needed by the planning alternative under consideration. On the other hand, this contributes to reveal differences in the configuration of the energy supply system, which are caused by specific planning alternatives and have to be considered adequately concerning their impacts on costs. Additionally, the analysis of the energy infrastructure facilitates detecting potentials for energy recovery and re-utilization, which also should be assigned to particular planning alternatives and energy consumers.

Hence, the proportional usage of energy infrastructure elements has to be determined for each end consumer. Based on that, also the costs caused by the facilities of the energy supply system subsequently can be allocated to the end consumers, to estimate the energy-related costs of the particular planning alternative (see Figure 3).

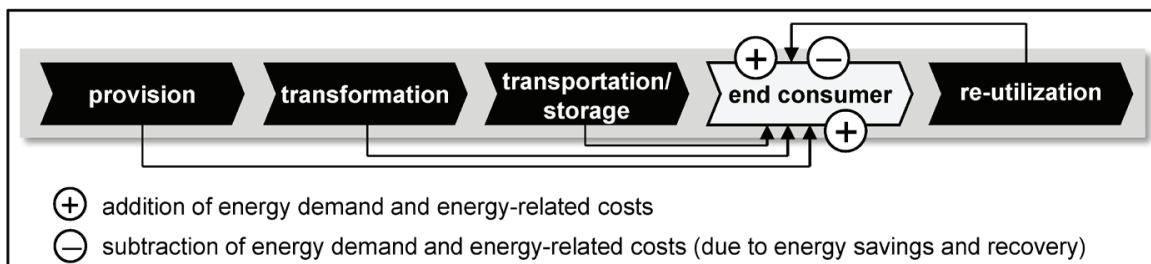


Figure 3: Allocation of Energy Demand and Energy-Related Costs

### 3.2.5 Identification of Relevant Cost Categories

For the identification of relevant cost categories, the classification of planning objects in energy consumers and energy infrastructure (see sections 3.2.3 and 3.2.4) is kept. According to the basic understanding of energy-related costs (see section 3.2.1), this facilitates clarifying the origin of all costs caused by the use of energy.

As shown in Table 1, only the costs of energy consumption are regarded for all machinery and equipment that can be considered as end consumers. So far, this

view matches the common cost category of energy costs. But, in order to determine all energy-related costs, the costs caused by the facilities whose functions are directed towards the provision, transformation, transportation or re-utilization of energy have to be captured as well. The consideration of these elements and of the related cost categories exceeds the immanent energy costs and takes into account further cost categories – for instance referring to costs for:

- the acquisition of facilities belonging to the internal energy supply system
- the labour to operate these facilities
- the maintenance of these facilities or
- their proportional usage of space (e.g. rent, building insurance).

Additional cost categories and cost breakdown structures, which might be relevant as well, are outlined in [23-25, 28, 29]. However one should pay attention that there is a relation between the cost categories considered and the specific elements to which they are assigned in each case.

**Table 1:** Structure of Energy-Related Life Cycle Costs

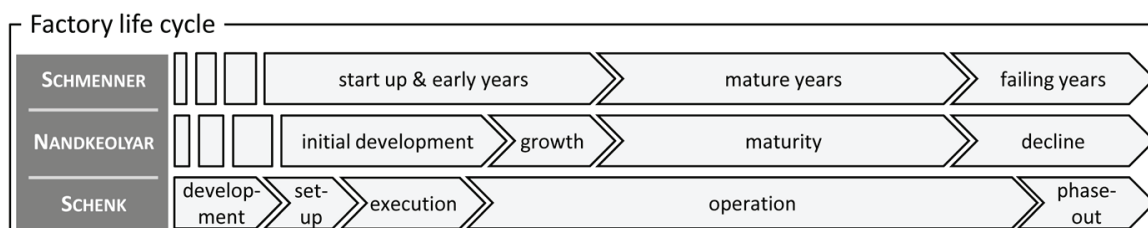
<b>Cost category</b>	<b>Energy supply system</b>	<b>End consumers</b>
<b>material costs</b>		
- energy (carriers)	x	x
- maintenance ...	x	
<b>labour costs</b>		
- operation of facilities	x	
- maintenance ...	x	
<b>depreciation</b>		
- machinery and equipment	x	
- buildings (proportionate)...	x	
<b>other costs</b>		
- insurance (proportionate)	x	
- external services ...	x	

### 3.2.6 Calculation of Energy-Related Life Cycle Costs and Evaluation of Alternatives

The basis of calculating energy-related life cycle costs is to determine the period under consideration and to subdivide it into relevant phases and time segments. This is required to assign the various costs and cost categories caused by a specific object to the point in time at which they presumably occur.

To structure the life cycle, general life cycle models – such as exemplarily shown for the factory (see Figure 4) – form a starting point. A further differentiation of the factory life cycle can be realized by regarding the life cycles of products and processes [21, 30]. They determine the configuration and equipment of the factory for specific periods within the factory life cycle and consist of characteristic phases themselves. Beyond that, a supplementary specification of life cycle phases – for

instance on an annual basis – should be aspired in order to achieve traceable and meaningful forecasting results.



**Figure 4:** Phases of the Factory Life Cycle (according to [14, 27, 31])

Please note, that in any planning case, the definition of the period under consideration and its subdivision has to be reasonable according to:

- the intended existence of the planning project and
- the available information (type, amount, quality) about future events (e.g. development of new technologies, changes in product range) respectively the economic effort to gather them.

Once the period under consideration is defined and all cost categories are assigned to specific objects and points in time, the particular costs have to be calculated. For this purpose, some assistance can be found in specific algorithms and formulas provided for several cost categories, for instance in [24].<sup>4</sup> To calculate the energy costs or rather the energy-related life cycle costs based on those formulas, a lot of information is required – among others referring to:

- use scenarios for the machinery and equipment (e.g. operating conditions and associated energy consumption),
- characteristics of machinery and equipment (e.g. wear behaviour, breakdown susceptibility),
- type and value of influencing factors, their interactions and cost impacts,
- the development of these aspects over time.

However, concerning the factory as a whole, such data are hardly available. Therefore, suitable methods for cost estimation, which work on higher levels of aggregation and do not necessarily need all data mentioned above, are essential – particularly for early planning phases which offer the most options to influence the cost. It can be stated that apart from building projects (in this regard, some advice can be found for example in [28]) there is a lack of such methods specified to factory planning and related long-term decisions. To resolve this deficit, the application and modification of the methods of product-oriented development-concurrent cost calculation and estimation [32] is recommended here as follows:

<sup>4</sup> The cost categories and formulas listed in [24] refer to machinery and equipment in general and are ordered by the life cycle phases (acquisition, utilization, elimination) at which the costs accrue.

- *Cost estimation by domain experts:* Such methods provide access to a wide range of expert knowledge (based on different experiences in actual planning projects) with relatively little effort. However, the traceability of the achieved results might be difficult, since these are affected by subjectivity. Therefore, the application of such methods seems to be useful primarily to estimate the general feasibility of a planning project and/or for time-critical projects with low investment volume. In order to expand the field of application, further bundling of expert knowledge might contribute to raise the objectivity and the accuracy of estimate.
- *Methods based on analogy and similarity:* These methods could be applicable for projects that refer to the construction or reconfiguration of similar factories at different locations (e.g. at international locations of an automotive manufacturer). To adequately use them in the context of energy efficiency-oriented factory planning, specific (energy-related) measures to determine the similarity of factories and their subsystems have to be developed.
- *Cost functions:* They are used to describe the behaviour of costs in dependency of a particular activity or of an influencing factor by means of statistical analysis or analytical relationships. Among others, cost functions might be applied for installation engineering to determine the energy costs based on consumption functions. However, in the context of factory planning, this requires methods for the determination of technical, physical and economic dependencies between relevant influencing factors and emerging costs.
- *Methods based on key-figures:* Such methods are already applied in building projects (e.g. using cost key-figures such as €/cbm) [28] and could also be transferred to the estimation of energy-related life cycle costs. For this purpose, specific reference parameters (e.g. area (sq m), quantity (pc.)) which describe factories, their subsystems and elements, and ensure the comparability of energy cost-related key-figures, have to be identified.

Based on the calculation or estimation of the energy-related life cycle costs, different planning solutions can be evaluated. For this purpose, the methods of investment appraisal are applied (see section 2.1). With regard to the consideration of effects dependent on time, there is a distinction of static and dynamic methods.

Due to the ease of use, the *static methods* of investment appraisal are frequently preferred in practice. Since these methods are based on simplified assumptions about representative average periods, they neglect differences in the timing of costs and related effects (e.g. interest, compound interest). Thus, the development of financial target measures over time is represented less realistic and the economic efficiency of energy-efficient alternatives might therefore be misjudged [10].

This deficit is met by the *dynamic methods* of investment appraisal. In contrast to static methods, they explicitly take into account several periods and typically work with payments (that are assigned to specific points in time).<sup>5</sup> Being based on the fundamentals of financial mathematics, they also contribute to an adequate consideration of interest and compound interest. Thus, the value resulting from long-term energy and associated cost savings is regarded accurately in this respect. Therefore, the dynamic methods of investment appraisal – particularly the net present value method – are recommended here to evaluate energy-efficient planning solutions. The “net present value” (NPV) represents the value of all future (energy-related) revenues diminished by the costs and discounted to the beginning of the planning period ( $t=0$ ), when investment decisions have to be made. For the determined period under consideration, the NPV of the energy-related life cycle costs (and revenues, which also may be relevant) can be expressed as follows [10]:

$$NPV = \sum_{t=0}^T (eR_t - eC_t) \cdot q^{-t} \quad (1)$$

with:

$t$  = time index

$eR_t$  = energy-related revenues

$T$  = last point in time when costs/revenues take place

$q^{-t}$  = discounting factor  
(where  $q = 1 + i$ )

$eC_t$  = energy-related costs

$i$  = rate of return

This value is typically negative, since the costs dominate the revenues and it should be tried to minimise the absolute value. In order to control the stability of the calculated NPV towards influences, additional sensitivity analyses are required within a comprehensive evaluation of planning solutions. Since estimation and forecast of costs inevitably are accompanied by uncertainties, sensitivity analyses are suitable for detecting the associated consequences. Besides, critical influencing factors, which might cause that the advantage of a particular planning solution goes into reverse, can be identified with the help of such analyses.

The applicability of the presented approach and the calculation of particular elements of the energy-related life cycle costs will be illustrated in the following case example. This refers to a significant period of the factory life cycle and the future costs which are determined by configuration decisions for the intralogistics.

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<sup>5</sup> Please note that, although payments have to be regarded to assess the (energy-related) life cycle costs by means of the dynamic methods and the NPV, the terms costs and revenues are synonymously used in the following due to reasons of simplification and the application in practice.

## **4 Case Example Material Supply Process**

### **4.1 Material Supply Process in the Experimental and Digital Factory**

A material supply process in the Experimental and Digital Factory of the Department of Factory Planning and Factory Management was chosen as case example. At first, the defined material supply process is analysed by a state-of-the-art method. Afterwards, the presented approach “Energy-oriented Life Cycle Costing” is performed in extracts to demonstrate its potentials for the economic evaluation of energy-efficient planning and operation alternatives. The focus of the case example is to demonstrate this approach rather than providing the calculated values. Finally, the results are compared and advantages are summarised.

The defined transport task in the Experimental and Digital Factory is to convey small load carriers from a warehouse to an assembly line in a defined quantity and time. Transports by a towing tractor and by an automated guided vehicle (AGV) are the alternatives to be compared. The material transfer is not considered in this example. The investigation was performed basing on experiences of former studies in industry [33].

### **4.2 State of the Art of the Economic Evaluation of Industrial Trucks**

Since the general methods of investment appraisal are not focused on a special application field, the VDI 2695 guideline “Calculation of operating cost for diesel and electrical fork-lift trucks” is used as approach tailored to the field of intralogistics [34]. This can be considered as a state-of-the-art method. Although the considered conveyors are not fork-lift trucks, the analysis is performed following the VDI 2695, because the cost categories are similar.

The cost calculation bases on static methods of investment appraisal and considers fixed and operations-dependent costs. The fixed costs contain depreciation and interests and the operations-dependent costs contain maintenance and energy costs.

The investments for towing tractor and AGV (including battery and battery charger) are estimated basing on market data. The empirical values of VDI 2695 are used for the rate of depreciation and the costs for maintenance<sup>6</sup>. The energy costs are calculated by multiplying the energy requirements (derived from battery voltage and

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<sup>6</sup> The linear depreciation rates are 12.5 % for the vehicle, 20 % for the battery and 10 % for the battery charger (each of the acquisition costs). The annual maintenance costs are calculated with 10 % of the acquisition costs of the vehicle.



capacity) with a fixed energy cost rate (0.097 €/kWh in this case example according to [35]).

As result, the total costs per hour of operation are calculated as sum of fixed and operations-dependent costs. According to this calculation, the towing tractor has total costs of 2.66 €/h, whereas the AGV has total costs of 3.89 €/h.<sup>7</sup> Therefore, the towing tractor is relatively profitable. Since the acquisition costs for AGV are higher than the one for towing tractor, only considering the acquisition costs as objective leads to the same decision.

### 4.3 Application of the Approach „Energy-Oriented Life Cycle Costing“

#### *Definition of System Boundaries*

The system boundaries were already defined in the presentation of the case example. The considered system contains the conveyors realising a material supply process. According to the hierarchical order of a factory, both systems are considered as single work stations. They can be assigned to the first periphery using the peripheral order of a factory.

#### *Determination of Energy Consumers and Energy Demand*

The energy consumers are the towing tractor and the AGV. Both need electrical energy for operation. The energy demand is estimated with the help of a cycle time and the related energy consumption of each alternative, which were measured on the real objects in the Experimental and Digital Factory.

#### *Analysis of Energy Infrastructure*

The energy supply of the industrial trucks is realised with lead batteries, which need a battery charger. The electrical energy for the battery charger is provided by the supply network. It is assumed that the alternatives do not differ regarding the structure of their energy infrastructure. The different costs for battery and battery charger applied are the same as in section 4.2.

#### *Identification of Relevant Cost Categories*

The relevant cost categories are acquisition, energy and maintenance costs. Considering these cost categories, the calculation is comparable to the one following VDI 2695 (see section 4.2). The objective “life cycle costs” is analysed in a continu-

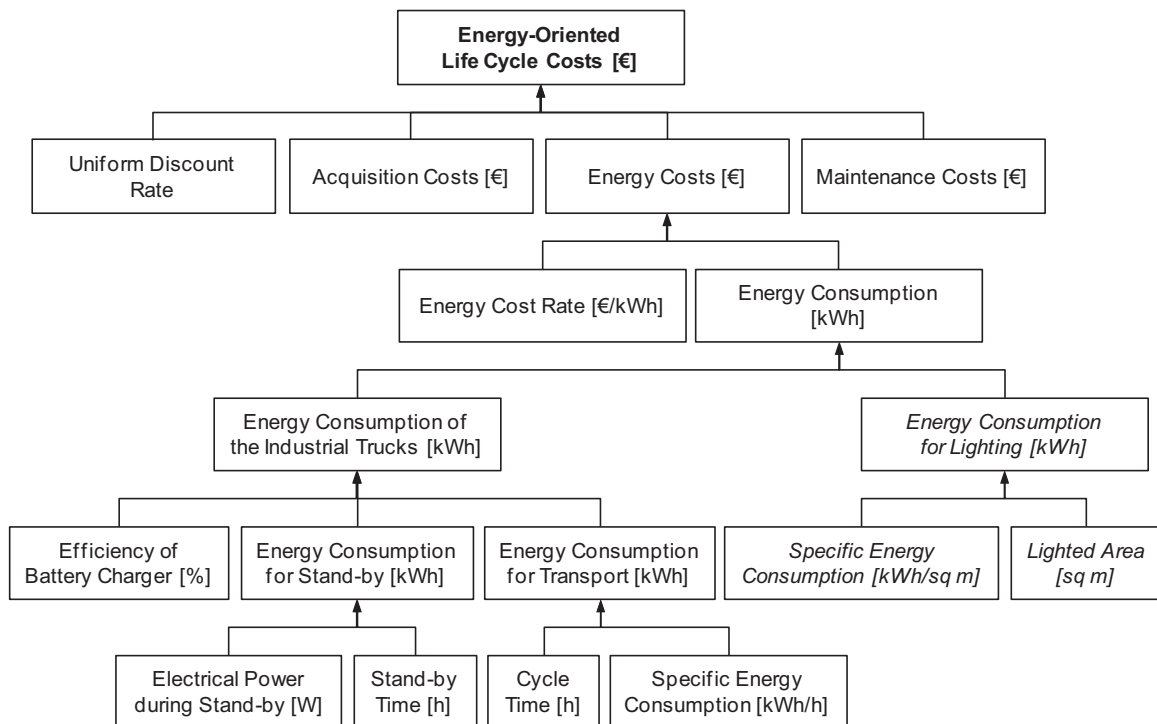
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<sup>7</sup> The total costs of both alternatives are only around half of the example values in VDI 2695 because of the lower acquisition costs for towing tractor or AGV compared to fork-lift trucks.

ous refinement in order to identify the influencing variables, whose values are necessary for the calculation (Figure 5).<sup>8</sup>

#### *Calculation of Energy-Related Life Cycle Costs and Evaluation of Alternatives*

First of all, the life cycle of the industrial trucks is divided into three phases: the acquisition phase, the utilization phase and the elimination phase. The planning period is set at five years. The investment (including battery and charger) incurs in the acquisition phase. There is a residual value assumed in the elimination phase. In the utilization phase, the maintenance costs from the VDI 2695 calculation are used. The energy costs are calculated by multiplying the energy cost rate with the energy requirements derived from measurements (see Figure 5). According to this calculation, the towing tractor is relatively profitable with a net present value of -13,900 € compared to a net present value of the AGV of -21,400 €.



**Figure 5:** Selected Influencing Variables on the Energy-Oriented Life Cycle Costs (Case Example)

#### *Extension I – Indirect Energy Consumers*

The presented calculation only included the industrial trucks as direct energy consumers. But in addition, indirect energy consumption is caused in the overall factory system [36]. The considered alternatives differ regarding the environmental conditions that need to be ensured, because the AGV does not need lighting in the ware-

<sup>8</sup> The different effects of the alternatives on logistical objectives are not further regarded. For example, the number of supplied assembly lines needs to be considered in practice, which is neglected here due to the purpose of the case example.

house area. This aspect is integrated with the help of key-figures. The reduced lighted area is assessed with an average energy consumption coefficient of 200 kWh/sq m (see the italic words in Figure 5). Then, the AGV is relatively profitable with a net present value of -28,400 € compared to a net present value of the towing tractor of -30,900 €.

Reducing the direct energy consumption of industrial trucks can also have an effect on replacement batteries or battery charging stations. Because the latter usually need ventilation, this again can influence the indirect energy consumption. These effects also need to be assigned to the considered alternatives in principle, but there is no ventilation required in the case example.

#### *Extension II – Data Acquisition in Planning Situations*

Measured values, which are used for the presented calculation, are costly to determine and in some situations (e.g. new systems) even impossible to determine by oneself. The VDI 2695 follows an empirical method for evaluating energy costs (see section 4.2). Another possibility is to use information about energy consumption that is provided by the manufacturer. Many manufacturers of industrial trucks structure their data sheets according to the VDI guideline 2198, which includes the energy or fuel consumption in a defined VDI cycle [37].

The manufacturer of the AGV provides a spreadsheet, with which the consumption power can be calculated. The basic values (current depending on speed and mass) are only given for a basic configuration. For another one of the many possible configurations, these values need to be measured by the customer.

Using the data of the manufacturer, the alternative with towing tractor is relatively profitable with a net present value of -14,500 € compared to a net present value of the AGV of -21,400 €. When the indirect energy consumption is integrated in this calculation, the AGV gets in turn relatively profitable (difference in net present value of 3,100 €). A summary of the results is shown in Table 2.

**Table 2:** Summary of the Results by Applying the Approach “Energy-Oriented Life Cycle Costing”

	<b>Alternative I – Towing Tractor Net Present Value</b>	<b>Alternative II – AGV Net Present Value</b>	<b>Difference of Net Pre- sent Values</b>	<b>Relatively Profitable Al- ternative</b>
<i>Basic Case (energy costs only for direct consump- tion of industrial trucks)</i>	- 13,900 €	- 21,400 €	7,500 €	<i>Towing Tractor</i>
<i>Extension I (energy costs ex- tended to the indi- rect consumption of lighting)</i>	-30,900 €	- 28,400 €	-2,500 €	AGV

<i>Extension II (evaluation of the energy costs by use of data from the manufacturer)</i>	-14,500 €	-21,400 €	6,900 €	<i>Towing Tractor</i>
<i>Extension I + II (direct consumption evaluated by data from the manufacturer and extension to indirect consumption)</i>	-31,500 €	-28,400 €	-3,100 €	<i>AGV</i>

### *Sensitivity Analysis*

Because of the uncertainty of some of the input parameters, a sensitivity analysis was performed afterwards. The uncertain parameters are especially the energy price, the uniform discount rate as well as the energy consumption of the industrial trucks and the lighting.

There are two possible questions for a sensitivity analysis [10]: How does the objective value change when input parameters are varied? And what values may the input parameters have in order to reach a defined objective value?

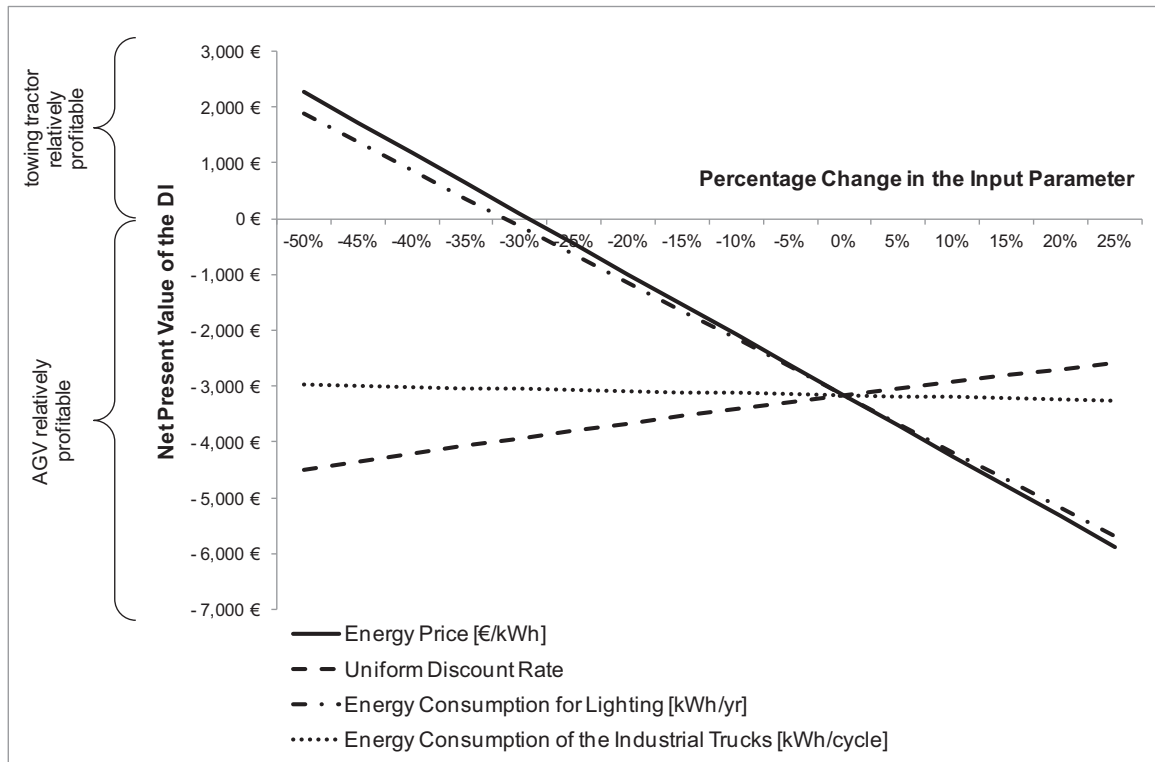
The first question is analysed to detect the most important parameters (in the sense of the highest influence in this example). The basis are the values from Extension I + II, which means that the data of the manufacturer is taken as information source and the indirect energy consumption of lighting is integrated.

The concept of the “difference investment” (DI) is used for this investigation. The cash flows of both alternatives are subtracted to obtain the cash flow of the DI. Then, the investment decision is made as follows: If the net present value of the DI is positive, the first alternative is relatively profitable and vice versa. The net present value of the DI is calculated depending on the percentage change in the input parameters (see Figure 6).

Accordingly, the most important parameters are energy price and energy consumption of lighting. Considering the energy price, the profitability between both alternatives would only change when the price decreases. Since this is not considered as possible scenario, only the energy consumption of lighting is analysed in more detail, referring to the second question mentioned above. This parameter is composed of the specific energy consumption as well as the lighted area. The critical values that lead to a net present value of the DI of zero are calculated with 140 kWh/sq m and 90 sq m less lighted area in the alternative AGV<sup>9</sup>. This means, if the specific

<sup>9</sup> The critical value refers to the value, up to that a parameter can be varied without affecting the profitability between the compared alternatives. The net present value of the difference investment

energy consumption or the saved lighted area decreases to the mentioned value, the alternative with towing tractor gets relatively profitable compared to the alternative with AGV. Because the specific energy consumption of lighting is calculated very roughly, this is a variable that would need a more detailed analysis. For example, another possibility lies in a workplace lighting, which would also reduce the energy consumption of lighting.



**Figure 6:** Net Present Value of the Difference Investment (DI) in Dependence of the Percentage Change in Input Parameters

#### 4.4 Comparison of the Approaches

The case example has shown that the approach “Energy-Oriented Life Cycle Costing” provides varied possibilities for evaluation. Especially the definition of the system boundaries has a great influence on the result of the analysis. As the evaluation of the effects on the overall system (e.g. lighting or energy infrastructure) is crucial in the factory planning context, this is a main advantage of the presented approach.

Additionally, the approach bases on the dynamic methods of investment appraisal and has therefore some advantages compared to the static methods. A static approach (like presented in section 4.2) considers only an average period, while dy-

becomes zero, when the profitability changes between the alternatives. In the investigation performed here, the parameter was varied *ceteris paribus*.

dynamic methods consider the cost structure over the entire planning period (see section 3.2.6).

A challenge in the application of the presented approach is the data acquisition, which is a general problem for investment appraisal. It is difficult to receive detailed data for the energy consumption of a system, when there is no possibility to measure. The presented approach to use data of the manufacturer is suitable in the area of intralogistics, but may be more difficult in other areas. At least, there is a development leading to more information and standardisation considering energy information (e.g. energy labels in industry [38]).

## **5 Conclusion**

In this paper, a life cycle costing approach specified to the demands of energy efficiency-oriented factory planning was presented and applied to a case example in the field of intralogistics. Based upon the net present value method and a broad comprehension of “energy costs”, the approach aims to meet deficits in the current practice of assessing energy efficiency measures mainly based on acquisition costs and therefore misjudging the related costs over the life cycle.

In order to make the approach applicable in all stages of factory planning, a major challenge still can be seen in the estimation of costs accruing over the life cycle. In this regard, the methods of product-oriented development-concurrent cost calculation and estimation form an essential starting point and can be suitable for different cases in energy efficiency-oriented factory planning. However, to exploit the potential of these methods, further research is required with respect to their case-related modification.

Besides, the realistic forecast of (energy-related) life cycle costs in general requires a lot of information, such as object-related influencing factors, their interactions and cost impacts. A comprehensive and assured basis of such information – especially concerning life time considerations of the factory as a whole – hardly exists. Therefore, concepts for factory-cost-related knowledge management should be developed, including structures to systematically gather (energy-related cost) information as well as adequate measures to control the (energy-related) life cycle costs.



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