State of Research and an innovative Approach for simulating Energy Flows of Manufacturing Systems

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Abstract

The paper addresses the issue of energy efficiency as an important topic in sustainability in manufacturing. Against the background of a necessary holistic system understanding and derived research demand, an innovative energy flow oriented manufacturing system simulation approach is presented. Besides the description of the conceptual approach, the applicability and the potentials of usage are shown in two different case studies.

Keywords:
Energy Efficiency; Sustainable Manufacturing; Production Management

1 INTRODUCTION

Due to its growing economic relevance and the related environmental impact, energy consumption is a major issue in both politics and companies nowadays. In very general, “energy is the capacity to do work” (e.g. [1]) so it is necessary to execute any kind of designated tasks. With mechanical, thermal, chemical, electric, electromagnetic and nuclear energy different forms of energy can be distinguished (e.g. [2]). Conversion is basically possible and also necessary to enable the usability of naturally available primary energy carriers like coal, oil or gas in industrial practice. However, practically this is always connected with certain losses. As an example of primary energy consumption and conversion processes Figure 1 shows an energy flow diagram for the case of Scotland which is basically quite similar for most industrialized countries.

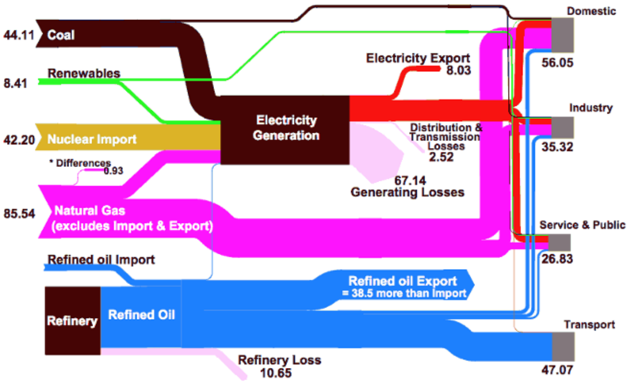

Figure 1: Energy flow Sankey diagram for Scotland (in TWh) [3].

On a national scale, industry is one of the major consumers of natural gas as primary energy carrier, e.g. in Germany the share is 36% compared to Scotland with approx. 28% (of direct used gas) [3] [4]. Additionally, industry consumes major share of electricity which is a secondary energy carrier and is produced using primary sources including significant losses. In Germany, industry is responsible for the consumption of 47% of the national electricity [4]. Within companies further conversions take place in order to generate the actual usable form of energy to fulfil the working task. Altogether the most typical energy conversions are from gas to process heat (e.g. generation of steam) and from electricity to mechanical energy (e.g. electric drives or generation of compressed air) [5].

As mentioned, energy consumption has a very strong relevance from both economic as well as environmental perspective. Thereby the pure energetic view as shown in Figure 1 is certainly just one perspective; whereas striving towards sustainability in manufacturing demands a more detailed analysis of connected economic as well as environmental impacts (here depicted with related CO_2 emissions). Therefore (based on the data from [5]) Figure 2 shows the estimated energy costs and CO_2 emissions for the German manufacturing industry for the main energy sources. The calculation is based on the average energy prices for the considered years and the emitted CO_2 for generating electricity (energy source mix for Germany) or directly burning oil, gas or coal. The calculations underline the major importance of considering electricity in comparison to primary energy sources (due to upstream chain). Only through its electricity consumption, industry is responsible for approx. 18% of CO_2 emissions (plus approx. 20% through direct industrial emissions) in Germany [4]. Additionally energy supply in general is naturally connected with the depletion of diverse non-renewable resources (e.g. oil, gas, coal). As a result, based on currently known securely mineable deposits and demand, the statically estimated supply range is approx. 40-60 years for oil and gas respectively [4]. Besides, the calculation also stresses the very strong economic relevance of industrial energy consumption. Energy prices for electricity, gas and oil are steadily increasing for the last couple of years [4]. As shown in Figure 2, energy costs for producing companies has been more than doubled from the year 2000 to 2008.

Against the background of these urging environmental as well as economic challenges, increasing the efficiency in using energy has become a major strategy. Different studies reveal the significant

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improvement potential within industry. The study of "Energy Efficiency in Manufacturing" prepared by Fraunhofer Gesellschaft underlines the relevance of production processes in single companies as well as on a global base and highlights the major potential of increased production process efficiency to optimize the environmental as well as economic performance [6]. The study "Energy Efficiency in Manufacturing: The Role of ICT" highlights the s saving potentials of 10-40% in manufacturing and stresses the importance of ICT (Information and Communication Technologies) as enabler for energy efficiency [7]. A comprehensive study for the case of Germany reveals similar significant potentials in the manufacturing industry regarding e.g. the efficient usage of energy [5]. Altogether, depending on the field of action a saving potential of 10-30% of energy consumption was identified based on the technology which was available in 2002. From today´s perspective the potential is likely to be even higher.

	energy consumption	energy costs (2000)	energy costs (2008)	related CO2 emissions
	[in PJ]	[in €]	[in €]	[in t]
electricity	819,1	10.012.650.793 €	20.073.221.336 €	130.933.135
gas	973,7	4.577.253.331 €	9.094.440.438 €	38.745.623
oil	231,2	10.558.553 €	22.046.590 €	10.395.556
coal	407,8	586.200.977 €	1.566.545.164 €	37.185.949
total	**2431,8**	**15.186.663.655 €**	**30.756.253.528 €**	**217.260.264**

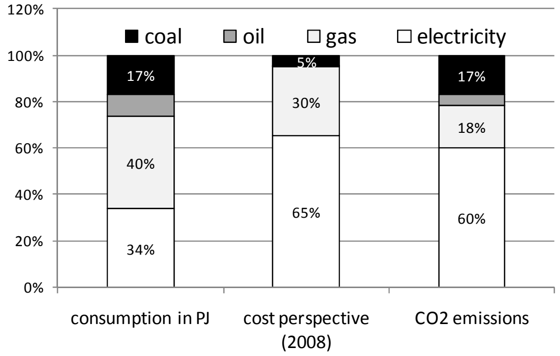

Figure 2: Estimation of costs and CO_2 emission related to energy (based on consumption data from 2002 from [5], in Petajoule).

Against this background an approach to foster energy efficiency in manufacturing companies is required. Hereby energy efficiency is the ratio of the production output (e.g. in terms of quantities with defined quality) to the total energy input (e.g. electricity, gas, oil) for the operation of the whole factory system. Considering the mentioned opportunities and the relevance of different energy input flows it becomes clear that there is a need for appropriate methods and tools incorporating a holistic perspective on all energy sources and forms to identify and tab the most worthwhile potentials for the individual company case. However energy is just one of several inputs for a production process and minimizing energy consumption is just one of the target objectives of a company (besides e.g. material and personnel costs, production time, quality). While different measures may also cause conflicts of goals an appropriate approach shall be able to consider these different perspectives.

2 THEORETICAL BACKGROUND

2.1 System definition

The consideration of all relevant energy flows necessarily requires a holistic factory definition with three partial systems: the production system itself (with machines and controlled through production management), the technical building services (TBS) and the building shell (Figure 3) [8]. These partial systems interact as a complex control system with dynamic interdependencies between different internal and external influencing variables. Production machines which execute or support the actual value creating processes directly need energy (typically electricity) to fulfil their designated processes. However they also need diverse other energy forms/media like compressed air, steam or cooling water which are provided by technical building services (TBS). Another task of technical building services is to ensure the needed production conditions in terms of temperature, moisture and purity through cooling/heating and conditioning of the air. The essential influencing variables are the local climate at the production site (e.g. seasonal influences) and also the exhaust air and waste heat that is primarily emitted by production machines or personnel. Altogether, besides direct energy consumption through production equipment, TBS need further energy to fulfil their tasks and enable factory operation. Referring to a study of the European Union, this consumption counts for a major part of the industry energy consumption [9]. Additionally high potentials for energy related improvement in that field were identified [5].

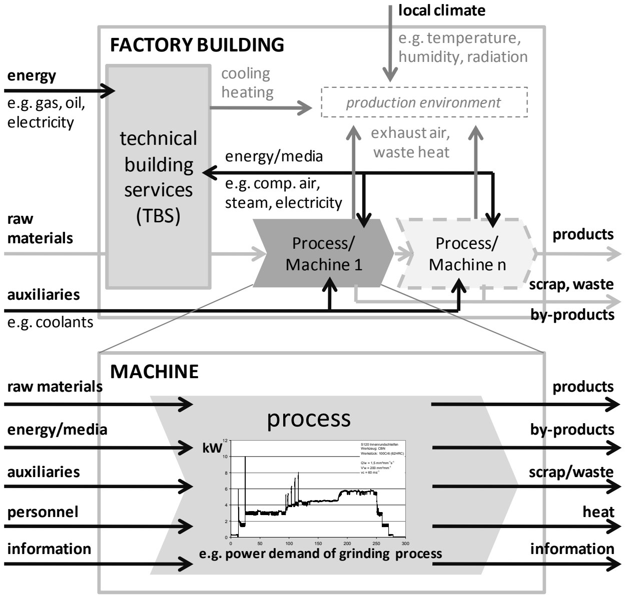

Figure 3: Holistic system definition on energy consumption of manufacturing systems [8].

A typical example for internal energy flows involving TBS is the generation of compressed air. Because of its advantages compressed air is broadly used in manufacturing companies for different purposes. It is basically a conversion of electrical energy to mechanical energy. Altogether about 10% of total industrial electricity consumption is caused by generation of compressed air (which means 80 TWh or 55 million tons CO_2) [10]. As one big disadvantage compressed air usage is often connected with very high system losses. Studies show that less than10% of the input energy ends up as an actual usable mechanical energy. As a result compressed air is actually one of the most expensive forms of energy in industry [11]. Studies reveal that saving opportunities are not used yet; potentials are estimated with 5-50% (average approx. 33%) for the next 15 years [10].

2.2 General requirements and solution approach

Against the background of the previous explanations some general requirements can be derived which have to be addressed when considering energy and resource efficiency in manufacturing (e.g. [12] [13]):

Extended process and holistic factory system definition: In order to avoid focusing on minor relevant issues (while neglecting major challenges) and local optimization with problem shifting, all relevant input- and output flows of production processes must be explicitly considered. This includes all energy (e.g. compressed air, electrical power, waste heat) and material (e.g. auxiliary materials as cooling lubricants) flows, which lead either directly or indirectly to additional energy and/or resource consumption Consequently applying these concepts to a whole factory leads to the holistic factory definition as shown above – including the consideration of manifold interdependencies between the constituting elements

Dynamics of consumption-/emission behaviour and reciprocal effects: All relevant input- and output flows are typically not static values but highly dynamic depending on the operating conditions of the processes and the machines. As measurements clearly underline, the usage of nominal values is not sufficient while they do not reflect the magnitude and the dynamics of actual consumption. Consumption and emission profile of single machines add up to cumulative load profiles on the factory level. In the end these dynamic cumulative load profiles (e.g. process heat demand, compressed air demand, heat flow into the factory building, electrical power demand) are decisive for design and control of the technical equipments (e.g. dimensioning of compressed air system) as well as for billing (e.g. energy supplier).

Thinking in process chains: final products are usually not the result of a single production processes, but are rather manufactured in several steps on different production lines in the sense of production process chains. Against the background of energy- and resource efficiency, the process chain has to be regarded and evaluated as a whole, as it may involve further potentials (e.g. combination of processes). Moreover, problem shifting might occur while improving measures in one process can possibly lead to worse performance of others.

Life-cycle-oriented perspective: Analogous to the thinking in process chains, all life cycle phases of products (this includes also all the technical equipment within the factory itself) have to be considered when it comes to deriving measures concerning the energy and resource efficiency. Thus, the decisive factor for increasing the energy efficiency of a machine tool, for instance, is not the improvement of single parameters of a specific process, rather the development of the machine itself. Moreover, the choice of a specific process (e.g. joining techniques) has direct effects on the use- and disposal phase which could lead to increased efforts in those phases.

Integrated evaluation: In order to deduce advantageous solutions, several relevant target dimensions must to be considered simultaneously. Besides an ecological evaluation (with a correct balance of the different input- and output parameters, e.g. environmental effects of electricity- and gas consumption), this includes a realistic economic (on the basis of a suitable cost model which integrates real contract conditions) and technical evaluation (e.g. effects on product quality). Possible conflicts of goals must be disclosed and decision support to their solution must be offered.

Analysing these requirements reveals that simulation is a promising approach. Discrete event simulation is an established method to analyse and improve manufacturing systems. With an extension towards energy consumption a realistic consideration of time based energy consumption behaviour and energy efficiency measures on system level would be possible.

3 STATE OF RESEARCH AND RESEARCH DEMAND

Whereas discrete event manufacturing system simulation augmented with relevant energy flows was identified as promising approach the question arises whether certain solutions are already available. A review of commercially available manufacturing simulation tools (e.g. Plant Simulation, Delmia) reveals that they do not support those considerations yet. The following section will analyze the state of research work in order to identify necessary research demand. For the matter of this analysis a deep review of relevant books and research papers, not only in the field of (e.g. manufacturing) engineering but also adjacent disciplines (e.g. operations research, computer science), was conducted. The analysis focuses on discrete-event multi-machine production system simulation with application to environmental aspects. In total twelve relevant research approaches were identified and considered. Authors included in the investigation are: Heilala et al., Rahimifard et al., Solding et al., Weinert et al., Junge, Hesselbach et al., Hornberger et al., Löfgren, Johannsson et al., Dietmair/Verl, Wohlgemuth et al., and Siemens AG (e.g. [13]-[23]). The following criteria were identified based on the system definition and requirements as stated above, as well as practical issues related to the application:

- completeness of energy and resource flows (ideal: all internal and external energy flows of manufacturing companies)
- realistic representation of consumption dynamics on machine and factory system level (ideal: cumulative load profiles for all energy flows)
- interdependencies with technical building services (ideal: interactions of all TBS subsystems considered)
- focused fields of action for improvement: technological measures/organisational measures (ideal: full range of levers for improvement in one solution)
- possibility of actual optimization studies (ideal: optimization can be used which was already proved in case studies)
- scale and scope of technical/ economic/ ecological evaluation (ideal: realistic full cost calculation scheme, automated LCA, wide range of technical performance criteria considered)
- provision of actual decision support (ideal: appropriate methods for integrated evaluation are provided)
- consideration of uncertainty (ideal: appropriate methods are provided and their applicability proved)
- transferability to different cases and industries (ideal: wide range of production situations can be depicted)
- modelling and simulation effort in terms of time, costs and necessary expertise (ideal: simulation study can be conducted with low additional effort from non-simulation experts)
- appropriate visualisation of material/energy flows and results (ideal: all key figures and relevant diagrams shall be provided automatically and continuously during runtime)
- embedment within application cycle (ideal: comprehensive application cycle is provided ensuring goal-oriented modelling and systematic derivation of improvement measures)

Each single research approach was evaluated with respect the different criteria using a specific four-step scheme (fulfilment of 25%, 50%, 75% and 100% with certain thresholds for each step). Based on these investigations, Figure 4 shows the average value (over all 12 considered approaches) for each criterion as well as over all criteria (dashed vertical line). Additionally the range is depicted as average of the six highest and lowest values in each category. Based on this analysis several findings can be observed:

- Having in mind that 1.0 (100%) is the maximum and ideal value of each criterion it becomes clear that there is a significant room for improvement in all areas towards the vision of a comprehensive integration of energy and resource flows into simulation based planning procedures.
- Some approaches fulfil certain criteria quite well – however they involve significant drawbacks in other areas. There is no approach with balanced and high fulfilment of all criteria.
- Criteria completeness (of energy and resource flows) and dynamics are fulfilled higher than the average (still at relatively

low level though). Typically technical variables are considered for evaluation, often in combination with other economic and/or ecological variables. Also the criterion visualisation is fulfilled above average.

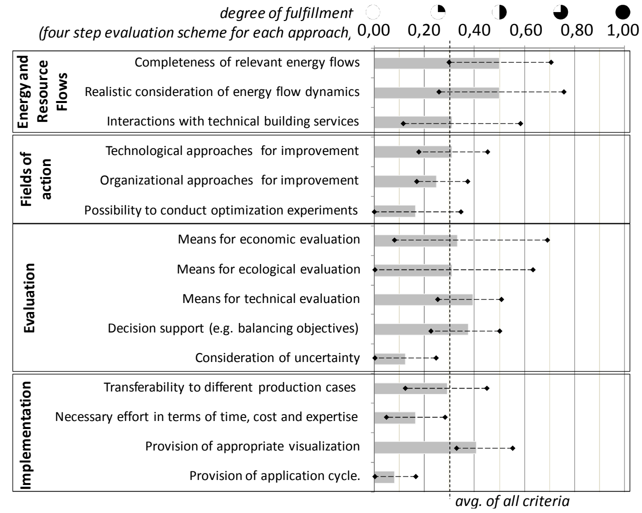

Figure 4: Evaluation results for state of research.

4 SIMULATION CONCEPT

After the evaluation of the previous work [24], a new concept of the proposed energy flow oriented simulation approach has been developed and depicted in Figure 5. As illustrated, it is not a specific simulation model - based on the simulation tool AnyLogic it is rather a modular simulation environment which allows the flexible modelling of any manufacturing process chain or factory as a whole.

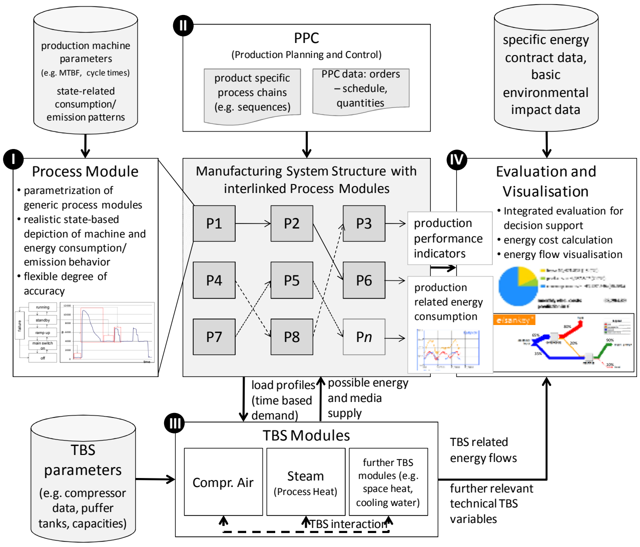

Figure 5: Conceptual structure of energy flow oriented manufacturing system simulation.

Four main modules can be distinguished which dynamically interact through defined interfaces. These modules are:

Process Module(s): Process modules are core elements for modelling of the actual production machines and processes. A process module is quite generic and can be parameterized in detail in order to achieve a sufficiently realistic model of a specific machine. Machine behaviour is depicted with state charts – each operating state has a definable duration (e.g. based on certain time or trigger events) and is connected with a certain consumption of a resource (described as value or equation, e.g. depending on process parameters). Thus, with this technique the dynamic consumption behaviour of (e.g. all forms of energy), any (auxiliary) materials or even emissions can be modelled.

TBS Module(s): TBS-related energy demand of the actual production equipment (e.g. compressed air) serves as input for appropriate partial TBS-models (e.g. for generation of compressed air). Herewith additional energy consumption (e.g. electricity needed to generate compressed air) of TBS is calculated based on detailed equation-based sub models. Additionally TBS models simulate the possible supply with energy or media – interacting with the production system, a lack of e.g. compressed air (air pressure to low) leads to failures of production machines.

Evaluation and Visualization Module: the total energy demand of the production site as a sum of consumption of production itself and TBS (standard resolution of 1 second) is passed to the evaluation and visualisation module. Based on specific contract models (e.g. including peak costs and different fees in the case of electricity) and environmental background data the actual economic and environmental impact of energy and resource consumption are calculated. Production performance variables are also being considered, e.g. in order to calculate key figure like the energy efficiency (as ratio of output and energy input) of the system. Additionally an interface to E!Sankey® (developed by IFU Hamburg GmbH, www.e-sankey.com) was established which allows a dynamic visualisation of energy flows in the factory with Sankey diagrams in order to provide decision support.

Production Planning and Control (PPC) Module: Production planning and control capabilities are also embedded which allow detailed configuration of capacity planning/machine allocation or lot sizes for several individual products/orders process chains . They can also run through the production simultaneously.

Through combination and parameterization of different modules any process chain or whole factory can be modelled. Thereby it is also important to mention that this is also true for flexible production systems without rigid coupling of machines (which typically requires significant effort in common simulation tools). The modelling of the production system structure and the specific parameterization can be done relatively fast and without extensive knowledge of manufacturing system simulation. Furthermore, through interfaces to common tools like MS Excel, those activities can be done totally separated from the actual simulation environment. In this case just starting the simulation run is necessary in the actual simulation tool. The proposed energy flow oriented manufacturing system simulation approach consequently focuses on the requirements given by the holistic factory system definition as shown above as well as resulting criteria. Compared to the current state of the research many advances can be pointed out: All relevant internal and external energy flows can be considered with their time based behaviour and interdependencies. Diverse field of actions can be addressed in order to derive and evaluate measures for increasing the energy and resource efficiency (e.g. evaluation of single machines or TBS measures on factory level, strategies for improved planning and control of process chains). Different dimensions of evaluation are being considered in detail simultaneously, actual decision support is given (e.g. illustration of consumption drivers) and also the issue of uncertainty can be addressed. Finally, the modular structure allows broad applicability. The possibility to depict flexible production structures of diverse scale and scope as well as the easy usability also addresses specific needs of SME (small and medium sized enterprises).

5 CASE STUDIES

Finally two quite different case studies (in terms of production structure and management) shall give an impression about the broad applicability and potentials of the developed approach.

5.1 Weaving mill

The first case study (in parts already introduced in [25]) considers a company running a large scale weaving mill to produce technical textiles which are being used for industrial purposes (e.g. supporting material for abrasive papers, printing industry). The factory of the weaving mill basically consists of a total of 41 weaving machines based on four different basic machines types operating independently (no linkage, every machine with own production program) and almost continuously in a three shift system. In context of energy, each machine needs electricity but also a significant amount of compressed air for operation. In reality the electricity needed for compressed air generation for the weaving mill is even higher than the direct electricity consumption of the machines itself. Actual time based values with respect to different speeds were measured for all machine types and could be transferred to equation based consumption models (Figure 6).

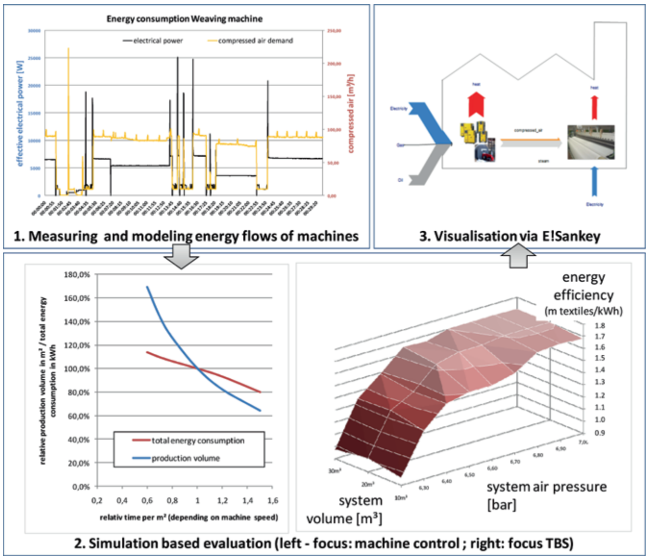

Figure 6: Procedure and fields of action for simulation based improvement of energy efficiency in weaving mill.

The weaving mill with all machines as well as the very sophisticated compressor park (actual dimensions and control of each compressor) was modeled with the proposed energy flow simulation environment and the consumption models for compressed air and electricity were embedded. The validation showed that significant accuracy could be achieved. Although the production program planning has obviously just minor impact in continuous production, two fields of action were identified. As first option, Figure 6 shows the influence of changing operation speed on total energy consumption (direct plus compressed air induced), energy costs and production output. The diagram sensitizes that operation at lower speed might save a significant amount on electricity (spread of >30%) which means a couple of thousand Euro per month on related costs in three shift production. While certainly being no strategy in times of economic upturn (due to less output) this could be a useful strategy for low utilization phases. The second field of action is the dimensioning and control of the compressor park itself. As an example, Figure 5 (step 2) shows the influence of typical parameters like nominal air pressure and system volume (e.g. buffer tank size) on the energy efficiency of the whole system. As an interaction of TBS with production system itself, this also includes the failure of weaving machines if the pressure is too low for operation. One can see that those considerations allow a convergence towards optimal compressor system setup while ensuring full production performance to improve total energy efficiency. Finally, Figure 6 also shows visualization in E!Sankey® on a factory layer. This Sankey diagram is automatically generated and provides a clear picture on energy inputs and outputs of the factory.

5.2 Printed circuit board assembly (SME company)

The second case study considers a SME company which assembles printed circuit boards in a very flexible production environment (no coupling of machines, free flow of orders). As previous analyses showed the total energy consumption of the company is mainly determined by few large processes (e.g. reflow oven, solder waves, compressor) partly with distinctive heating periods before operation. Those consumers and further machines (with smaller energy consumption) which are relevant to depict the logic of the process chains were modeled with the energy flow manufacturing simulation approach and measured consumption patterns were integrated. A typical production program with different products/orders differing in process chain structure (involved machines, sequences, lot sizes) was also applied. Figure 7 shows the simulated total electrical power demand (direct consumption and compressed air induced, here as 15min interval) for a whole production day.

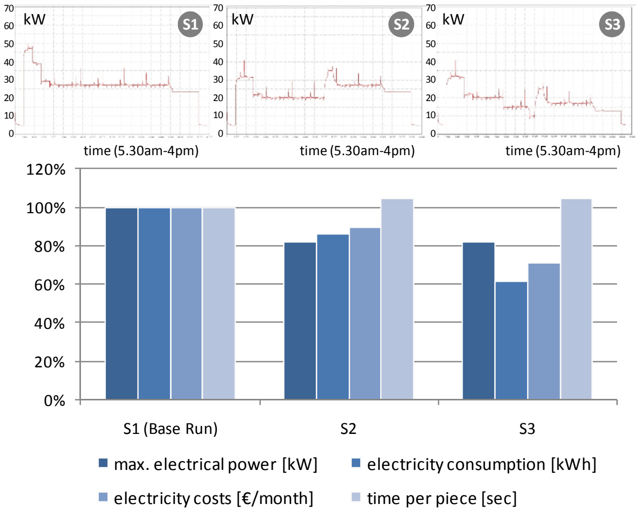

Figure 7: Simulation results for second case study - daily load profile for electrical power for different scenarios (15min interval).

S1 as base run depicts a typical case where all machines were just turned on at shift start (6am) for pre-heating and run the whole day (either in standby or operation mode) in order to guarantee ideal availability over the day. The load profile reveals the significant start-up peak and the quite constant consumption over the day on relatively high level (until shift end at 4pm). S2 shows the effect of a more energy conscious operation of the company while firstly turning machines on at the time when an order actually occurs. The results show that a significant decrease of maximum power and total electricity consumption can be achieved through this measure with just minor effect on production performance (through higher waiting times due to start-up/heating processes). S3 goes even further and reveals the effect of an (automatic or operator induced) shut-down after certain time of machine idleness (but just for machines where it is technically feasible). This results in even more savings on electricity consumption and related costs. Certainly, since this is just a sample day, the effect of these measures needs to be verified for different production scenarios and in industrial practice. However, the general potential looks like promising and the achievable order of magnitude encourages to actual application in the company. Since just selected scenarios were considered, through a more systematic design of measures even more saving potential seem to be possible for certain cases.

6 SUMMARY AND OUTLOOK

Based on the necessary holistic factory system definition towards energy and resource efficiency and against the background of the urging research demand in that field, the paper presents an innovative energy flow oriented manufacturing simulation approach. The concept was described and the advances in comparison with the state of research were pointed out. To underline the broad applicability and potentials of the developed approach two very different case studies were presented and different measures to improve energy and resource efficiency on diverse fields of action could be identified. Besides practical application further research will focus on the development of more detailed TBS modules, the conduction of actual optimization studies and the coupling with detailed machine/process simulation.

7 ACKNOWLEDGMENTS

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