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.

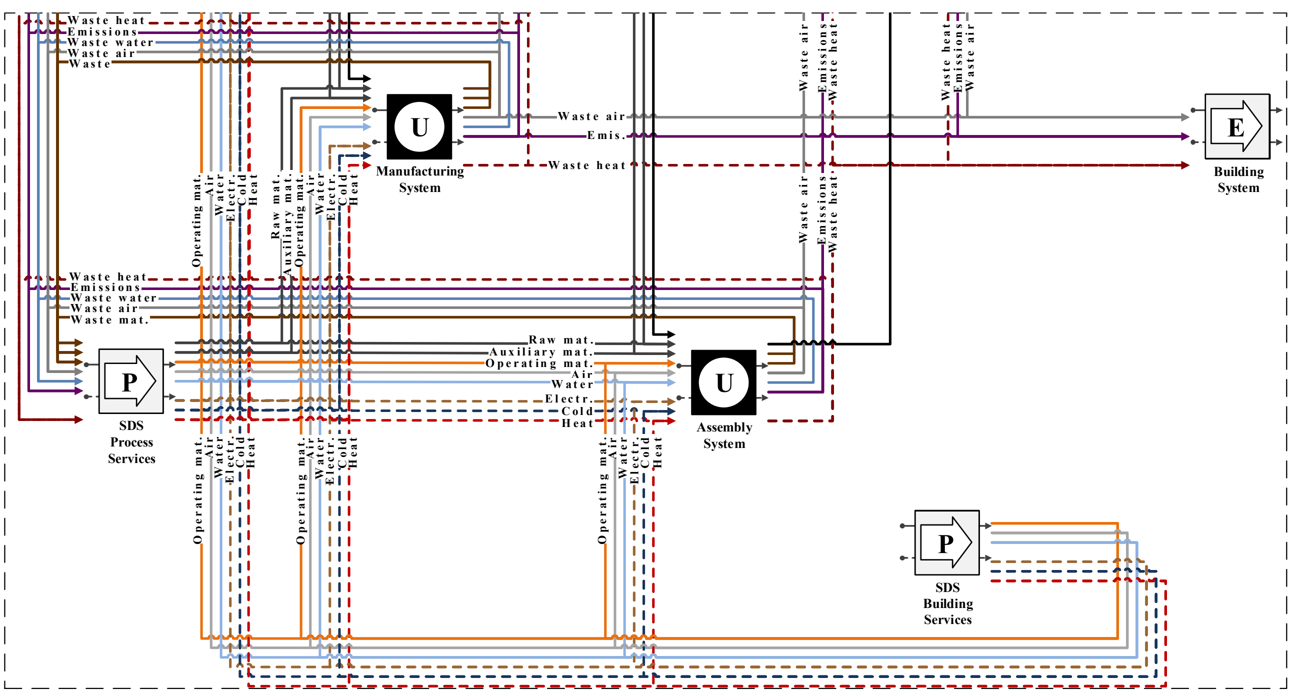

Fig. 5. Excerpt of the partial model for the structure of the Production System [9]

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*ER*). Based on that, the application of these models for practical planning projects is explained by the Procedure Model (procedure section of FSM*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.

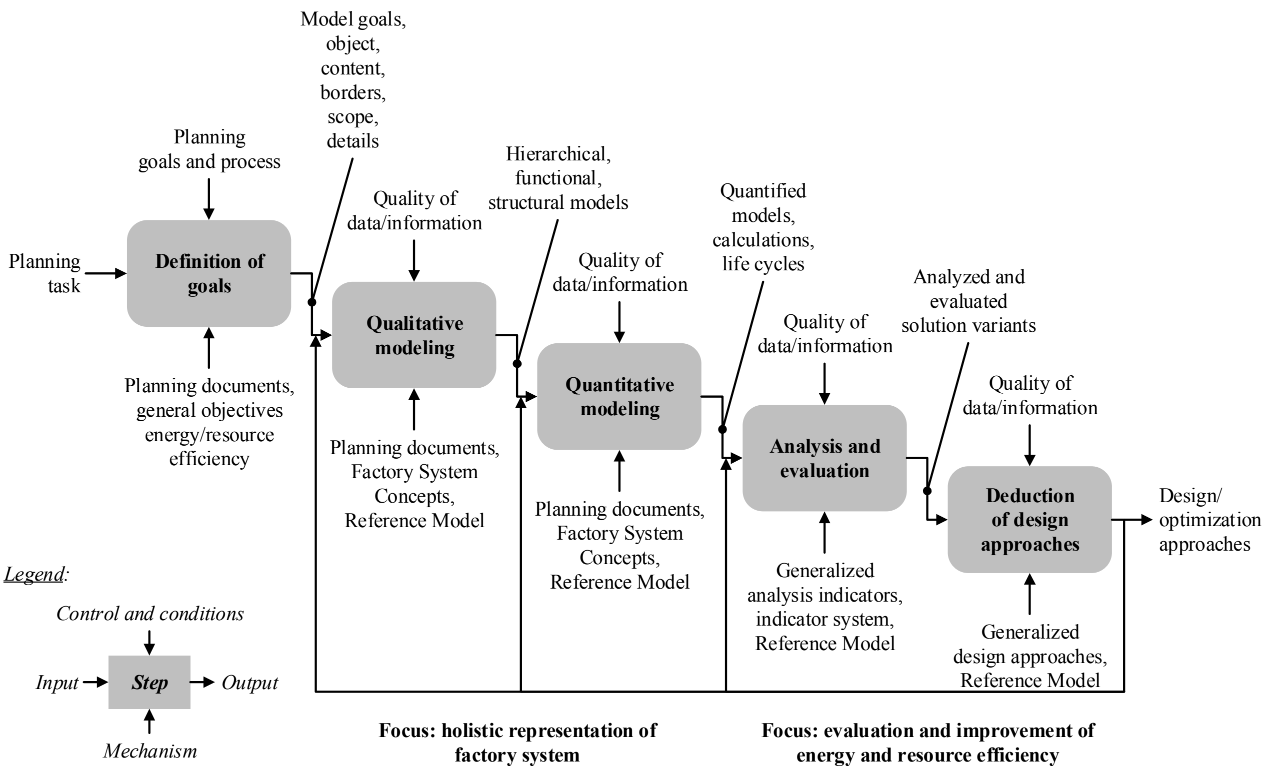

Fig. 6. Procedure Model for modeling the factory system [9]

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.

IV. Evaluation

An overview on the evaluation procedure of FSM*ER* is given in this chapter. According to the underlying, practice-oriented research approach, the practicability of the FSM*ER* 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 FSM*ER*. 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 FSM*ER* 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 are 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 FSM*ER* 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 FSM*ER*. In Figure 9, an excerpt of an analyzed and evaluated manufacturing line is shown as an example.

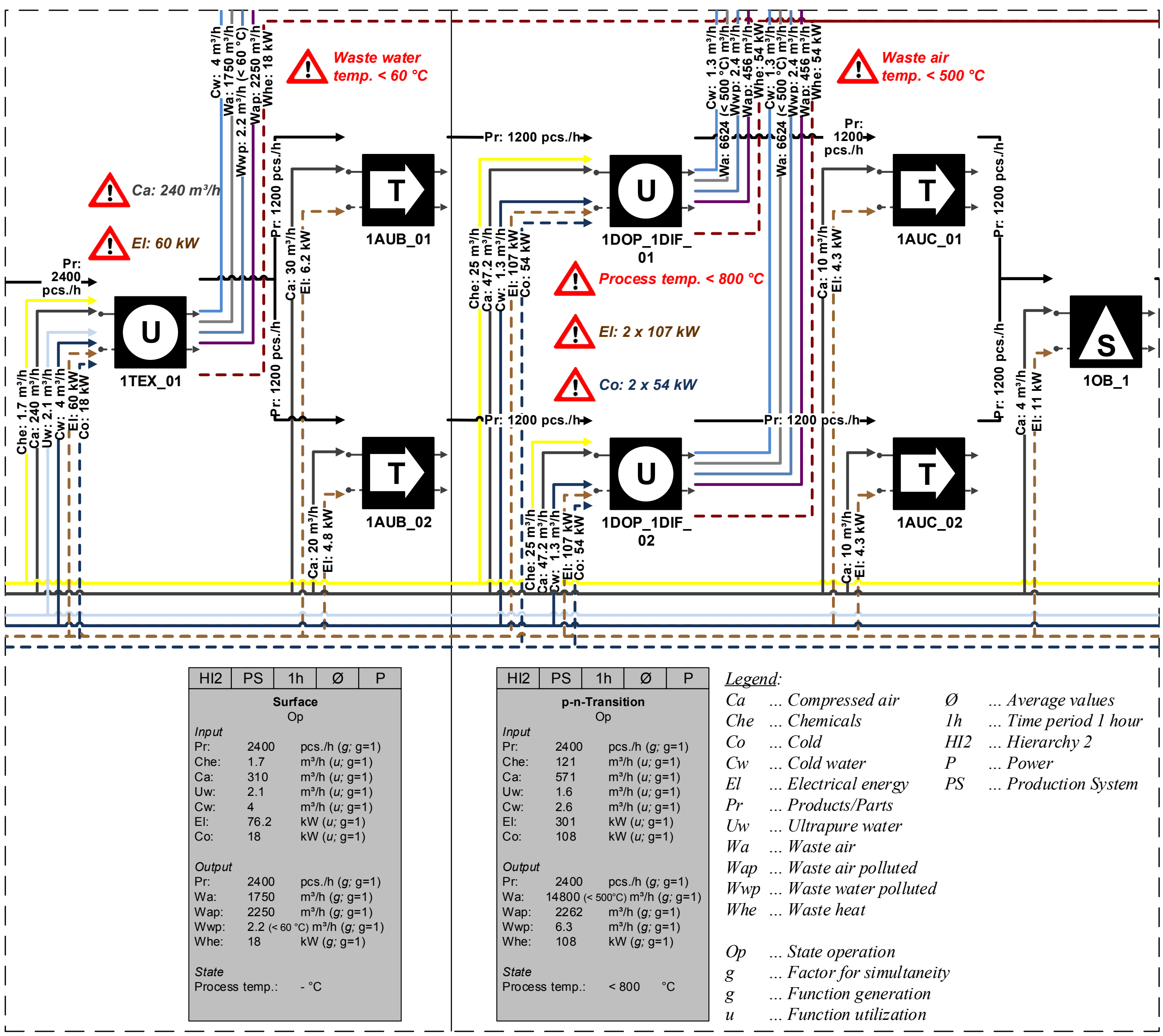

Fig. 8. Excerpt of an analyzed and evaluated manufacturing line [9]

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 proofed by the transferability and feasibility of the conceptual method FSM*ER* in form of prototypes. For this, the possibilities for the visual representation of model components (object section of FSM*ER*) as well as for the support of the modeling (procedure section of FSM*ER*) 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 FSM*ER* is partly possible and the application of FSM*ER* is improved by the software tools.

In summary of the evaluation, it can be stated that FSM*ER* 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" (FSM*ER*) 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 FSM*ER* as well as the extension regarding the modeling of information flows and systems are intended.

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