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Development and application of a modular- based, multi- level approach for increasing energy efficiency

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ABSTRACT

This paper presents a methodology how energy consumption and energy inefficiencies can be quantified for industrial processes based on a general, branch- independent approach for the purpose of increasing energy efficiency. For many companies the information of the actual energy use of their processes is very limited. Therefore, knowledge of energy consumption is only available on an overall basis and the product- specific energy costs are often calculated with a common cost- plus system. This deficiency in information is part of the reasons, why energy efficiency potentials are often neither known nor realized. For that reason a general approach is needed, which (1) uses the actual economic data of a company and (2) combines and compares it with thermodynamic analyses in order to (3) calculate the actual energy consumption of processes and products to (4) identify and quantify the energy efficiency potentials.

The suggested general approach is branch- independent and analyses energy efficiency potentials. Firstly this is conducted through a modular- based, three- level industrial model mapping process. Each module contains production units (industrial plant assets), where main industrial processes are integrated into one module. The different modules are then connected on different levels in order to find product- specific production pathways. Secondly, both a top- down and a bottom- up approach are implemented. The top- down approach uses economic and overall energy consumption data and transfers it to the modular view. The bottom- up approach applies technical data of the used production units and quantifies energy consumption based on thermodynamic and general technical data.

Through this methodology it is possible to derive actual energy consumption of processes and corresponding manufactured products, which furthermore helps to understand energy cost generation for various products. It also divides the possible inefficiencies into a technical and an organisational part which leads to technical, organisational and social measures.

The described modelling of industrial processes on a modular, multi-level approach is applied to case studies for several Austrian foundry companies. Actual data is used for (1) building the model (2) evaluate the model and (3) make the actual energy consumption of processes more transparent. The case studies show that important information is concealed through wrong energy allocations and thus prevents the knowledge of energy efficiency potentials.

The application of the model approach in foundry companies enables to (1) calculate energy consumption for various important modules, (2) transfer economic and technical data to a process- oriented picture of the energy use, (3) calculate energy demand of various products and (4) provides the first basis for energy efficiency potential analysis.

INTRODUCTION

In the last decades companies (e.g. industry) around the world were faced by serious efforts to reduce energy consumption and increase energy efficiency on national and international levels. Besides a push from scientific communities from different disciplines, like technology, natural sciences, economics, or psychology, also legal framework conditions were developed and established to support the implementation of energy saving strategies (Geller et al., 2006; Thollander et al. 2007; Gupta & Ivanova, 2009; Kanellakis et al., 2013). A recent contribution to this issue is the commencement of the European Energy Efficiency Directive in late 2012 (European Commission, 2012). There it says that '… all EU-28 countries are required to use energy more efficiently at all stages of the energy chain, …'. Thus European Countries had to develop national energy efficiency plans and targets to achieve the overall objectives of the directive. As current trends show only about half of the targeted 20 % of reduction in energy use will be reached by 2020 (EEA, 2013).

Especially energy-intensive industries, as is the foundry industry, are challenged to reduce their energy consumption substantially, to increase their energy efficiency and their environmental performance in general to reach the given target values. As these industries are accountable for 30 % of the total energy end-use (Eurostat, 2011) this leads to the assumption of important saving capabilities. Foundry operations are known as very distinguished and complex, and shifts in the production and applied processes favor this trend. Besides the production of raw castings, foundries nowadays also design the parts, build the tooling, cast the prototypes, make the castings, machine them, assemble the castings, and produce components or assemblies to be placed in downstream assembly lines (CFA, 2013). The increased complexity of foundry products leads to a growing need of energy, which is already innately high.

Although the branch is engaged in rising their energy related performance (CFA, 2003; Helber & Steinhäuser, 2011; Davies, 2012; Eronen et al., 2012) there exists an unused potential for improvement. Main improvement areas include waste heat recovery, the optimization of heat treatment, processes and cast pieces, the substitution of raw material, and residual gas recovery (Krause et al., 2012). According to a study of the Institute of Founding, foundries assess themselves a potential cut down of 15% of their energy consumption (Svensson & Sommarin, 2011). This induces the presumption of existing barriers to implement energy conservation measures in these companies as source of an „energy-efficiency gap" (Rodin et al., 2007).

As several studies show, barriers can be classified to economic, behavioral or organizational causes (Sorell et al., 2000; Sorrell et al. 2010; Rodin et al., 2007; Trianni et al., 2013) and mainly refer to a lack and imperfection of information. Economic obstacles include hidden costs of providing information, risk aversion against short-paybacks and limited access to capital, as well as inconveniences resulting from principal-agent-relations. Other important barriers may result from different values, rationalities and commitment affecting the attitudes to support energy conservation measures. Not least organization cultures and the power of energy managers or responsibles have strong influence on real efforts in this field. At the same time, the most important drivers for energy efficiency measures refer to long term company strategies and committed individuals (Sorrell et al., 2000; Trianni et al. 2013). Practical experiences from industry complete these theoretical findings, whereat a combination and interdependence of various barriers implicate an increase of the complexity of the challenge: to overcome implementation obstacles and to close the „energy-efficiency gap".

The focus on an extremely heterogene sector like the foundry industry evocates an integration problem of technical, economic and ecologic methods and assessment proceedings to enable an integrated view on energy efficency measures on a product level. On one hand unclear energy cost allocations on company level deduced from controlling do not reflect a detailed picture of real energy consumptions. On the other hand energy efficiency analyzes are in most cases oriented towards the past (trend developments) and not determined by a route specific proceeding. This means that a systems oriented viewpoint of energy costs and energy consumptions on product level is needed to identify promising potential to integrated cost-effective energy effiency realization. The initial situation and first research analyses lead to the assumptions that (1) efforts regarding controlling and energy conservation techniques provide energy reduction and improve costs (Torielli et al., 2011), and (2) that product-related energy efficiency has to be evaluated over the lifetime of a product for complete information regarding potential efficiency measures.

MODEL DEVELOPMENT

In order to confirm the hypotheses and investigate the efficiency potential in the foundry industry, the modular- based, multi-level approach was developed. The model/approach was generated through collaboration between the experience and know-how of the Austrian Economic Chamber – Association of Austrian foundry industry and their commercial partners, and science, i.e. the Montanuniversitaet Leoben and the Austrian Foundry Research Institute (ÖGI). Furthermore it is result of bringing together exiting knowledge from theory and praxis gathered in the foundry sector.
The approach enables the derivation of actual energy consumption of processes and corresponding manufactured products, and leads therefore to a better understanding of cost generation. Moreover, the methodology identifies energy efficiency potentials and merges them to a model based approach for the planning, evaluation and optimization of energy consumption in the foundry industry.

The model is based on three scientific aspects:

- Heterogeneity aspect – e.g the foundry industry is a very heterogeneous branch including the production of various different products and production processes.
- Benchmarking aspect – it is important to be able to compare different systems in foundry production sites.
- Life-cycle aspect - the whole product life cycle should be included in the model development.

Based on these requirements three main evaluation systems are defined and implemented into the model composition (figure 1).

DEFINITION OF THE MODEL COMPOSITION

The first requirement of the model is to be able to analyze a heterogeneous branch with its different production sites and units on either a lower or higher level. For that reason the system analysis is based on a modular approach which enables to fulfill the mentioned criteria. Modules are defined as main processes of foundry production sites and contain various different production units which are used for the same main processes.

A typical foundry process can be characterized through several main processes e.g. pattern making, mould and core production, melting and metal treatment, casting, post-casting operations, heat treatment, finishing operations etc. (European Commission, 2009). Those typical processes, which occur in different forms in any foundry company, are defined to be the main or primary modules of the model (Ke et al., 2013). Besides those core processes, several other processes can occur. For instance sand making and preparation processes may occur in lost-mould casting used in steel casting foundries, whereas other foundry products are produced with permanent metal moulds. For those foundries, sand making and preparation is of no importance. Due to this fact, several secondary modules are to be defined. At last, in addition several support processes may occur due to the specific foundry product, e.g. pressurized air units. Those will be defined as support modules. Important to notice is that only the primary modules are directly needed for the product to be produced and others only provide operating materials or process energy.

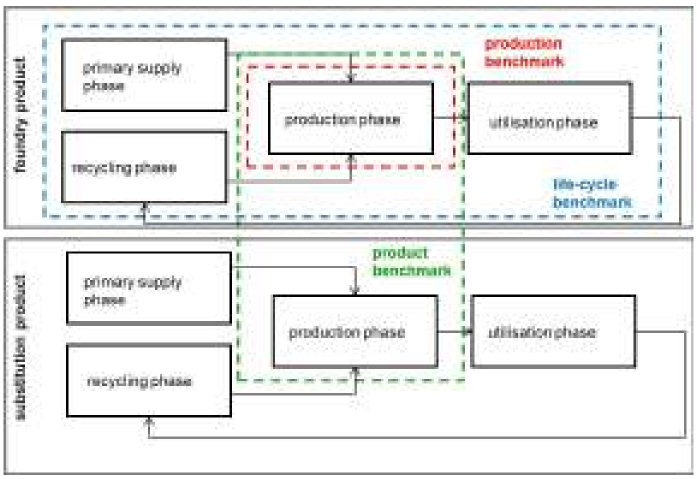

Figure 1 Evaluation systems of the model

The modules are part of the whole production process, where the use and connection of the modules completely describes the production site of a foundry. This level is set to be level 2, whereas the production site is set to be level 1. The different modules are no physical units and are completely depending of the production units which they contain (level 3). Furthermore, the modules contain a group of different production units (e.g. heat treatment for heat production) (figure 2).

This model design offers the possibility to analyse all three given systems (figure 1). Due to this modular representation it is possible to define various key processes. Furthermore it is possible to analyse key performance indicators, like energy efficiency, on a multi-level basis (offers the possibility to benchmark production units), key processes (modules) or even the whole production site. In addition, modular design allows the usage if the economic (top-down) and a thermodynamic approach (bottom-up) to analyse energy efficiency.

DEVELOPMENT OF THE MODEL DESIGN

As the hierarchic composition of the approach is defined, the next step was to develop the model design. The question is which information or data should be used in order to gain insight into energy efficiency potentials. The analysis of Austrian foundry companies shows that the data consistence and availability are limited on process or product level. For instance, electricity demand is only measured on a monthly basis, natural gas flow meters only measure natural gas demand of several melting furnaces together, mass balances are completely missing.

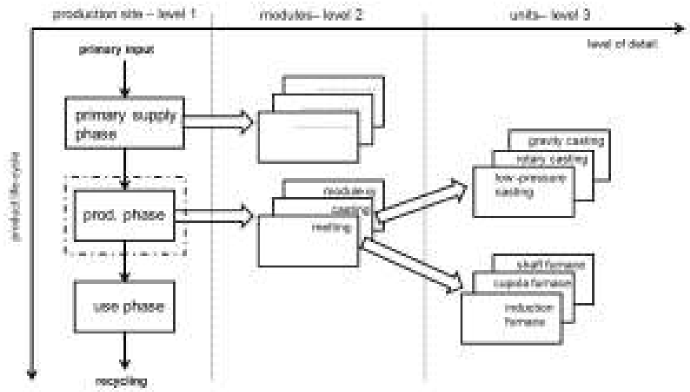

Figure 2 Hierarchical model composition

The data source which is available in any foundry company refers to economic data from the controlling department. This data is used for (1) the accounting of energy costs, (2) invoice and billing and (3) target cost calculations. The accounting data are then segmented into cost centres which burden the energy costs of the produced products. From this point of view, energy consumption can be calculated from the allocated energy costs of every cost center. The analysis of those energy consumptions can give first information about energy efficiency potentials, while energy demand is calculated directly from the energy costs. However, this conclusion cannot be generalized due to two reasons: (1) constitution of cost centers and (2) application of the allocation principle.

The first problem describes the fact that cost centres not necessarily correspond with the physical production units and are therefore not representative for their energy utilization. Secondly, allocation of energy costs, and therefore energy consumption, is allocated through arbitrary formulas based on historical or empirical data. However, economic data are expected to be available in every foundry and the utilization of these data is necessary.

This principle of using economic data in order to characterize energy utilization and energy efficiency analysis is integrated into the model design through the top-down approach. On the other hand side, a bottom-up approach is applied in order to determine the actual energy utilization based on thermodynamic relationships and physical properties. In comparison to the top-down approach, which uses aggregated data on level 1 and level 2, the bottom-up analysis is applied on the production units of the site (level 3). The objective thereby is to determine (1) the actual energy consumption and (2) the theoretical energy consumption of the foundry production units based on a unit-model for different foundry products in order to characterize the production side based on thermodynamic calculations. The calculated production units can then be used to determine the corresponding module key indicators. With an attached database which contains benchmark and evaluation data the model design is outlined in figure 3.

Through either an economic allocation or a thermodynamic calculation, energy consumption is determined on the module point, as well as for the higher and lower levels. This level design allows comparing indicators either for the production units, for modules or even the whole production site. This comparison of indicators within the company's site is defined as internal benchmark (figure 3). Using this methodology allows to compare the main processes of metal melting throughout different companies with the indicators of the module metal melting, where boundaries are clearly defined. Self-evident is the possibility to compare melting chambers through their characteristic indicators, like thermal efficiency.

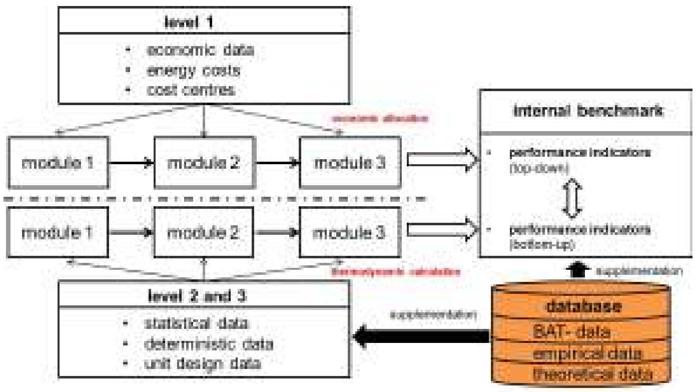

Figure 3 Model design

Through the integrated calculation of the modules from the bottom-up approach it is further possible to compare performance indicators as well on company level. On this level the direct comparison between product-specific energy consumption is of interest. From the top-down approach, usually, only the calculation of a mean product is possible due to missing product-specific data of the cost centers. However, the bottom-up approach determines every specific product through the chosen process steps within the modules. It is therefore possible to simple determine product-specific indicators, based on different process routes in combination with product-specific information like product weight. The internal benchmark can then be carried out between a mean product and a specific product in order to find the related energy costs. This is relevant due to the evaluation design in figure 1, which demands for a product-view in order to carry out the substitution and life-cycle evaluation.

The database provides the scale for the evaluation of actual energy utilization through theoretical, Best-Available-Techniques (BAT) and empirical data, like branch-typical energy utilization indicators. Through this evaluation scale it is possible to either compare the analyzed company with the theoretical minimum, to best-practice processes or to mean values of the same branch. The first benchmark shows the absolute energy efficiency potential, whereas the second one shows the difference between the company's efficiency and best practice efficiencies. The third benchmark offers the evaluation of the company to its branch or to other companies, which offers an opportunity for companies to identify real potential for energy efficiency.

THE TOP-DOWN APPROACH

Economic data is used in order to quantify energy consumption based on a modular, process-oriented view. For that reason five steps are developed:

- economic data acquisition
- allocation of the cost centres to the modules
- calculation of the standardized energy consumptions
- calculation of energy consumption for each module and cost unit
- calculation of energy indicators

The first step is to gather data from the controlling department or any other department which is able to supply the needed information from cost accounting. This information mainly contains the definition of the cost centres and their corresponding energy costs. The data acquisition process is crucial for the whole approach, because the quality of the data has influence on the calculated indicators. The data should be analysed in detail in order to know how the energy cost data was generated for each cost centre. Costs could be calculated based on the physical consumption of the corresponding production units or can be arbitrarily allocated in the cost-plus system.

A pessimistic approach would assume that costs derive from the latter case. However, the analysis of foundry companies in Austria showed that the first case also appears. In this case detailed measurements of energy carriers like electricity or natural gas were available as well as a list of production units assigned to their cost centers. The result of this step is a matrix (A) containing m rows, one for each cost center and n columns, representing the used energy carriers in their original units.

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} (m \times n) \quad (1)$$

with a_{mn} representing the energy consumption of the nth energy cost unit of the m th cost centre in original units (Nm³, kWh,m³).

The second step is to allocate the different cost centre to the modules.

This step transforms the function-based view to a process-based view of energy consumption through a simple boolean assignment. Matrix (I) represents this allocation matrix, where 1 means full allocation and 0 stands for no allocation.

$$I = \begin{bmatrix} i_{11} & i_{12} & \dots & i_{1k} \\ i_{21} & i_{22} & \dots & i_{2k} \\ \dots & \dots & \dots & \dots \\ i_{m1} & i_{m2} & \dots & i_{mk} \end{bmatrix} (m \times k) \quad (2)$$

with i_{mk} is representing the allocation of the mth cost centre to the kth module. Note that the number of rows must be equal to the number of rows from matrix (A) and that

$$\sum_k i_{mk} = 1 \quad \forall m \quad (3)$$

If energy consumptions of the cost centres are calculated from the corresponding production units and they can be clearly assigned to one specific module, energy consumption of the modules can be directly calculated.

However, this ideal case usually does not apply due to the reason, that either (1) cost center energy consumptions are arbitrarily assigned from the overall energy consumption or (2) the production units assigned to a cost center are not physically part of the module to which they are assigned through step two. This problem is called the allocation problem (figure 4). In order to solve this problem and generate the right process view of the cost centre-energy consumption, step three is introduced.

In this example all production units (Ai) are determined through measurement equipment and the consumption of cost centres 1 and 2 are calculated as sums of the single units. The cost centers are assigned to module 1 and 2, which shows that the production unit 3 (A3) is clearly assigned to the wrong module. This unit is physically part of module 1 but its consumption is assigned to module 2 due to the boolean allocation. Therefore corrected energy consumptions for those cost centres must be calculated before assigning them to modules. Note that it is not possible to make a different cost centre-module assignment through allocating f.e. 50 % of a cost centre to one, and 50 % to another module, because different energy carriers are part of this assignment which would partition all energy carriers in the same way, even if the assignment would be wrong. This correction of energy consumption must be therefore calculated for each and every involved energy carrier or cost unit.

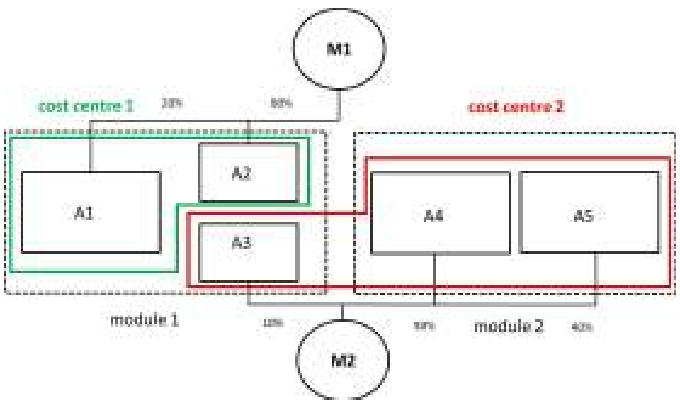

Figure 4 Graphical view of the allocation problem

The corrected energy consumption values can then be calculated for every cost centre represented by the corrected matrix (Ac).

$$A_c = \begin{bmatrix} a_{c,11} & a_{c,12} & \dots & a_{c,1n} \\ a_{c,21} & a_{c,22} & \dots & a_{c,2n} \\ \dots & \dots & \dots & \dots \\ a_{c,m1} & a_{c,m2} & \dots & a_{c,mn} \end{bmatrix} (m \times n) \tag{4}$$

where $a_{c,mn}$ represents the corrected energy consumption for every cost centre and energy carrier.

Step 4 is the crucial step in order to transfer the functional-based view of energy consumption to a process-based one. For that, energy consumption values of (Ac) must be transferred to every module, based on allocation matrix (I). This is done through a simple matrix multiplication, multiplying the transpose of the corrected matrix (Ac) with allocation matrix (I).

$$M = A_c^T I \ (n \times k) \tag{5}$$

The result is the module-energy matrix (M) which contains the energy consumption of the nth energy carrier of the kth module. Through this method of transferring the energy consumption to a process-view, the top-down analysis fulfils the requirements of the described model design. The energy consumptions of the modules can be compared through different company sites.

Since the energy consumptions are still in original units, they have to be converted into one standard unit which can then be added up. This unit is set to be kWh and will be calculated for every energy cost unit, according to a simplified version of the quality equivalent method (Patterson, 1996) which describes conversion factors for each energy unit into kWh. The unified module-energy matrix (Mu) is then calculated through

$$M_u = M \cdot c_n \tag{6}$$

with c_n to be the conversion factor of the nth energy cost unit, calculating the energy consumption of the nth cost unit for the kth module in kWh.

The last step is the calculation of two energy indicators which (1) represent the module-energy matrix as an indicator and (2) open up the analysis of energy efficiency potentials from two different views. The first indicator is called the energy carrier intensity and describes how intensive one specific energy cost unit is used in a specific module. The following formula defines this indicator:

$$eci_{nk} = \frac{m_{u,nk}}{\sum_n m_{u,nk}} \tag{7}$$

An energy carrier intensity of 0.1 for a defined cost unit and module means that 10 % of the overall energy consumption of the module is caused by this specific energy carrier. This information is very useful when focusing on the optimization of modules or their key processes or in evaluating the corresponding energy cost generation for a module. If the energy consumption of a module should be optimized, this indicator shows on which energy cost unit to focus.

The second important indicator which can be derived from the unified module-energy matrix, is the module intensity. It describes the share of module for the generation of a specific energy carrier.

$$mi_{nk} = \frac{m_{u,nk}}{\sum_k m_{u,nk}} \tag{8}$$

A module intensity of 50 % for a specific energy cost unit means that 50 % of its energy consumption is generated by a specific module. The definition of this indicator supports energy cost unit optimization.

For both presented indicators, ABC-analysis can be worked out for calculating either where to locate energy reduction potentials when a specific module should be optimized (energy carrier intensity) or to locate which module should be optimized with the highest priority if a certain energy carrier should be reduced (module intensity). Both energy indicators are derived from the top-down methodology and describe the energy consumption on a process-based view using only easy-accessible economic data.

THE BOTTOM-UP APPROACH

In contrast to top-down approach, the bottom-up analysis uses thermodynamic and physical data of the production units itself to calculate energy indicators. Those production units are summarized into modules which are then connected to find the energy indicators on production site-level. The bottom-up approach is divided into 5 steps:

- assignment definition of the production units to modules
- modelling of production units
- determination of key indicators
- linking of actual used production units to calculate corresponding module
- linking of modules to calculate the whole production site

The first step is to define which production units appear in foundry processes and to which module they should be assigned. This is conducted either through literature research (e.g. BAT documents) or through field research in Austrian foundries. The module melting for instance contains production units which occur in the melting shop of a foundry. Examples are the induction furnace, the cupola furnace or different gas-fired furnaces. Overall energy-relevant mass and energy streams which occur for those units are described in literature (European Commission, 2009). Those descriptions build the basis for the second step, where the units are modelled for all energy relevant streams. Figure 5 shows how production unit is generally modelled in this study.

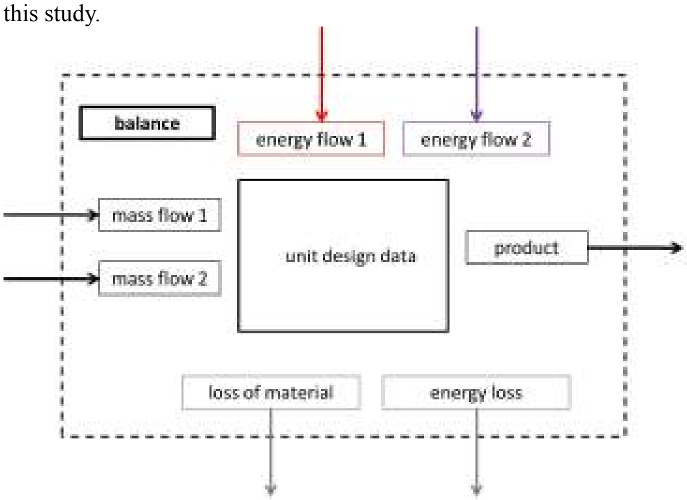

Figure 5 General model of a production unit

This general model (it can be applied with adaptions to any production unit) is used to determine the physical-thermodynamic properties of the units which are based on unit design and production data. The balance of the model is calculated with indicators relevant for the downstream steps e.g. (1) primary, secondary and recirculation shares of the product, (2) specific energy consumption for all energy streams, (3) specific loss of material, flue gas and general specific heat loss and (4) thermal efficiency. However, not all of them can be calculated for every production unit (e.g. calculation of thermal efficiency for a production unit which uses electricity for cooling is not relevant).

The key issue in this general model is the word specific. The reference is always presented by the product-output, thus all specific indicators are calculated based on the product-output. This has the advantages that particularly energy consumptions and energy and material losses are automatically balanced and no further calculation for recirculation material has to be included. With the actual design data of a production unit and the corresponding modelling, the determination of the production units focusing on energy utilisation is independent of the dynamic operating mode.

A descriptive example is the operation of a melting furnace, which is f.e. melting primary aluminium with the help of a gas-fired melting furnace. The operation of such a furnace can be clearly determined through either a statistical or deterministic approach (Giacone & Manco, 2012). However, the main purpose of the bottom-up approach is to calculate specific energy consumption of various products. If for instance material losses or scrap occur in any further process unit, specific energy consumption of the product is increasing for the furnace.

The fourth step represents the link between the design condition of every production unit and the actual operation. Every product is characterized through inherent properties like f.e weight and through a defined process route in the production site, since different products may use different process steps. For that reason, every product has a specific module characteristic determined through the choice of its production units. In this step the calculated key indicators on production unit level are now used to calculate specific indicators for the product on module level. The indicators contain, amongst others, the specific energy consumption of the product for every module and energy carrier. It can be seen that the choice of the calculated indicators corresponds with the indicators generated in the top-down approach, due to the fact that the goal of this approach is to compare energy efficiency potentials based on two different data sets.

In the final step, the same methodology as in step 4 is used, with the difference, that now the calculated modules are linked based on the company's production site in order to calculate the key indicators on production level. Those can be again compared on site-level with the indicators from the top-down approach.

SETTING UP THE DATABASE

The database (figure 3) is implemented for two reasons. First, it provides the basis for the internal and external benchmark. Data from BAT documents, theoretical minimum energy consumption of productions units and mean values of the whole branch are implemented in order to compare it with the derived energy indicators from the model. Secondly, it contains specific production unit data, which are able to complete missing data during the model process sequence.

MODELL PROCESS SEQUENCE

The last step in developing the model is the definition of the model sequence. In order to fulfil the model design, the basic sequence of calculation steps must be defined. Figure 6 and figure 7 show the result.

The process sequence of the model starts with the data input which is required through the data acquisition in the foundry companies. In addition, the database can support the data input if necessary data is missing. The next step is the model analysis through the described approaches including the internal and external benchmark. Through the model analysis the status-quo of the actual energy efficiency can be determined. Followed by the optimization procedure, which contains different optimization tools like exergy- and pinch analyses the optimized system is determined. The exergy analysis is therefore the basis for a first quantitative evaluation of the thermodynamic processes. The next step is the pinch-analysis which determines the possible heat recovery throughout the company's processes. Both methods are used simultaneously in the model procedure. Parallel the database works out the minimum or theoretical system focusing on energy efficiency and provides the scale for the evaluation. Figure 7 shows how the different systems are then evaluated. The comparison between the status-quo and the optimized energy consumption profile describes the energy efficiency potential which can implemented through defined measures, determined during the optimization procedure. The systems are always compared with the theoretical minimum in order to determine the theoretical potentials. The defined energy efficiency potentials are categorized into technological, organisatorical and social measures which depend on the energy efficiency potentials to be found.

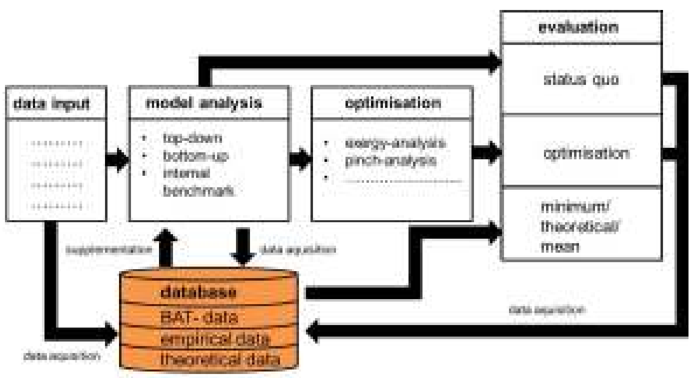

figure 6: model sequence part 1

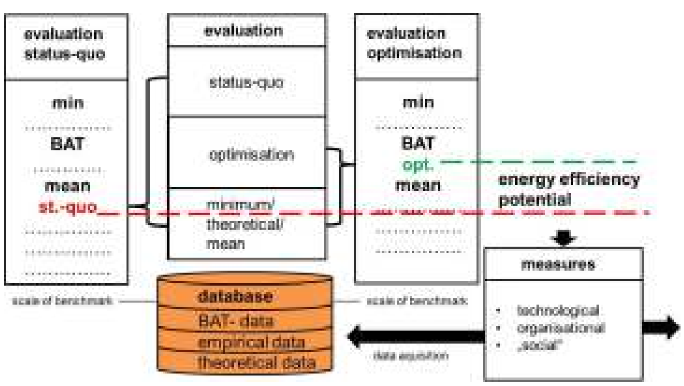

Figure 7 Model sequence part 2

APPLICATION OF THE MODEL APPROACH

The application of the presented model was carried out in three Austrian foundries. Data are anonymized due to privacy reasons. The application of the model includes (1) evaluating the applicability of the designed model to the foundry industry and (2) to determine actual energy consumption.

DATA ACQUISITION METHODOLOGY

To collect all relevant data needed as input of the model, a specific data acquisition methodology was applied. First it has to be noted, that the analysed companies show different data sources, in terms of quantity and quality. While one company is able to deliver detailed data on production equipment and their design and operating data as well as cost centre energy consumptions, others only provide yearly unassigned consumption data. However, the claim of the model approach is to use both economic and thermodynamic data to gain a first insight into energy consumption. Even if thermodynamic data is missing, inefficiencies can be detected through careful analysis of allocated energy costs.

Figure 8 shows the data acquisition methodology, which was developed for the application process.

First, a literature review of the behold companies in order to collect basic information on products, processes and production units was done, which included a survey of different sources[Fachberband der Giessereiindustrie (editor), 2012; Umweltbundesamt (editor), 2012].

Based on this information, a questionnaire and specific data sheets are developed in order to collect more details. The questionnaire serves as the tool for data acquisition (level 0 in the model nomenclature) and can be used for a first evaluation of the company's energy strategy. It contains several key questions, which can be used to evaluate the energy strategy of the company. Questions and analysis methodology is based on earlier results dealing with energy strategy evaluation [Posch W., 2011].

The data sheets are formulated to acquire actual design and operating data of production units with high detail (level 3 in the model nomenclature). Those data sheets contain all relevant parameters, like temperature, pressure and mass flow, in order to determine energy, exergy and pinch analysis.

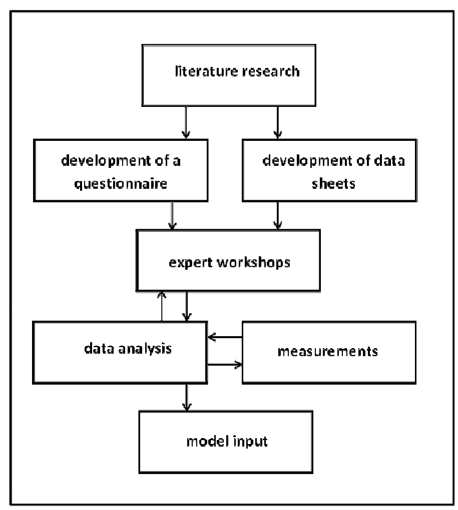

Figure 8 Data acquisition methodology

In the best case, data acquisition methods are finished before starting with the first workshop. However, it appeared, that some companies had problems to provide the required data, even such of low quality (f.e. rough estimates). The duration of the workshops last around 1.5 days, where at least people from three different functions should be included:

- Energy managements department or energy manager
- Economics department
- Maintenance department

The people from economics and maintenance department are able to provide reliable economic and thermodynamic data, whereas the energy manager can contribute through his knowledge of earlier energy improvement actions.

Due to that reason two more parallel steps were implemented to analyse given data with a focus on quantity and quality. Quality issues especially involve the analysis of the type of data, like measured, calculated or estimated values. Depending on the need for further data acquisition, either further workshops or measurements were carried out, till data quality was acceptable and could be freed and issued as model input.

APPLICATION OF THE TOP-DOWN ANALYSIS

The second step in the model application process is the execution of the top-down analysis. For this reason, the steps described in 0 were chronologically carried out. The cost centres and their energy cost units were assigned to the modules, followed by the determination of the module-energy matrix which provides the process-oriented view of the company's energy consumption. The original data was given through energy consumptions of cost centres in original units and transferred into an overall consumption for each module. If the whole energy consumption is divided by the amount of foundry products in terms of mass, a mean specific energy consumption indicator (SEC) can be calculated. Note that this indicator describes a mean SEC of a fictitious product. Figure 9 shows this SEC split for every module, occurring in the analysed companies.

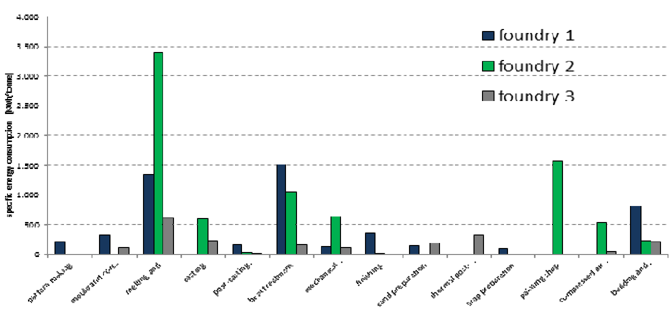

Figure 9 Mean SECs of the foundries

Figure 9 shows the specific energy consumption per tonne of finished casting products for the three foundries. Huge differences in the absolute energy consumptions are clearly visible. Foundry 2 not only shows the highest specific energy consumption in the melting module, but also the highest energy consumption as a whole (210 GWh/a). In comparison, foundry 3 shows the lowest SEC for nearly every module and thus only demands around 51 GWh/a. Note, that not all modules are used in every foundry company due to different products and production processes. However, the claim of the model approach was to provide the possibility to analyse any foundry with a focus on energy consumption, which refers to the applicability of the model.

Not only energy consumptions varied between the companies, but also specific consumptions between the same modules. Focusing on heat treatment, considerable consumption appeared in foundry 1 and 3. This is again due to production process reasons. If consumption per tonne of finished product is used as indicator for the evaluation, foundry 3 consumes less energy for this key process. SECs of modules can then be compared and evaluated between different companies.

The SEC could also be calculated for a foundry unit itself, but the calculated SEC would imply that only one kind of product is produced with the given energy consumption – which, of course, is not the case. Nevertheless SECs of foundry products can be clearly calculated if the share of energy consumption of a product in different modules is known.

The next step is to calculate characteristic energy indicators, described in section 0. First, a determination of module intensities was done. For the underlying companies only electricity and natural gas consumption were important, because they showed the highest consumption rates. Figure 10 shows the module intensities for electricity while Figure 11 shows the indicator for natural gas consumption.

The module intensity provides an insight how a specific energy carrier is split throughout the modules. Thus, if the consumption of a specific energy carrier should be reduced, module intensity provides the basis for which module energy efficiency potentials should be analysed. The module intensity for electricity shows great differences throughout the companies. For foundry 1, highest consumption of electricity can be found in the melting module, whereas the other two use electricity mainly in the modules casting, mechanical- or heat treatment and compressed-air and buildings. Foundry 3 shows a substantial amount of 22.8 % electricity consumption in the module buildings and auxiliaries. The reason for that is the misaggregation of electricity consumption to buildings through cost allocations in the cost-plus system. This misaggregation therefore prohibits the real determination of energy efficiency potentials and is counterproductive for further energy efficiency analyses.

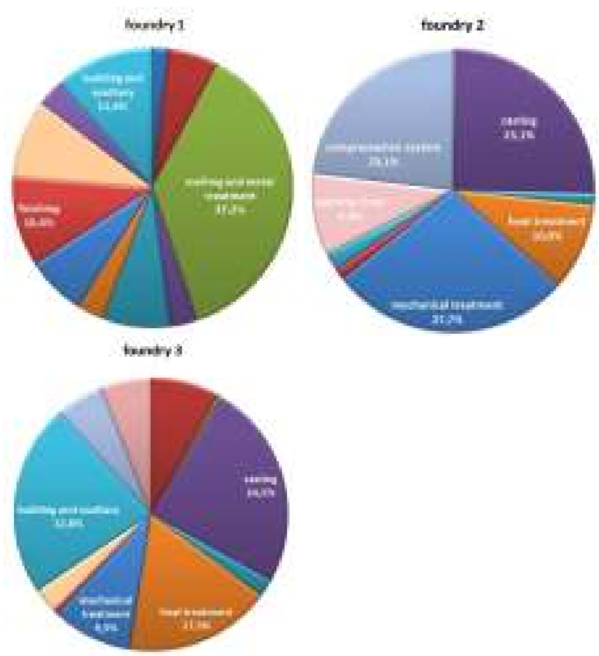

Figure 10 Module intensities for electricity

Focusing on the module intensity for natural gas, the melting shop, represented by the module melting, shows to be the highest consumer. For foundry 2 and 3 the majority of natural gas consumption occurs while melting. Foundry 2 still consumes 32.9 % in the melting module, while the majority is consumed in the heat treatment. Thus if natural gas consumption should be reduced, the melting shop for foundry 2 and 3 and the heat treatment processes for foundry 1 should be further analysed.

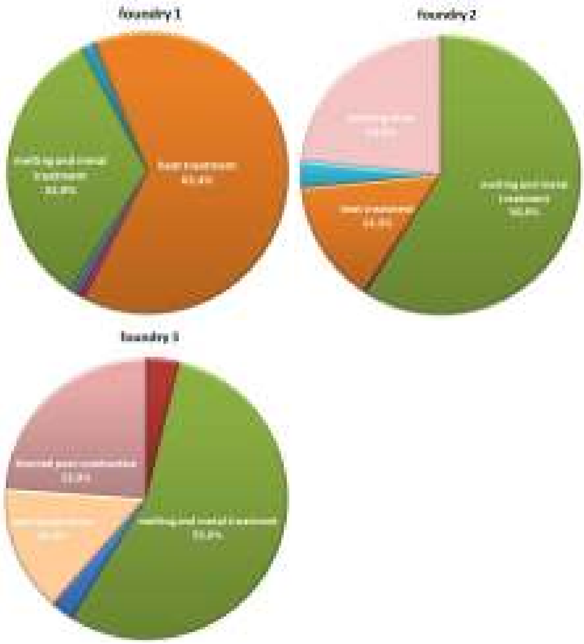

Figure 11 Module intensity for natural gas

The calculation of the module intensity gives a fast insight into energy consumption for different energy carriers and provides the basis on which modules energy efficiency potential analyses should focus on.

The second indicator is the energy carrier intensity which is illustrated in Figure 12. It is calculated for every company and module, but due to a better comparison, the figure only shows those modules which occur in at least two foundries.

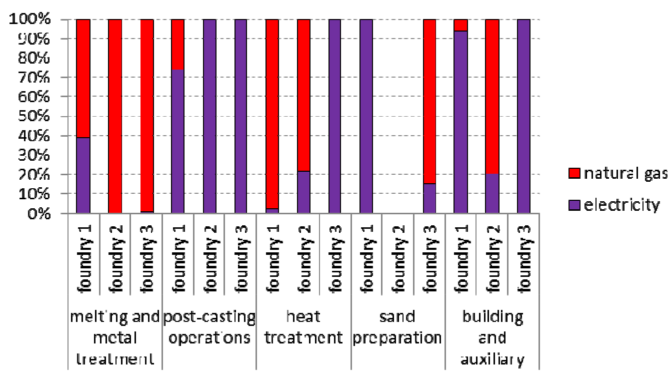

Figure 12 Energy carrier intensities

The energy carrier intensities represent the consumption of different energy carriers in a specific module. F.e. regarding on post-casting operations, foundry 2 and 3 mainly use electricity while foundry 1 uses natural gas as well. Further differences in the usage of energy carriers occur in the building and auxiliary module. Foundry 2 mainly uses natural gas while the other two mainly use electricity.

The model design is defined to enable the analysis of an indefinite amount of energy carriers. Since energy indicators are calculated as numerical values, an ABC- analysis can be used for both energy indicators in order to find either the best module when reducing a specific energy carrier or the right energy carrier if the consumption of a specific module (and therefore key process) should be reduced.

APPLICATION OF THE BOTTOM-UP ANALYSIS

The bottom-up analysis is carried out as the next step in the model process sequence. Through the data input of the acquisition methodology, described in 0, a first survey regarding current production units including their design and operating parameters is possible. The result is a complete definition of operating production units and their assignment to specific modules. For the bottom-up approach a calculation of specific products is crucial. A product is defined through its specific production route (usage of production units) and other parameters like f.e. mass. After analysing the production units, relevant parameters and indicators used for higher level analyses were calculated.

First the modelling of the production units as well as the calculation of the production unit's balances was done. The modelling design of a production unit is described in 0. Based on unit models different results were obtained:

- mass- and energy balances
- material and energy parameters
- energy indicators

The left side of table 1 shows the mass- and energy balance based on the unit modelling. Those balances (1) assure the correct calculation of the production unit and (2) offer the basis for the calculation of relevant parameters and indicators which are presented on the right side.

Table 1 shows exemplarily the result for a melting unit in the module melting.

The parameters are used to specify the production unit in terms of material and energy usage. Due to the fact that energy consumption should be calculated for different products, all material- and energy streams must be balanced on the output side of the unit.

Thus, all specific values are balanced to the net output of molten metal, measured in tons. Knowledge regarding the input of primary- and recycling material used by this unit is crucial, as this is (1) needed for the correct balance of recycling material and (2) for the right calculation of SECs. The advantage of this approach is that operational issues like wastages and other recirculation material are integrated and fully balanced and therefore offer a more realistic view on the reasons for energy consumptions.

Regarding the parameters, the share of primary, secondary and recycling material is important. Primary input describes how much material is delivered from outside the company's boundary. Secondary input is internal input, f.e. the output from another production unit used as input, while recirculation input is the sum of recirculation material like scrap or swarf material. The energy parameters, like SECs of the energy carriers or specific flue gas losses, are required (1) as a basis for higher-level calculations, (2) for the evaluation of the production unit and (3) for the downstream optimization procedure (f.e. recovery of flue gas losses). Note that either parameter is balanced on the product output of the production unit.

Table 1 Modelling result of a melting unit (M1)

mass balance	input	output	
pig metal	735.79		kg/h
swarf	478.20		kg/h
recycle material	195.22		kg/h
molten metal		1,394.02	kg/h
material loss		15.19	kg/h
natural gas	60.99		kg/h
combustion air	1,408.84		kg/h
flue gas		1,469.82	kg/h

material parameters		
primary material input	52	[%]
secondary material input	34	[%]
recirculation material input	14	[%]
material loss	1	[%]
turnout	99	[%]

energy parameters		
SEC natural gas	602	kWh/T
SEC electricity	0	kWh/T
specific flue gas loss	150	kWh/T
specific heat loss	262	kWh/T

energy balance	input	output	
pig metal	0.00		kWh/h
swarf	137.17		kWh/h
recycle material	0.00		kWh/h
molten metal		396.19	kWh/h
material loss		4.41	kWh/h
natural gas	840,12		kWh/h
combustion air	0,00		kWh/h
electricity	0,00		kWh/h
flue gas energy loss		210,10	kWh/h
heat loss		366,58	kWh/h

energy indicators		
SEC total	602	kWh/T
spec. heat recovery pot.	150	kWh/T
thermal efficiency	41	[%]
flue gas loss	25	[%]

The last step is to calculate energy indicators, which enable an evaluation and comparison of the production unit, as definied in the model design.

Different production units may have different energy efficiencies and therefore yield different energy indicators. Table 2 shows all melting units which are part of the melting module of one specific company and the variation of SEC for natural gas.

Those SECs of the melting units are calculated on a statistical approach, where annual mass and energy data was used in order to calculate specific energy consumptions of operating production units. A more detailed analysis of the actual consumption can be done through a deterministic approach, where energy consumptions are modelled on the basis of technical parameters. The gained results are represented in Table 1. Table 2 shows that the melting units have different SECs from 40 to over 124 Nm^3 per tonne of melted metal. Thus the production route of a selected product has great influence on the SEC and therefore the energy efficiency for the whole product. This calculation gives a first insight on which production units optimization procedures should focus.

Table 2 Specific natural gas consumptions of melting units

melting unit	[Nm^3/T]
M1	54.69
M3	55.32
M4	39.73
M5	48.35
M6	62.81
S1	124.69
S2	114.41
S3	103.50
S4	102.01
S5	92.98
S6	103.38
Morgan 1	61.64
Morgan 2	81.66
Morgan 3	81.87
mean	80.50

The next step is to connect the production units as they are needed for a specific foundry product in order to find the higher-level parameters and indicators on the modular and company level. Up to this point, the production units are independent from the actual production process. On the modular level the mass of the product as well as the recirculation of wastage material gets important. On this modular level, all connected production units are balanced on their specific output streams. Assuming a product with a specific production route (and thus the connected production units), the module balances are calculated through the mentioned procedure, where the results are shown in Table 3.

Table 3 Result of the module calculation

modules:	melting	casting	
turnout	95.13	94.09	[%]
input material factor	1.05	1.06	[1]
material loss	4.87	5.91	[%]
primary material input	52.89	0.00	[%]
secondary material input	0.00	100.00	[%]
recirculation material input	47.11	0.00	[%]
SEC natural gas	20.05	3.09	kWh/unit
SEC electricity	0.04	5.37	kWh/unit

The results of the module calculation are based on the parameters and indicators derived from the connected production units; see Table 1. In this example the input for the foundry product is 20 kg. The product specific parameters of all production units in one module are used to determine the relevant parameters on the modular-level. This example only considers the results for the modules melting and casting. The first three parameters represent how material is used in this module. The input material factor is the reverse of the turnover and describes how much more input of material for a specific material output is needed. The material inputs describe how much primary, secondary and recirculation material is used. The last two SECs for electricity and natural gas are again determined through the parameters and indicators of the production units in combination with the actual product- specific parameters. The final result requires over 20 kWh/unit of natural gas in melting, and 5.37 kWh/unit of electricity in casting.

The same calculation was applied for the calculation of these parameters on company level. The applied modules were connected and further input e.g. wastage was integrated into the calculation procedure. Table 4 shows the result.

Table 4 Company result

company level		
primary material input	53	[%]
recirculation material input	47	[%]
material loss	19	[%]
material input factor	1.23	[1]
SEC natural gas	27.30	kWh/unit
SEC electricity	7.22	kWh/unit

The first four parameters describe again how material is used on company level. 53 % is primary material, 47 % is internal recirculation material, while material losses account for 19 %. The overall material factor is 1.23. This means that 23 % additional input material is required for one unit of output. This parameter is relevant if material use is evaluated through life-cycle analysis. The example only considers the modules melting and casting. Thus it is clear that SECs will rise when more modules, f.e. the mechanical treatment module, will be considered. The overall SECs of natural gas and electricity are 27.30 and 7.22 kWh/Unit, respectively.

Through this approach of modelling and connecting production units from the bottom to the top it is possible to correctly describe the production units but also to take into account recirculation material, wastages and product weight on three different levels. This proceeding offers the possibility of (1) comparing production units but as well key processes through a modular-design between companies and (2) of evaluating energy consumption with the help of f.e. theoretical values or BAT data. The presented parameters in Table 4 only represent a selection of possible indicators, which can be calculated. Regarding the comparison of the top-down and the bottom-up approach, SECs can also be calculated on the basis of mass, f.e. tons. Those would be directly comparable with the results given in Figure 9 and provide a basis for:

- the evaluation of SECs of specific products and for a fictive mean product,
- the determination of the misaggregation of energy consumptions to several cost centres and
- a future LCA analysis through a coherent material and energy balancing throughout the company's processes

The optimization procedure can be carried out with the derived parameters like share of material losses or theoretical heat recovery, where f.e. the pinch-analysis can bring optimization results. It is also possible to determine best routes for product production, and the technological efficiency of their production units. Those questions will be answered through future research work and the application of the model.

SUMMARY AND CONCLUSION

This paper presents a new methodology for analysing energy efficiency in the foundry industry. The methodology consists of the development of a model, which uses both economic and thermodynamic data, in order to determine energy efficiency potentials. The model is also providing the basis for benchmarking inside and outside the company's boundaries, like the benchmarking of substitution products on different system levels. It therefore determines energy efficiency for production units, key processes (modules) and for the whole company site. The focus lies in the estimation of product-specific energy efficiencies in order to compare and evaluate different products.

The modular mapping of linked production units to key processes offers the possibility to compare key processes between different companies and enables the flexibility to analyse the whole foundry industry with its heterogeneous companies. Through the top-down and bottom-up approaches it is possible to use easy accessible economic data to generate relevant energy indicators, which can be internally benchmarked to analyse intransparencies of energy efficiency potentials through wrong cost allocations and for further optimization procedures.

Followed by the application of the model on three different foundry companies in Austria, the implementation of the approaches is shown. The top-down analysis is able to generate energy indicators which can be used as a basis for further energy efficiency potential analysis. Also it can be seen, that energy consumption varies throughout the companies, but consumption can be transferred from a functional to a process-oriented view, and therefore, get comparable.

The bottom-up approach shows the calculation of production units either on a statistical or a determinist approach, which enables the calculation of energy indicators on the module- and company level. Different products can be compared and energy intensive and non-intensive energy products can be identified. Furthermore recirculation material and material losses are integrated in order to quantify the real energy consumption of a product, which simultaneously provides the basis for life-cycle analysis.

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