FSM
er – Systematic Approach for Modeling Energy and Resource Efficient Factories

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Abstract—Energy and resource efficiency, as main instruments of sustainability, have become important objectives for industrial companies. Innovative tools and methods are needed to design sustainable, energy and resource efficient systems and processes of a factory. Against this background, the “Method for Factory System Modeling in the Context of Energy and Resource Efficiency” (FSM
er) has been developed and evaluated. The method FSM
er consists of a Meta Model, four comprehensive Factory System Concepts for the description of hierarchy, function, structure and life cycle, a Reference Model and a Procedure Model. The method aims at the holistic, methodical and model-based description of the factory in order to consider the objectives energy and resource efficiency in early conceptual planning phases. In addition, interrelationships are explained and potentials for efficiency improvements are identified. Therefore, FSM
er supports the representation and evaluation of the complex factory system in a simplified and graphical form. By this, effects of planning decisions can also be visualized. In the paper, the method and its evaluation are described.

Keywords—energy efficiency; factory planning; resource efficiency; sustainability; systems engineering

I. INTRODUCTION

In the context of sustainability, energies and resources have become essential objectives for the society. Due to fundamental global developments, such as the climate change [1] and the growth of population [2], the need for resources is increasing dramatically until the middle of this century. For example, it is assumed that the global energy demand will increase for more than one third in the next 20 years [3, 4], the water demand will even rise by more than half by 2050 [5]. Accordingly, the sustainable management of resources is becoming more and more important for the global development.

This issue is also relevant for industrial companies. From an environmental but also economical perspective, sustainability must be integrated in the company’s strategies, policies, systems and processes in addition to the classical objectives costs, time and quality. The energy and resource efficiency represents basic instruments and targets of sustainability. These objectives describe the ratio of useful output/benefit and the required input of energies or resources [6, 7, 8]. Energy comprises, for example, electricity or heat and cold which are contained in energy carriers. Materials, energies, area/room and emissions in form of sources and sinks are defined as resources in this paper.

Against this background, factories have to be planned and operated with focus on energy and resource efficiency because the main energy and resource consumption of a manufacturing company is significantly determined by the production itself. The factory planning process is changing and requiring appropriate models, methods and tools to support the planning participants and activities. Therefore, in this paper the “Method for Factory System Modeling in the Context of Energy and Resource Efficiency” (FSM
er) is presented [9]. The remainder of the paper is organized as follows: Chapter 2 collects the requirements and approaches for designing energy and resource efficient factories. The developed method FSM
er is explained in chapter 3. The evaluation of this method is illustrated in chapter 4. Chapter 5 finally summarizes the main facts of the research work.

II. DESIGNING ENERGY AND RESOURCE EFFICIENT FACTORIES

The energy/resource efficient factories are defined as new types of factories which are focused on the efficient and effective use of energy and resources in a holistic view. This includes at least optimized systems and processes with minimal consumptions as well as consistent energy/resource flows and closed cycles (Figure 1).

For the realization of this kind of factories, factory planning, as an interdisciplinary field, plays an important role. In general, factory planning is defined as systematic process to design the factory step-by-step and in phases [10]. Especially in early planning phases, the energy/resource demand can be influenced significantly [11]. The level of the future demands are determined in these phases. In the subsequent planning and operation phases, improvements are just realizable within these
borders. Thus, the objectives energy and resource efficiency have to be considered early in the planning process. However, this leads to an extension and integration of appropriate planning contents of different disciplines (e.g. manufacturing, building or supply and disposal technologies) with the result that the complexity of the planning process as well as of the planning object (factory) are continuing to grow.

![Characteristics of energy/resource efficient factories](image)

To meet these requirements, instruments are required to support the planning participants in their planning tasks, for instance, by increasing the transparency and understanding of complex planning solutions. On closer examination of existing methodical instruments, it can be seen that there are few approaches which aim directly at factory planning and its topics [e.g. 7, 12, 13, 14]. Most of the approaches are located in the field of factory operation and focus on the analysis and optimization, the balancing as well as the control and simulation of existing processes and systems (e.g. manufacturing tools) whereby quantitative data (e.g. measured energy consumptions) is mostly necessary [e.g. 15, 16, 17, 18, 19]. Nevertheless, these information are often not available during early planning phases.

As a consequence, it appears that mainly sections of the factory (e.g. tools, equipment, processes or products) are regarded, but not the entire factory as a holistic system. However, a factory covers a variety of technical systems. Thus, an integrative consideration and a connection of the different sections and disciplines have to be targeted in the planning process. Especially, the structure and the functionality of the factory must be described and represented systematically for a holistic view. For this, the model and system theoretical perspective can be used to illustrate the factory as a system in an understandable way in order to support the planning process. The method FSMER, which is based on that approach, is explained in the following chapter.

**III. METHOD FOR FACTORY SYSTEM MODELING IN THE CONTEXT OF ENERGY AND RESOURCE EFFICIENCY**

**A. Objective and Structure of the Method**

Against the background of the described scientific and practical problem, the “Method for Factory System Modeling in the Context of Energy and Resource Efficiency” (FSMER) was developed and evaluated [9]. FSMER aims at the holistic, methodical and model-based description of the factory as a system focusing on the objectives energy and resource efficiency. Especially, early conceptual planning phases should be supported by the method to consider the enormous opportunities to influence the future energy/resource demands. With the help of FSMER, the structure and interrelationships of the factory system are explained as well as potentials and design approaches for efficiency improvements are identified and evaluated. Therefore, FSMER supports the planning process by representing the complex relationships of a factory system as well as by the visualization and the assessment of the impact of planning decisions in a simplified, graphical form.

The method consists of interrelated models which are divided in two fields: the object and the procedure section (Figure 2). The object section provides the framework, models and model elements for the holistic description and explanation of the factory system. The procedure section includes the systematic approach for the step-by-step modeling, evaluation and optimization of the factory system. The individual components of the method are explained in the following.
B. Meta Model

The factory is declared as a system based on model/system theoretical perspectives by the Meta Model. Thus, the general components of a system (e.g., elements, functions and relations) are transferred to the factory and the relationships between these terms are made. In addition, an own modeling notation was developed to visualize the system types, functions, flows etc. in a simplified, graphical form. This is used in the next figures. As a result, besides the overview on the components of a factory system, the Meta Model serves as framework for the development of the following Factory System Concepts.

C. Factory System Concepts

According to ROPOHL, a complete system model consists of the three system concepts for hierarchy, function and structure [20]. Therefore, the Hierarchical, the Functional, the Structural and an additional Life cycle-based Factory System Concept are established for the holistic representation of the factory system. This is why the Factory System Concepts are the main parts of FSMER. These concepts comprise description, explanation and forecast models to depict the components of the factory system and their interrelationships in detail and with focus on the objectives energy and resource efficiency.

With the help of the Factory System Concepts, the factory is integrated into higher-level systems and separated in its own lower-level systems (hierarchy), the interactions with the environment are explained (function) as well as the elements and their relations are illustrated (structure). These consideration can be projected to different time periods or planning horizons (life cycle). Thereby, the relevant energy and resource aspects (e.g., energy and resource inputs/outputs, functions, states, system types, relations and structures) are highlighted in each perspective.

The general functional model plays a key element in the Functional Factory System Concept. It can be used to describe the functional relationships of the factory or of individual subsystems of a factory with the environment (Figure 3). In this figure, a functional model of a logistics system (conveyor system) is shown as an example. The system usually transports workpiece carriers (primary function or purpose of the system), so it is declared as a transport system (T) with the function transport (t). Electrical energy as well as compressed air are required for its operation (left side). The system is able to run in different operation states (e.g., Wo for working or Sa for standby) in which the energy and material consumptions vary. The detailed profile for electrical energy with the operation states is added below. Moreover, properties of the system (e.g., location, floor space or cycle time) are summarized in the middle. In addition, model characteristics (HI1 for first hierarchy, PS for part of the Production System, 1h for the regarded time period of one hour, 0 for average values and P for power perspective) are given on the top of the middle. Thus, the function of every system in a factory can be modeled and visualized in detail.
The structure of the factory is described with the Structural Factory System Concept. The structure results from the connection (relations) of the individual systems, for instance, by temporal, spatial or functional criteria. An exemplary energy flow structure is shown in Figure 4.
On the one hand, this structure is separated by the energy form (energy 1 and 2). On the other hand, it is divided into the energy flow functions (e.g. energy provision, generation or transport). The first energy is supplied from outside (e.g. electrical energy), converted and transported to the utilization systems. Energy 1 is also required for the generation of the second energy (e.g. cold or heat). Thus, it can be seen that the both energy flows are linked with each other. As a result, the interaction (e.g. dependencies of upstream and downstream systems) of the different system types are clearly illustrated in this example.

Building on that, the factory is separated in its three main functional sections Production System (PS), Building System (BS) as well as Supply and Disposal System (SDS) according to the primary function or purpose of each system. The PS includes the manufacturing, assembly and logistics systems which represent the main systems for the value-adding processes. The BS comprises the building, rooms, roofs, walls etc. The SDS consists of process services for the PS (direct relation to the main processes, e.g. generation of compressed air) and building services (indirect relation to the main processes, e.g. generation of room heat). Therefore, the fundamental relationships between these sections can be explained, especially the exchanges of materials and energies based on demands on the one hand and capacities on the other hand. Thus, the PS and the BS act primarily as users or consumers of energy and material. In contrast, the SDS is responsible for meeting the needs of the PS and BS as well as for having appropriate capacities for generation, storage, transport etc. Furthermore, advanced cycles between these sections have to be designed (e.g. reuse of waste products for other processes). This perspective is also described by the following Reference Model.

D. Reference Model

The fundamental energy and resource aspects of the Factory System Concepts are summarized in the Reference Model for factory systems. This model is separated in several partial models for different hierarchies and functional sections. The Reference Model acts as template to derive specific factory system models in practical use cases. In addition, it is also used as comparison model to check whether all relevant energy and resource aspects are considered in the specific models. And finally, the general energy and material relationships of a Factory System are represented by the Reference Model. For example, an excerpt of the partial model for the structure of the Production System is illustrated in Figure 5.

Fig. 5. Excerpt of the partial model for the structure of the Production System [9]
E. Procedure Model

Generalized models and model elements to holistically represent the factory system and for different use cases are given by the Factory System Concepts and the Reference Model (object section of FSM\textit{ER}). Based on that, the application of these models for practical planning projects is explained by the Procedure Model (procedure section of FSM\textit{ER}). This model describes the systematic, step-by-step approach for modeling, evaluation and optimization of the factory system in terms of energy and resource efficiency (Figure 6).

At the beginning, the objectives for the model are defined in consideration of the underlying planning task (e.g. designing of a production area). In the next step, the qualitative modeling of hierarchies, functions and structures is executed to get model-based solution variants. With these models, first design/improvement approaches (e.g. substitution of environmentally hazardous substances) can be tested without the need of quantitative data. In the third step, quantitative aspects are added to these models, if appropriate data and information (e.g. measured energy data) are available. Thus, for instance, energy or resource demands for operation can be considered.

In the second part of the procedure, the energy and resource efficiency of the modeled planning solutions are evaluated and improved. Therefore, the developed models are analyzed, interpreted and assessed with the help of generalized analysis indicators (e.g. identification of type, quantity and location of materials or energies) and an indicator system. In the last step, specific design or optimization approaches are deducted to improve the modeled planning solutions (e.g. usage of renewable energy).

As a result, energy and resource aspects can be considered in early planning phases to develop concepts for energy/resource efficient factories by the step-by-step qualitative and quantitative modeling and the following analysis and evaluation according to the existing data and information.
An overview on the evaluation procedure of F$\text{SMER}$ is given in this chapter. According to the underlying, practice-oriented research approach, the practicability of the F$\text{SMER}$ is tested in the evaluation. Therefore, three methods are used to consider both theoretical as well as practical requirements. In the first part, the practicability is examined against the objective quality to theoretically evaluate the design of F$\text{SMER}$. For this, the principles of proper modeling (correctness, relevance, efficiency, clarity, comparability and systematic structure) are used [21]. As a result, the conception of the method corresponds to these requirements.

In the second part, a complex case study represents the main part of the evaluation. In this study, the practicability is checked in context of the objective effectiveness. The method F$\text{SMER}$ is used in this study to model a planned factory concept. The field of application is a new planning of a solar cell factory during the concept phase. The information basis for the case study is four feasibility studies for planning cell productions which were developed by the company AEP Energie-Consult during several years for its customers [22]. On this basis, the planning solutions for the factory are modeled with F$\text{SMER}$ to represent the actual state of planning, to evaluate it in terms of energy and resource efficiency and to derive approaches for optimization. Therefore, qualitative and quantitative models for the Production System, the Building System as well as the Supply and Disposal System are created, analyzed, evaluated and improved step-by-step according to the Procedure Model of F$\text{SMER}$. In Figure 9, an excerpt of an analyzed and evaluated manufacturing line is shown as an example.
It can be seen that there are several production (U), transport (T) and storage (S) systems which work together in the product flow. Furthermore, these systems are supplied with required energies and materials by the upstream supply system (e.g. chemicals, compressed air or electricity; not shown in the figure). Waste products are given to the downstream disposal system (e.g. waste air, heat or water; not shown in the figure). Energy and resource demands are quantified for both individual systems (incoming and outgoing arrows for energy and material flows) as well as summarized manufacturing sections (gray boxes). Points for weakness or improvements are identified and localized in this model (warning symbols), for example, high temperatures for processes or in exhaust air or high demands for electrical energy and cold. Finally, design approaches are derived to improve the energy/resource efficiency of the factory concept (e.g. design of closed heat and cold cycles).

In the third part, the practicability is proved by the transferability and feasibility of the conceptual method FSMER in form of prototypes. For this, the possibilities for the visual representation of model components (object section of FSMER) as well as for the support of the modeling (procedure section of FSMER) in form of existing functionalities or extensions are tested in three software tools for visualization, (material and energy) balancing and event-driven simulation. As a result, it was found out that the integration of FSMER is partly possible and the application of FSMER is improved by the software tools.

In summary of the evaluation, it can be stated that FSMER can be used to represent complex factory concepts in a simplified, graphical form to support the interdisciplinary planning process.

V. CONCLUSION AND OUTLOOK

Energy and resource efficiency are fundamental objectives and instruments for sustainability. For this purpose, the “Method for Factory System Modeling in the Context of Energy and Resource Efficiency” (FSMER) to support the sustainability-oriented factory planning is presented in this paper. With the help of this method, conceptual planning solutions can be represented, evaluated and improved in a holistic, methodical and model-based way, especially for early planning phases. Thus, the energy and resource relationships of the factory system are explained and design approaches for optimizations are derived. Therefore, the method acts as an instrument for planning participants to represent the factory as a system and the effects of planning decisions in a simplified, graphical form. As a consequence, the design of sustainable factory concepts in interdisciplinary planning teams is supported. In future research work, the implementation of an appropriate modeling/planning software tool for FSMER as well as the extension regarding the modeling of information flows and systems are intended.

REFERENCES


**BIography**

**Hendrik Hopf** is a Research Assistant at the Professorship of Factory Planning and Factory Management of Technische Universität Chemnitz, Germany. In 2009, he obtained his diploma degree in Industrial Management and Engineering at the University of Applied Sciences in Zwickau, Germany. In 2015, he earned a PhD in Mechanical Engineering (modeling of energy and resource efficient factory systems) from the Technische Universität Chemnitz. He has published journal and conference papers. Dr. Hopf has done research projects with, among others, Audi, Continental, Fraunhofer and Volkswagen. His research interests include energy and resource efficiency, factory and logistics planning, modeling, sustainability and digital factory.

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