Identification of Energy Efficiency Measures during Factory Planning Processes

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Abstract—**Due to several reasons, the importance of energy efficiency as objective for industrial companies has been rising for several years. So far, the existing methods to analyze energy efficiency and optimize processes and systems need detailed quantitative insights of the considered objects as input information (e.g. measured energy consumption data). Therefore, the applicability of these methods during factory planning processes is limited due to the high effort to acquire the necessary data.**

A new methodical approach was developed to identify energy efficiency measures in factory planning processes. The goal is to provide a manageable and transparent approach to effectively identify proper energy efficiency measures with low effort for data acquisition. Industrial enterprises currently struggle to implement energy efficiency holistically because of deficits in know-how and lacking time. The systematic identification of energy efficiency measures is based on the qualitative description of a factory planning task. Based on that, proper energy efficiency measures are identified and additional content regarding the implementation of these measures is provided.

In the paper, the overall methodical approach is described based on the components of a qualitative model. A use case demonstrates functionality and applicability of the method.

Keywords—factory planning; operations management; energy efficiency; energy management

I. INTRODUCTION

Energy efficiency is becoming an important objective for industrial enterprises in view of ecological and economic developments. Global greenhouse gas emissions are steadily increasing since the late 19th century. Industry causes a 20 % share of global carbon dioxide emissions and additionally accounts for 18 % due to electricity and heat generation [1]. Prices for energy are rising. For example, European industry faced an annual increase of 3.5 % in electricity prices between 2008 and 2012 [2]. Therefore, energy consumption in industrial enterprises needs to be reduced. During the last few years, several methods and tools for increasing energy efficiency have been developed. Yet, there are barriers for their adaptation. These include lack of information, lack of time and the assignment of responsibilities within the structural organization [3].

Against this background, this paper suggests a method that addresses the aforementioned barriers by providing information on energy efficiency measures while reducing the effort for the method's application. The method is based on a qualitative model of the initial situation which includes a description of the relevant objects and actors within the enterprise. The qualitative description allows the application in factory planning processes, which are characterized by limited information on the planning objects.

The remainder of the paper is organized as follows: Section 2 describes basics about factory systems and factory planning processes in order to explain the background and derive methodical requirements. Afterwards, the state of the art regarding methods and tools to support energy efficiency in factory planning processes is presented. The developed method is explained in section 4 and illustrated by a use case in section 5. The method and its application are discussed in section 6. Finally, section 7 summarizes the results and gives an outlook on further research.

II. FACTORY SYSTEMS AND FACTORY PLANNING PROCESSES

A. *Factory as a system*

The theoretical basis to describe factories is the system theory. A system may be defined as an entity of elements that have specific characteristics and relations among each other [4]. The decision whether an element belongs to a system or not is made by the strength of the relation to other elements, i.e. the interdependences within a system are stronger than between a system and its environment [5]. The system follows a purpose, i.e. the elements and their relations are arranged in order to conduct a certain behavior. In technical systems such as factories, the purpose is to transform the system input (e.g. material) into system output (e.g. products). An important approach of system theory is to consider hierarchical structures within a system: From this perspective, a set of elements within a system may be considered as a subsystem.

The elements within the factory system are the production factors equipment, material and personnel [6]. The equipment contains the technical systems, such as machinery and other devices. Material comprises the raw material that is used to manufacture a product and auxiliary material that does not enter the product (e.g. lubricants). The personnel fulfills (production) tasks by using the equipment. Relations and processes describe the connection of elements within the factory system [7]. They may be characterized as information, material, energy, capital and personnel flows [6]. Systems may be modelled from a functional, structural or hierarchical perspective [8]. The functional perspective only describes the input to and output from a system ("black box"), whereas the structural model considers the internal structure, i.e. the elements and their relations within a system ("white box"). The hierarchical model addresses the hierarchical relations between system elements. For example, the functional model of a manufacturing line may describe the relation between the amount of input material and final product as well as the energy that is required to perform the manufacturing task. A structural model in this case describes the machines as elements within the manufacturing line and their interrelationships in terms of material and information. The hierarchical model explains the hierarchical structure of the components, e.g. the machines as part of the line and single components (e.g. drives) as parts of a machine.

B. Factory planning tasks and processes

Factory planning is defined as the systematic process to plan a factory and encompasses tasks, beginning with the definition of objectives until the start of production [9]. This may relate to all planning functions that refer to the production system or, in a broader perspective, include the selection of the factory location and external logistics. The main tasks that refer to the production system cover planning the building (e.g. building structure), production processes (e.g. manufacturing equipment), peripheral processes (e.g. media supply), logistics and personnel [10, 11]. These tasks are structured by means of process models that describe sequential planning phases. This model simplifies actual planning projects since tasks may overlap and/or be realized in an iterative manner in practice.

The VDI guideline on factory planning describes the following planning phases [9]: During the *setting of objectives*, the planning task is detailed and the structure for the planning project is defined. This includes the analysis of objectives and constraints in order to deduce the evaluation criteria, which are used later on to assess the planning alternatives. The *establishment of the project basis* acquires necessary information for the subsequent planning tasks (e.g. product data, production data). The following *concept planning* aims at conceiving the factory as a totality. This includes the planning steps structure planning, dimensioning, ideal planning and real planning. Structure planning means to structure the processes and systems resulting in an ideal function scheme. The task of dimensioning is to define quantitative values (e.g. capacities, areas, amount of equipment resources). Ideal planning is used for the spatial and temporal assignment of the dimensioned units without considering restrictions. These restrictions are integrated during the real planning (e.g. orientation of existing buildings). The conceived solution variants during this phase are evaluated against the criteria that were defined initially. Hence, the result of concept planning is an evaluated preferred variant. Within the *detail planning*, the selected concept is planned out. This means to design the factory elements to a more fine level of detail, prepare approval applications and specifications of products and services which are required for the factory. During the *preparation for realization*, contracts for products and services are concluded and the realization of the factory is planned (e.g. construction site, relocation of production resources, personnel development). The subsequent *realization monitoring* aims at securing the proper implementation (e.g. coordination and documentation tasks). This is followed by the *ramp-up support*, during which the factory is put into operation. Finally, the *project close-out* includes the evaluation of the planning project and the documentation of knowledge.

III. STATE OF THE ART OF ENERGY EFFICIENCY IN FACTORY PLANNING

It is a well-known fact that there is a high influence on a factory's energy consumption during planning processes since these create the framework for later operation [12]. Thus, concepts to integrate energy efficiency in factory planning processes have been developed within the last years. For example, CHEN postulates the concept of sustainability in factory planning and presents the interdependence of factory system elements and sustainability aspects [13]. However, meta-concepts like this do not provide methodical support to identify energy efficiency measures within a factory planning project.

In general, tools to support energy efficiency-oriented factory planning and management can be divided into energy efficiency guidelines, principles and methods [14]: Guidelines provide an overview on energy efficiency measures within a specific industrial sector or a specific field of application (e.g. lighting). Energy efficiency principles contain a collection of a small number of general approaches to increase energy efficiency. Energy efficiency methods describe a systematic approach on the identification and realization of energy efficiency improvement opportunities. A selection on energy efficiency methods is described in the following.

ENGELMANN and MÜLLER developed the energy efficiency-oriented factory planning process which describes how to integrate activities considering energy efficiency in several planning phases [15, 16]. The identification of measures is supported by means of a collection of general guiding principles (e.g. increase efficiency factor of equipment). This tool may assist as a checklist to identify measures. However, in a certain use case, it needs to be transferred from a general level to the concrete application which requires expert knowledge. F. Müller et al. developed a concept for green factory planning that contains methods and tools in order to support the "green" objective in planning processes [17]. This concept aims at generating green planning modules for supporting planning tasks. However, the concept focuses on a general level and does not describe an approach to identify action approaches during factory planning. Hopf developed a method for modeling factory systems considering the objectives energy and resource efficiency [18]. It is mainly based on a qualitative model of the function, structure, hierarchy and life cycle of a factory and may be further extended by quantitative information if available. The main purpose is to create transparency on the energy flows within a factory system. Again, identifying improvement potentials is only supported by a collection of general guiding principles.

A different approach to consider energy efficiency during planning steps can be found in simulation studies. The purpose of simulation is to forecast the energy consumption of a system in different scenarios in order to evaluate the savings effect of improvement measures. Wolff describes the goals and procedure of simulating energy consumption of manufacturing systems [19]. However, information on the power load in different operational states of the machine is necessary. If these values cannot be measured, they need to be estimated using nominal power values or manufacturer specifications. An integrated methodology for planning and optimizing the energy consumption in factories is suggested by Haag [20]. Yet, the quantitative model is based on data sources such as field data or expert knowledge.

Reviewing the state of the art shows that there is a gap between meta-concepts for the general factory planning process and detailed methods for identifying improvement measures. The latter ones mainly follow the scheme of a quantitative analysis in order to create transparency and prioritize the equipment in terms of energy consumption. However, these approaches require data on energy consumption which might not be available during early planning phases. Furthermore, a focus on manufacturing processes can be recognized although a holistic perspective on a factory's energy consumption is necessary for long-term improvements. Therefore, a methodical approach for reducing energy consumption in the entire factory system without the need to collect energy data through measurements is required.

IV. Method to Identify Energy Efficiency Measures during Factory Planning Processes

A. Methodical framework

The method aims at supporting factory planning participants in identifying energy efficiency measures during planning processes [14, 21]. The procedure model for the method's application is presented in Figure 1. The first step is to analyze the situation. This includes a description of the factory system as well as the definition of project characteristics. The factory system is regarded as a socio-technical system, i.e. it is represented by technical and social components. The *object system* contains the relevant technical resources of the factory system that is addressed by the energy efficiency project (e.g. machine tool, manufacturing area). It is furthermore characterized by its *energy efficiency influential parameters*, i.e. parameters that influence the energy consumption.

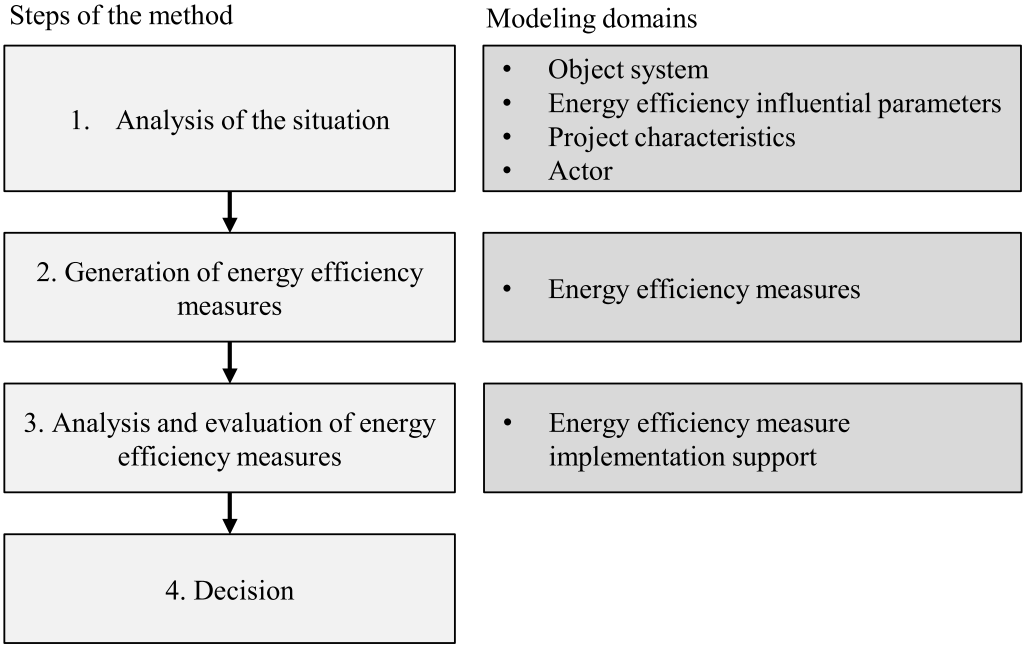

Fig. 1. Procedure model of the method and applied modeling domains

The *project characteristics* consider the frame conditions for realizing the energy efficiency project that may be limited by the enterprise (e.g. costs). This also includes the description of the planning situation, for example whether it is a greenfield or brownfield project. The *actor* fulfills one or more roles towards the object system and thus, may influence the energy consumption (e.g. a building service engineer defines the requirements for the heating system, which influences the heating energy demand).

The results of the first step are qualitative models of the modeling domains object system, energy efficiency influential parameters, project characteristics and actor. Based on this information, *energy efficiency measures* are deduced in the second step. A prerequisite to perform this task is to describe the measures in a structured manner. Afterwards, the measures may be analyzed and evaluated qualitatively by using additional information on the measures' implementation (*measure implementation support*). Finally, the planning participants may decide to realize a selection of energy efficiency measures. In the following, the required modeling domains are described in more detail.

B. Object system

As introduced above, factories may be represented as systems by modeling their hierarchy, function and structure. From a hierarchical perspective, the following levels can be distinguished [9, 22]: The *factory* represents the entire production site which may include several buildings and additional outside areas. The next level is the *building*. Within the building, the *divisions* production system, building services and process services exist [17]. The next hierarchical level is the *segment* that is composed of several *work centers*. Differentiating between segment and work center is made by the individual purpose of a work center (e.g. machine tool). Opposed to that, a segment contains work centers that are interlinked by a specific cause (e.g. spatially close to each other, connected by interlinked production processes). Finally, a *component* is part of a work center that does not fulfill a purpose in terms of the production system by itself (e.g. drive). The hierarchical model of the object system is presented in Figure 2a.

The function of an object system describes its task within the factory as well as the input and output in terms of energy. The functional tasks may be explained with reference to the product flow or energy flow: From a product perspective, the functions of factory systems are differentiated into technological factory systems, building systems and systems for supply and disposal [21]. When considering the energy flow, the function of a system may be either provision, generation, conversion, storage, transport, usage, recovery or emission of energy [24]. The input and output may be described in form of energy flows (e.g. electricity as input and exhaust heat as output). It should be noted that the energy function of a system might be different for each considered energy flow. For example, a pneumatic compressor uses electricity and generates compressed air, which means that the energy flow 'electricity' is connected to the function 'usage' and the flow 'compressed air' to the function 'generation'. A general functional model of the object system is presented in Figure 2b.

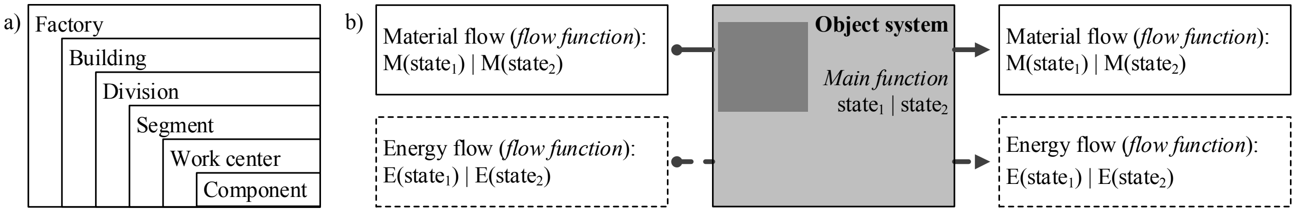

Fig. 2. Description of the domain object system: a) hierarchical model, b) functional model

C. Energy efficiency influential parameters

Since the goal of the methodical approach is to reduce a system's energy consumption, a model is required to describe variables that influence the energy consumption. Herein, this is understood as a qualitative description of parameters that influence the quantity of energy flows of a system. This definition aims at energy flows since it is not limited to energy consumption but may also consider other energy functions (e.g. generation). It should be noted that the quantitative effect is not considered within the model. For example, the energy consumption of a heating system is affected by the targeted room temperature, which is identified as an influential parameter. The quantification, i.e. how much energy can be saved by reducing room temperature, is not part of the model.

Usually, the energy consumption varies between different operational states of a system, e.g. whether it is in stand-by mode or processing. An operational state can be described by the states of the components (or subsystems) within a system. For example, the stand-by mode of a machine tool may be characterized by the spindle being switched off, whereas the control unit is switched on. Therefore, influential parameters may vary between operational states as well. Thus, the model considers both parameters that affect the total system energy consumption and parameters that influence the energy consumption within a specific operational state. The modeling of influential parameters is conducted by extending the model of the object system.

D. Project characteristics

Besides the description of the object system, an energy efficiency project is indicated by "soft" aspects, which are understood as project characteristics. These contain the ordering party, business value, project content, novelty, complexity, organization, project control, geography, size and project role [25]. The main distinguishing criterion to assign energy efficiency measures is the project size and may be expressed in terms of costs and time. The costs for an energy efficiency project include the initial expenditure (e.g. for new equipment) and transaction costs (e.g. for implementing new organizational processes) [26]. Regarding the project time, short-term, mid-term and long-term projects may be distinguished, whereas the differences are marked by the length of product and process cycles [4]. Additionally, factory planning projects are characterized by their planning phase or stage (see models of planning processes above). It is important to consider the possibilities to influence energy consumption which vary depending on the planning stage. For example, organizing the location of equipment within a factory in order to reduce the length of media pipes (e.g. for cooling water or compressed air) is possible within the planning step structuring.

E. Actor

The actor is an important aspect to describe a project since the influence of a user varies with his or her role within the object system (e.g. a machine operator has different influential opportunities than the process planner). This means, that the relevant roles need to be modeled for a use case. Following the system theory again, roles may be differentiated according to their function (e.g. manufacturing, maintenance) and hierarchy (e.g. worker, team leader). Due to diverse requirements, a factory planning project is usually performed in interdisciplinary teams [10].

Describing a role may contain the perspectives competences, tasks, permissions, organizational structure and behavior [27]. The influence on energy consumption within a factory is closely related to the tasks of a role. Therefore, the tasks and activities of a role need to be modeled. This serves as a basis to describe the influence of an actor on specific parameters within the energy consumption structure. For example, the setter of a machine tool defines the computer numerical control program and hence, has the main influence on the feed rate which is an influential parameter on the power load during operation. It should be noted that several actors may influence the same parameter, which means that a further differentiation is necessary. Therefore, the relations are classified into main influence, supportive influence and accountable, i.e. the role is liable for the realization (adapted from [27]). The structure for modeling the actor's influence is shown in Figure 4.

a)

Actor	Organizational unit	Task
A_1	…	…
A_2	…	…
A_3	…	…
…	…	…

b)

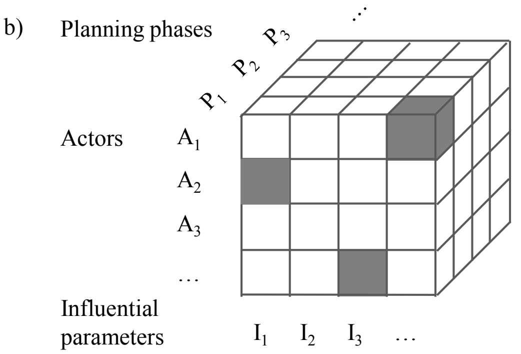

Fig. 4. Description of the domain actor: a) list of actors, b) influence of actors

F. Energy efficiency measures

An energy efficiency measure (EEM) is understood as an activity that leads to a measurable or assessable increase in energy efficiency [29]. It may be achieved by technological, behavioral or economic changes. Energy efficiency is defined as the ratio between a defined output and the energy input that is required to achieve the output [16]. In this context, increasing energy efficiency is understood as reducing the energy consumption while at least maintaining the output.

The task to assign EEM's to a factory planning project requires the characterization of measures by classifying criteria. As a first step, a literature review was performed to identify suitable classifying criteria [30]. Depending on their purpose, three groups of criteria can be distinguished: The first group, the identification criteria, are used to identify the fit between the planning situation and the EEM (e.g. application area). The second group, the assessment criteria, are used to evaluate the costs and benefit of EEMs and thus, to decide for their implementation (e.g. pay-back time). The third group, the implementation criteria, contain information to prepare the measure implementation (e.g. extent of changes). The matching algorithm between a factory planning project and EEMs requires quantifiable information. Therefore, identification criteria and quantitative parts of the assessment criteria may be used for this assignment. Since implementation criteria are represented as qualitative information, they are provided to the user separately, i.e. through the measure implementation support.

G. Energy efficiency measure implementation support

The purpose of assigning measure implementation support to the factory planning project is to provide additional information to support the realization of an EEM. This information should be tailored to the EEM and to the actor's role. For example, information categories, such as technical details or economic benefit may be distinguished. The structure of the measure implementation support has been published in [30].

V. USE CASE

After explaining the components of the qualitative model, on which the methodical approach is based, a fictive use case demonstrates basic functionality of the method. The use case addresses the implementation of new equipment for an internal transport process. In the initial situation, forklift trucks are used to transport large load carriers from a warehouse area to an assembly line. The planning project is targeted on the usage of automated guided vehicles (AGV) in order to reduce the personnel expenditures. When implementing this new process, energy efficiency should be considered as an objective. This means that the goal of the method's application is to identify appropriate measures for the new process with an AGV.

The first step to analyze the situation is to model the relevant object system (Figure 5). The object system AGV is assigned to the hierarchical level of a work center since it follows the individual purpose of material transport. It consists of several components, e.g. drive, control and the sensor system [31]. The function of the object belongs to the group of technological factory systems. More specific, the production-relevant function of material transport is performed. Hence, the main function of the AGV is characterized as product function transport (indicated by the T in Figure 5). The input energy is electricity which is provided by a battery within the AGV (main function of the battery is energy storage). When the capacity of the battery decreases below a defined level (e.g. 40 %), it needs to be charged at the battery charging unit. Thus, the battery charging unit has the main function to convert energy. This visualization represents the functional model for the AGV, the battery and the battery charging unit. The operational states of the battery charging unit are stand-by (sb) and charging (ch), each of which resulting in a different level of energy consumption ($E_{sb,BCU}$ and E_{ch}).

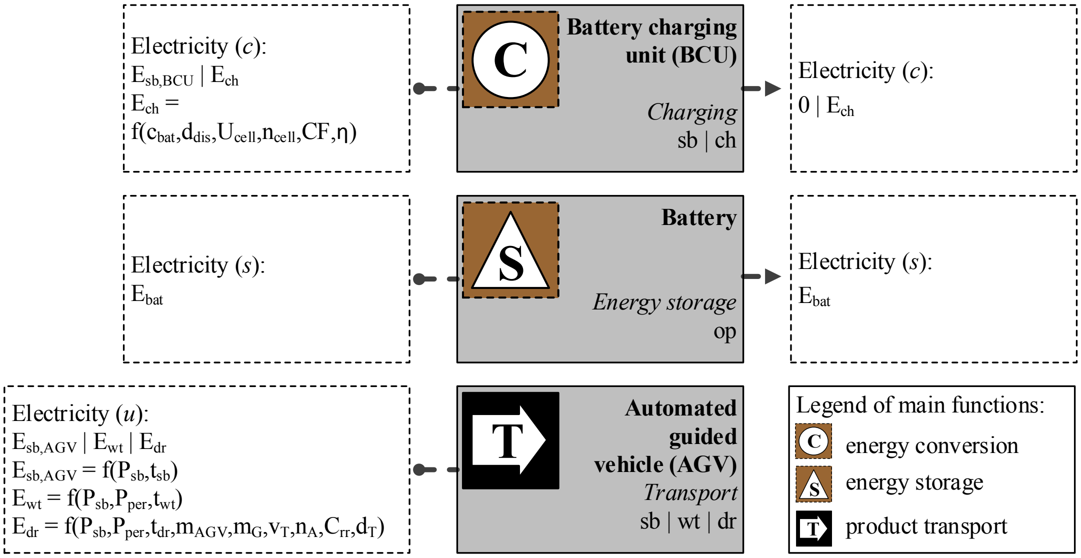

Fig. 5. Model of the object system and influential parameters for the use case of an AGV (modeled with the method FSM*ER* from [18])

An AGV is classified as a non-continuous conveyor, which means that it performs a transport process in discontinuous operation cycles [32]. This leads to higher variations in the power load as compared to continuous conveyors. Yet, an operation cycle can be combined of several basic operational states of an AGV, namely stand-by (sb), waiting (wt) and driving (dr). The difference between stand-by and waiting is based on the fact whether the AGV is ready to perform a transport process. For example, some control units may be switched off during stand-by. Therefore, the AGV's energy consumption is characterized by $E_{sb,AGV}$, E_{wt} and E_{dr}. The main function is to transport material, which is only possible during the operational state driving.

The next step is to describe the influential parameters on energy efficiency (see Figure 5). The main influential parameters on the power load of the AGV are velocity, acceleration, mass of the goods, mass of the AGV and rolling resistance. Furthermore, the energy consumption for an operation cycle is influenced by travelling distance, proportion of empty trips and number of stops (adapted from [33]). Hence, the following equations represent the energy consumption structure of the AGV (adapted from [31]):

$$E_{sb,AGV} = P_{sb} \cdot t_{sb}, \tag{1}$$

$$E_{wt} = (P_{sb} + P_{per}) \cdot t_{wt}, \tag{2}$$

$$E_{dr} = (P_{sb} + P_{per}) \cdot t_{dr} + 0.5 \cdot (m_{AGV} + m_G) \cdot v_T^2 \cdot n_A + C_{rr} \cdot (m_{AGV} + m_G) \cdot g \cdot d_T. \tag{3}$$

The energy consumption during stand-by mode $E_{sb,AGV}$ is composed of the stand-by power P_{sb} and the time spent in stand-by mode t_{sb}. Similarly, the energy consumption for waiting E_{wt} contains the power level of peripheral units P_{per} and the waiting time t_{wt}. The peripheral units summarize all components within the AGV that are active during waiting mode but switched off during stand-by mode (e.g. control, engine idle). The energy consumption while driving contains three components: First, the power load for stand-by and peripheral units is active during driving time t_{dr}. The second part is the energy that is required to overcome the acceleration resistance, which is influenced by the mass of the AGV m_{AGV}, the mass of the goods m_G, driving velocity v_T and the number of acceleration processes during this operation cycle n_A. Finally, energy consumption is caused by rolling resistance, which includes the rolling resistance coefficient C_{rr} and driving distance d_T.

The influential parameters on the energy consumption of the battery charging unit may be represented by

$$E_{ch} = \frac{c_{bat} \cdot d_{dis} \cdot U_{cell} \cdot n_{cell} \cdot CF}{\eta}, \tag{4}$$

where E_{ch} is the energy consumption for a charging process, c_{bat} the nominal capacity of the battery, d_{dis} the degree of discharge before loading, U_{cell} the average voltage of a battery cell, n_{cell} the number of cells, CF the charging factor (depending on the battery system and charging method) and η the efficiency of the charging unit [34].

The next step is the definition of project characteristics, especially regarding the relevant planning phases. Within this use case, the following phases of the planning process should be covered: concept planning, detailed planning, installation and operation. The *concept planning* has the purpose to design the entire transport system including the steps structure planning (i.e. definition of transport processes), dimensioning (i.e. amount of logistics equipment and required area), ideal planning (i.e. ideal layout of equipment) and real planning (i.e. considering restrictions on the layout). The result of the concept planning phase is the decision for a concept alternative of the transport process including the transport processes on the layout. Afterwards, during the *detailed planning* phase, the details for this alternative are described. This includes, among others, specifications for logistics equipment, details on routes and planning the energy supply. After inviting offers and concluding the contract, *installation* means to set up the logistics equipment, qualify the personnel and control whether the specifications are complied with. During the *operation* phase, the equipment is used for the process, which means that adjustments are possible for the usage.

The only role that is directly addressed within the use case is the logistics planner. However, the role of logistics management is important when the use case is extended into the AGV's operation phase. The tasks of logistics planning include the definition of logistics concepts, the selection of type and amount of logistics resources as well as the operative planning of detailed logistics processes (e.g. capacities). The logistics management is responsible for initiating and monitoring concrete transport tasks (including the control of the logistics fleet) and may intervene in case of disturbances (e.g. use different transport paths when the usual route is blocked).

The influences of these roles within the different planning phases need to be defined with reference to the influential parameters. Table I presents the identified relations between planning phase, role and influential parameter. Based on the qualitative model of the planning project that is composed of the object system, its energy consumption structure and the role responsibilities, energy efficiency measures can be identified. The measures are available within a database and are characterized by the criteria as described in section IV *F* (hierarchical level, product function, energy form, energy function, influential parameter and planning phase). Therefore, a selection of measures is possible for the use case. Table II shows the resulting energy efficiency measures distinguished into the considered planning phases, in which they may be applied primarily.

The assignment between EEM and actors is represented by using the influences of each role on the identified parameters (see Table I). For each EEM, the database contains the information which influential parameter is affected by this measure. For example, the EEM "summarize transport orders" results in higher transport masses but reduces transport distances and the number of acceleration processes. Taking this information combined with the respective planning phase for each EEM, the responsibility of actors may be assigned. Table II shows the responsibility of both logistics planning and logistics management in brackets.

TABLE I. ASSIGNMENT OF ROLE'S INFLUENCES ON PARAMETERS IN THE USE CASE

	Object system	Battery charging unit						Automated guided vehicle										
	Parameter	$E_{sb,BCU}$	c_{bat}	U_{cell}	n_{cell}	CF	η	P_{sb}	t_{sb}	P_{per}	t_{wt}	t_{dr}	m_{AGV}	m_G	v_T	n_A	C_{rr}	d_T
	Roles																	
Concept planning	Logistics planning (LP)								X		X	X		X	X	X		X
	Logistics management (LM)																	
Detailed planning	LP	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	LM																	
Installation	LP																	
	LM																	
Operation	LP																	
	LM								X		X	X		X	X	X		X

TABLE II. RESULTING ENERGY EFFICIENCY MEASURES FOR THE USE CASE

	Concept planning	**Detailed planning**	**Operation**
Battery		• Use fuel cells *(LP)* • Use lithium-ion batteries *(LP)*	
Battery charging unit		• Use Ri charging method for lead acid batteries *(LP)* • Use high frequency chargers with electrolyte circulation *(LP)*	
AGV	• Reduce masses to be transported *(LP)* • Reduce transport needs between process steps *(LP)* • Reduce in-house transport processes *(LP)* • High utilization rate of transport containers *(LP)* • Reduce mass of containers and packaging material *(LP)* • Reduce vertical material movements *(LP)*	• Recovery of braking energy *(LP)* • Improve the ratio between mass of the conveyor and loading capacity *(LP)* • Use transport management systems *(LP)* • Use sensor and control system with low power need *(LP)* • Use vehicle wheels with low rolling resistance *(LP)*	• Reduce number of acceleration processes *(LM)* • Switch off vehicle when in stand-by mode *(LM)* • Summarize transport orders *(LM)* • Reduce shunting movements *(LM)* • Reduce driving velocity *(LM)*

The measure implementation support is demonstrated exemplarily for the EEM "Reduce number of acceleration processes" (see Figure 6). In the upper section, the sheet subordinates the EEM to the categories hierarchy, function and energy form in order to support the understanding of the measure classification. The information contains the categories fundamentals, initial situation, function, applicability, external information and benefit-effort analysis.

The *fundamentals* serve the purpose to define relevant terms and to explain theory that is necessary to understand the EEM. The category *initial situation* provides information on the identification and evaluation of the current state. This may include causes for energy waste, relevance of the problem and benchmarks, which allow comparing an empirical value to the individual situation. The *function* describes the principle of how the EEM works. Additionally, it may describe different realization variants. The section on *applicability* describes what else needs to be considered for implementation, such as the transferability, the measure's focus, challenges and difficulties as well as further information that need to be acquired for the technical evaluation of an EEM. The *external information* explains frame conditions for the implementation (e.g. norms, standards, legislation and manufacturer's data). Finally, the *benefit-effort ratio* gives details on benefits (energy and cost savings) and effort (investment). Side effects on other objectives, such as productivity, or on other EEM's may be described as well. If available, a best practice example is presented in this section.

Energy efficiency measure

Reduce number of acceleration processes

Classification

- Hierarchical level: Work center
- Product function: material transport with non-continuous conveyors
- Energy function: utilization
- Energy form: electricity

Fundamentals

Theory

The energy demand to accelerate a transport system depends on the mass (including mass of the transport system and mass of goods) and the targeted velocity [32].

Theoretical energy consumption

The physical work to accelerate 1 ton to a velocity of $v = 10$ km/h is:

$$E = \frac{1}{2} \cdot m \cdot v^2 = 3.860\ Ws$$

Initial situation

Cause

Stopping and accelerating any vehicle in a logistics process is part of the necessary transports. Additionally, these may occur due to waiting, disturbances and high traffic volume.

Relevance

A study in an assembly line of an automotive company identified that 47 % of the energy consumption of a forklift truck is due to acceleration processes [35].

Function

Principle

The energy consumption for acceleration decreases when the number of acceleration processes is reduced. This can be done by a layout with a low number of intersections or by introducing a one way system [36]. In general, calming the traffic within the factory reduces acceleration processes of the vehicles. Furthermore, employees using floor conveyors need to be sensitized regarding this topic.

Applicability

Application focus

Since the energy consumption for an acceleration process depends on vehicle mass and velocity, this measure is especially recommended for heavy-weight and/or fast-driving vehicles.

Employee involvement

If the measure is applied at manually operated vehicles, trainings for employees are necessary.

External information

Standardization

Manufacturers may structure the data sheet of a floor conveyor following the requirements in VDI 2198 [37]. In this case, the data sheet contains information on vehicle weight, acceleration time and energy consumption of a defined cycle which includes 60 acceleration processes.

Benefit-effort ratio

Side effects

A reduced energy consumption for acceleration processes leads to a longer utilization time of the battery which may save battery changes and hence, reduce the number of required batteries. Furthermore, a calm intralogistics traffic increases production safety.

Fig. 6. Measure implementation support for the EEM “Reduce number of acceleration processes”

VI. DISCUSSION

The use case demonstrated the application of the methodical approach for an example of logistics planning. Based on the planning task, the relevant objects AGV, battery and battery charging unit were described in terms of hierarchy and function. Afterwards, parameters that influence the energy consumption of the entire system were identified. The social components of the system were considered by modeling actors and their influences. By using these criteria, an existing database on energy efficiency measures was searched and 22 measures were identified as being relevant for the use case. The measure implementation support which provides information towards the realization of a measure was demonstrated for one measure.

The application only requires qualitative information on the relevant systems and thus, reduces the effort to acquire energy data through measurements. Therefore, it may be applied in early factory planning phases, in which quantitative energy data might not be available. On the other hand, the level of detail of provided measures is close to the concrete application as compared to general guiding principles. Thus, expert knowledge on energy efficiency is not necessary for identifying measures.

The measure implementation support demonstrates additional information that supports the measure’s realization. However, the level of detail of this information might not be enough for a detailed assessment, especially in terms of the economic effects. In summary, the proposed methodical approach compromises between data gathering effort and details of the results. Yet, even in cases where a quantitative assessment is required for economical appraisal, the method’s results are helpful. In this case, the identification of possible energy efficiency measures demonstrates the relevant influential parameters, which prepares subsequent quantitative analyses.

VII. CONCLUSION AND OUTLOOK

Within this paper, a new methodical approach to identify energy efficiency measures in factory planning processes was presented. In contrast to existing methods to analyze and optimize factories with regard to the objective energy efficiency, this method does not need quantitative data on energy consumption. This reduces the effort of the method's application on one hand and allows its usage during factory planning projects, in which quantitative data is hardly available. The core of the method is to provide suitable energy efficiency measures for a factory planning task. For this purpose, a qualitative model of the planning project is generated. This model contains the definition of the technical system, its energy efficiency influential parameters, project requirements and the relevant actors. Based on this information, the influential opportunities on energy consumption are analyzed. This leads to the identification of energy efficiency measures which are described by classifying criteria. Furthermore, implementation support is provided to support the measure's implementation.

A fictive use case demonstrated the functionality and applicability of the methodical approach. Within this use case, the planning of a transport process by means of an AGV was analyzed. The technical systems were modeled by a system consideration of input and output and by equations that represent the systems' energy consumption. Based on this, relevant influential parameters were identified and classified depending on the actors who may influence these parameters within the planning project. Based on the qualitative description of the planning project, 22 energy efficiency measures were assigned to the task. The main results of the methodical approach are transparency on important parameters that influence energy consumption and on the influence of user roles on energy efficiency. The significant advantage compared to state-of-the-art approaches is the low application effort since no quantitative energy data is required.

In future research work, it needs to be analyzed whether it is possible to tie the measure implementation support to the user roles. Furthermore, the methodical approach is planned to be applied to planning projects in industrial practice in order to validate the applicability and advantages compared to state-of-the-art approaches.

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