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Master thesis

# Development and application of a model for energy efficiency evaluation

## Theoretical development with an application to the foundry industry

submittet to the

**Chair of Thermal Processing Technology**

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## EIDESSTATTLICHE ERKLÄRUNG

Ich erkläre an Eides statt, dass ich diese Arbeit selbstständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

## AFFIDAVIT

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

Place/Date

Signature

## Acknowledgment

I want to thank my family and my friends for their continuous help and support throughout my studies. I furthermore want to thank Prof. Harald Raupenstrauch and his team at the TPT for the innovative and successful work environment, which led to a positive professional and personal development.

## Abstract:

The actual energy policy of the EU and the regulations which derive from that, lead to a variety of challenges for the industry in general. Energy-intensive companies, like foundry companies, are encouraged to increase energy efficiency in order to fulfill current and future legal targets.

The objective of this work is to develop a framework or model, which helps to achieve those targets through the analysis and evaluation of energy consumption and energy efficiency. Several benchmarks are defined, which can be carried out with the model results.

First, all elements of the model development are shown. A data acquisition methodology, including a questionnaire and data sheets, is developed, followed by the definition of the model design. The model design consists of two approaches containing an economic and a technological focus. Indicators for evaluation purpose are defined and the applicability is shown through the application to a case study in an Austrian foundry.

All relevant indicators are determined, which results can be used for evaluation and optimization purposes. Contradictory results show that future research should further develop the model. For optimization purpose, methods like Exergy- and Pinch analysis should be implemented.

## Kurzfassung:

Die aktuelle Energiepolitik der EU und deren Verordnungen zur Energieeffizienz führen zu großen Herausforderungen für energieintensive Industrien wie die Gießereiindustrie in Europa.

Das Ziel dieser Arbeit ist die Entwicklung eines Modells die den Gießereien hilft den aktuellen Energieverbrauch sowie die Energieeffizienz zu messen sowie durch definierte Benchmarks bewertbar zu machen.

Zu diesem Zweck wird zu Beginn eine Vorgehensweise zur Datenaufnahme entwickelt. Anschließend wird das Modeldesign vorgestellt, das einen betriebswirtschaftlichen und einen technologischen Ansatz zur Analyse des Energieverbrauchs und der Energieeffizienz beinhaltet. Kennzahlen zur Durchführung der Benchmarks werden erarbeitet. Am Ende wird die Anwendbarkeit des Modells anhand einer österreichischen Gießerei dargelegt.

Die Ergebnisse zeigen, dass Weiterentwicklungen des Modells notwendig sind, sowie Methoden der Optimierung wie Exergie-und Pinchanalyse integriert werden sollten.

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# Nomenclature

| Symbol | Description | SI Unit |
|---|---|---|
| $C$ | Cost centre matrix | [-] |
| $c_P$ | Specific heat capacity | [J/kgK] |
| $E$ | Yearly energy consumption | [J/a] |
| $\dot{E}$ | Energy stream | [J/s] |
| $eci$ | Energy carrier intensity | [1] |
| $\dot{e}$ | Specific energy stream | [J/kgs] |
| $f$ | Factor (specified by subscript) | [1] |
| $h$ | Enthalpy | [J] |
| $I$ | Allocation matrix | [-] |
| $M$ | Module-energy matrix | [-] |
| $mi$ | Module intensity | [1] |
| $\dot{m}$ | Mass stream | [kg/s] |
| $\widehat{\mathrm{m}}$ | Entry of the module-energy matrix | [€] |
| $p$ | Piece | [-] |
| $q$ | Specific enthalpy | [J/kg] |
| $\dot{q}$ | Specific Heat transfer | [J/kgs] |

| | | |
|---|---|---|
| $r$ | Material input ratio | [1] |
| $T$ | Temperature | [K] |
| $To$ | Turnout | [1] |
| $t$ | Time | [s] |
| $U$ | Production unit | [-] |
| $\propto$ | Specific heat transfer coefficient | [J/kgKs] |
| $\eta_{th}$ | (Thermal) efficiency | [1] |
| $\vartheta$ | Flue gas loss ratio | [1] |

| Subscripts | Description |
|---|---|
| $A$ | Ambient |
| $c$ | Corrected |
| $ca$ | Compressed air |
| $cair$ | Combustion air |
| $el$ | Electricity |
| $F$ | Furnace |
| $fg$ | Flue Gas |
| $fuel$ | Fuel |
| $hl$ | Dissipative heat loss |
| $hr$ | Heat recovery (potential) |
| $M$ | Metal |
| $ng$ | Natural gas |
| $P$ | Product stream |
| $ph$ | Phase |
| $s$ | Sensible |
| $th$ | Theoretical |
| $w$ | Wastage |

| Superscripts | Description |
|---|---|
| $in$ | Inflow/Input |
| $out$ | Outflow/Output |
| $p$ | Primary |
| $s$ | Secondary |
| $r$ | Recirculation |
| $L$ | Loss |

| Abbreviations | Description |
|---|---|
| CO2 | Carbon dioxide |
| EC | European Commission |
| EU | European Union |
| GDP | Gross domestic product |
| LCA | Life-cycle analysis |

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# 1 Introduction

## 1.1 Background and problem setting

With the upcoming problems of excessive use of fossil fuels for energy utilization and production, the European Union (EU) was and is still establishing new policies and regulations regarding those problems. It is well known, and undoubtedly proven, that the utilization of fossil fuels during the last two centuries is the main driver for increasing CO2-concentration in the earth's atmosphere. This in turn, leads to the so called "Greenhouse Effect", resulting in temperature growth of the atmosphere. Climate change is irrevocably the result of higher temperatures, which is causes problems to mankind and society stability. The goal is a maximum of 2 °C of absolute temperature growth, which set as upper limit by researchers and experts, to keep the impact of climate change limited. Different policies take effect to achieve this goal and reduce the usage of fossil fuels.

The EU's energy policy is based on three columns, which goals are:

- The security of energy supply
- The existence of a (well running) energy market
- Environmental protection

The security of energy supply is the eldest reason for active policy making and dat back to the oil crisis in the 1970s. During this crisis it was found out, that energy supply is crucial for the economy of a country. The existence of an energy market was established during the last twenty years, which goal is to create competitiveness between all kinds of businesses related to energy-production or services in order to provide energy at market prices. The most recent policy dealing with this issue is the directive concerning the single European market [RICHTLINIE 72/EG (2009)].

The third goal focuses on environmental protection and is probably the most controversial one. Policies for environmental protection in Austria date back to the middle of the 20$^{th}$ century, concerning the conservation of air, water resources and forests. Since then, a huge amount of different approaches were set up and different policies were implemented. The last one's concerning environmental issues with a focus on energy have been:

- The directive on the development of renewable energy sources [RICHTLINIE 28/EG (2009)]
- The directive on energy efficiency [RICHTLINIE 27/EU (2012)]

The first directive is providing new regulations for the further development of renewable energy sources, which are based on the 20-20-20 goals of the EU. The 20-20-20 goal demands a reduction of 20 % CO2-emissions, an average ratio of renewable energy of 20 % and the growth of 20 % in energy efficiency till 2020 for the whole EU. The second directive is also based on those goals and focuses on increasing energy efficiency. The main idea is to raise energy efficiency in the member states through the definition of overall and compulsive targets for the EU. Since directives have to be transferred into national law in each member state, the federal law on energy efficiency was adopted in Austria [Bundes-Energieeffizienzgesetz (2015)].

In its newest version, the law defines how the committed targets of Austria should be achieved. Through the analysis of this act it can be seen, that mainly three groups are affected by the national regulations in achieving energy efficiency goals:

- The Republic of Austria itself and its regional authorities
- The energy providers (production-and service companies)
- Private companies (also non-energy providers)

For the first two groups, compulsive energy efficiency targets are defined. Private companies, which do not provide energy, based on the definition of the law, are excluded from compulsive targets. However, they are encouraged to raise energy efficiency through the implementation of other activities like energy audit regimes. It is clear, that this will lead to higher auditing costs for the companies, resulting in generally higher "business costs". Another impact of the new law is, that companies, which main activities are not energy-production or service, will be treated as energy providers if they f.e. sell waste as a secondary energy resource. The law will on the other hand stimulate the analysis of actual energy consumption and their corresponding energy efficiency potentials in the industrial sector. Since no compulsive targets were set for non-energy providing companies, energy efficiency measures are maybe detained. Further regulations may also include those kinds of companies into the target regime and will force non-energy providers to implement energy efficiency measures.

It can be seen, that companies face several new challenges, which derive from the new energy policy. First, companies are classified as energy providers resulting in compulsive energy efficiency targets, even if their main activity is f.e. manufacturing. A prominent example is a manufacturing site providing their wastes for further utilization (thermal recovery). Other issues mainly concern energy-intensive industrial branches like the foundry industry. There, energy demand is continuously rising due to higher and more complex requirements of their products, which is in opposition to energy consumption reduction in general. So if legal regulations may also include energy-intensive branches like the foundry industry, energy efficiency potential analyses have to be carried out in order to fulfill those future targets.

## 1.2 Scope and objective of the thesis

The description of the background and the problem analysis show that foundry companies are facing challenges in order to fulfill current and future legal requirements. The scope of this thesis is to develop an approach which will help to fulfill these requirements through a model for energy-analysis and optimization. This thesis is part of the research project "Energy efficiency in the foundry industry", which is carried out at the Montanuniversitaet Leoben, Austria. Two chairs are involved in executing the project namely the Chair of Thermal Processing Engineering and the Department of Economics-and Business Management. The author of this thesis was scientific staff at the Chair of Thermal Processing Engineering during the first project year from fall 2013 to winter 2014. Several reports were written and one conference-extended research paper was published in a special edition of the Journal of Thermal Engineering during this period. This thesis finally recollects the results of this project year. Readers ought to consider, that parts of this thesis are already published in the mentioned paper, and will be not explicitly cited, except if parts are taken unchanged.

The objective of this work is to develop a model, which is able to:

- Analyze and evaluate energy consumption-and efficiency of a foundry company
- Gather information on possible energy efficiency potential

Co-objectives is the application of the model on a foundry process, to show its applicability.

## 1.3 Methodology

This section briefly describes the methodology to achieve the objectives of this work. Figure 1 graphically shows the methodology, where the numbering correspond to the chapters of this work

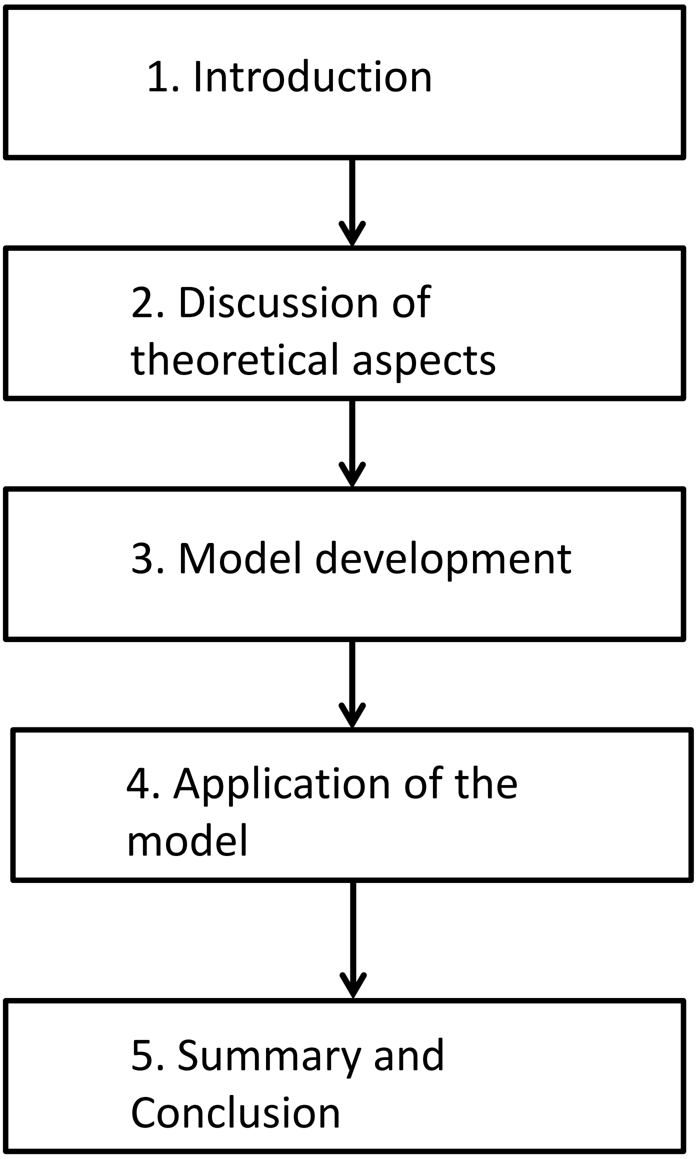


Figure 1: Graphic presentation of the methodology

After the introduction to the topic, a discussion of relevant theoretical aspects is carried out. This discussion contains the analysis of the impacts of the new energy efficiency policy in Austria and proved a brief basis of thermodynamics needed during the application of the model. It therefore provides the basis for the model development in the next chapter. The model development together with its application to an Austrian foundry company is the main parts of this thesis. In the end the thesis summarizes the results and draws the conclusion.

# 2 Discussion of theoretical aspects

## 2.1 The federal law on energy efficiency in Austria

In this section the background of the new law on energy efficiency is outlined and important impacts are presented. The law was carefully analyzed in its recent version in German issued at the 01.01.2015; see [Bundes-Energieeffizienzgesetz (2015)].

The law transfers the regulations of the European directive on energy efficiency into national law, which has to be done for every European directive in general. The European directive states that indicative targets must be set by the member states in order to fulfill the 20 %-target of higher energy efficiency. It furthermore defines important terms like “energy efficiency”, “energy efficiency improvement”, “energy audits” and many more.

The overall target of the EU is a primary energy use of max. 1.483 m. toe or a max. of 1.086 m. toe end energy use in 2020. To achieve this goal, the member states have to implement measures to contribute in achieving this target. Furthermore, the directive defines the areas in which measures on energy efficiency measures can or have to be taken and finally presents conversions tables for energy indicators and energy carriers in the Annexes.

The European directive provides the framework in which each member states can define its own targets, which must be agreed upon by the European Commission (EC). The agreed specific targets are then transferred into national law, which, in the case of Austria, result in the “Federal law on energy efficiency”. This law is briefly outlined to study the impacts on the industry sector.

The law consists of 8 parts including 34 paragraphs in which all regulations are stated. Those 8 parts are:

1. General regulations
2. Energy efficiency in companies
3. Commitments of branches
4. Energy efficiency of the federal state
5. Energy services and energy audits
6. Securing and purchasing of energy efficiency measures
7. Monitoring of energy efficiency
8. Final regulations

Special attention is given to part 2, which defines the general framework and specific targets for private companies. The other parts deal mainly with definition of terms, targets for the federal state and the implementation of a proper monitoring agency.

First, companies are classified into large, medium and small companies, which are affected differently by the law. Large companies are defined to be companies with more than 250 employees. Companies with less than 250 employees are classified to be small and medium-sized companies. Furthermore, the law differentiates between energy providing companies and non-energy providing companies. Energy providing companies have to fulfill absolute targets of energy reduction. Private companies are therefore classified into size and main activity.

Large companies must implement a proper energy monitoring system, with which energy efficiency potentials are measured, monitored and implemented if applicable. This monitoring system can be an energy management system including the execution of energy audits every 4 years. If the company has already implemented an environmental management system, it can be extended and adapted for energy auditing purpose. Energy audits have to fulfill certain criteria set by the national law and results have to be documented and sent to the energy efficiency monitoring agency, which is in charge of monitoring all energy efficiency activities. Small and medium companies are encouraged to implement those regimes, but are excluded from a definite commitment.

Energy providing companies must reduce their energy sales quantity in the amount of 0.6 % every year. The basis for the yearly calculation is the average energy sales quantity of the past three years. Furthermore, a cumulative energy reduction of 159 PJ must be completed till 2020. Companies affected by these targets can implement energy efficiency measures within their costumers, in which 40 % of the reduction must be implemented in the housing sector. The transport sector is fully excluded from definite targets. If new energy facilities, like power plants with more than 20 MW nominal power are constructed or modernized, energy efficiency potential analysis has to be carried out, which in turn raises the overall costs of those projects. Table 1 classifies the company in terms of size and main activity and shows by which regulations they are affected.

Table 1: Classification of companies including must-regulations

| | **Energy providing** | **Non-energy providing** |
|---|---|---|
| **Large- sized** | • -0.6 %<br>• 159 PJ 2020<br>• Energy audits | • Energy audits |
| **Medium-sized** | • -0.6 %<br>• 159 PJ 2020 | --- |
| **Small-sized** | • -0.6 %<br>• 159 PJ 2020 | --- |

While large energy-providing companies have to fulfill regulations concerning absolute energy consumption reduction and the implementation of energy audits, large non-energy providing companies only have to implement energy audits. Small-and medium sized companies are completely excluded from strict targets if their main focus is not energy provision. However, those companies are encouraged to implement energy audit-and management regimes on a voluntary basis.

The foundry branch, which is studied in this thesis, can be generally classified as small- and medium sized non-energy providing companies. Only few foundry companies in Austria have more than 250 employees. Thus, regulations on energy efficiency do not define specific targets for them, but further regulations may also include those kinds of companies, resulting in definite energy reduction targets. Due to the fact that most foundries are component supplier for larger branches like automotive, the implementation of energy audits and energy reduction may be driven by their customers through cost reduction and increasing quality standard.

## 2.2 Definition of evaluation indicators

In this section the theoretical basis for the evaluation of energy efficiency is developed. In order to define relevant criteria for the model development, proper indicators must be defined, which are able to evaluate energy-usage in industrial foundry processes.

In general, efficiency is defined as the ratio of the useful output to the needed input of a given system. In the BAT document for energy efficiency [BAT (2009), p.18 ff], energy efficiency is generally defined as “a ratio between an output of performance, service, goods or energy, and an input of energy”. The underlying system can be a single industrial process, an industrial system as a whole, or even an economic system like product life-cycles or whole economies.

However, the use of energy efficiency as a proper indicator for energy consumption reduction is criticized by many authors [Herring H. (2006)]. Authors state, that a more efficient use of energy carriers will force market prices to drop, leading to lower energy costs, which finally result in higher consumption back again. This mechanism is called the “rebound effect” [Greening L.A.; et.al. (2000)].

When using indicators for energy evaluation, different indicators can be constructed for different evaluation purposes. Those indicators can be generally divided into four groups [Patterson M.G. (1996)]:

- Thermodynamic indicators
- Physical-thermodynamic indicators
- Economic-thermodynamic indicators
- Economic indicators

Thermodynamic indicators are used to evaluate energy efficiency for single industrial processes, like heating-or cooling processes. They are calculated through thermodynamic state functions. Examples for thermodynamic efficiency indicators are the so called “first-law”-and “second-law” efficiencies, like the thermal-or enthalpic efficiency and the exergy efficiency, respectively.

Physical thermodynamic indicators are used if energy utilization is compared with the physical unit for which it is needed f.e. natural gas usage for melting a given amount of metal.

Economic-thermodynamic-or economic indicators use market prices for the evaluation of the underlying system. Examples for that are the energy input per GDP ratio or the energy price per GDP ratio.

It can be seen, that the construction of those indicators differ in terms of their applicability. The first two indicator groups are mainly used for evaluating industrial processes, whereas the last two are applied to economic systems on different levels.

Furthermore it should be mentioned, that methodological problems arise when using such energy efficiency indicators [Patterson M.G. (1996)]:

- Value judgment problem
- Energy quality problem
- Boundary problem
- Partitioning problem

The first problem arises from the general definition of efficiency, where the useful output is compared with a needed input. But the definition of "useful" and "needed" is always based on human judgment and can therefore not be fully objective. This problems occurs both in thermodynamic and economic indicators, where f.e. recoverable waste heat is not part of a thermodynamic efficiency. Another example is the change in energy use per unit of GDP, due to a change in GDP calculation, which clearly does not affect energy efficiency at all. The consideration of waste heat for efficiency calculation is clearly dependent on the usefulness for further utilization f.e. for residential heating. If residential heating is possible in terms of technological or economic feasibility, waste heat is either "useful" or "not useful". Human value judgment is therefore always an inherent part of any efficiency definition and was first pointed out by Boulding [Boulding K.E. (1981)].

The energy quality problem arises when energies of different qualities are summed up. This occurs for the enthalpic efficiency when energies of different qualities are added. Examples are the summation of different energies containing different work potentials (exergy) or economic indicators, where energy input changes are neglected on the macro-level, due to a variation of the energy carrier composition.

The boundary problem occurs in every efficiency calculation, because the definition of the system boundary is the first step in analyzing any kind of system. An example of this problem is, that "free" energy streams like solar radiation energy for a given system boundary are not considered. Another example corresponds to the definition of the system boundary itself. The question is here is if f.e. solar energy input should be taken into account for a system of hydro-energy electricity generation?

The partitioning-or joint production problem is a prominent problem in many disciplines dealing with industrial processes or systems in general. A famous example is cost allocation in accounting, where f.e. energy costs of lightning are allocated to different cost centres based on a more or less arbitrary physical unit like square meters. The question hereby is, how to allocate energy input to different outputs if the energy transformation process is unknown? Different methods based on proportional allocations are proposed to overcome the partitioning problem but are also based on arbitrary assumptions.

The choice of proper evaluation indicators for evaluating energy usage and efficiency is crucial. The methodological problems occurring in this context are interdependent and must be considered while using such indicators.

The next step is to analyze how those methodological problems can be overcome. First, it has to be accepted that any energy efficiency indicator is not free of human judgment and therefore always subjective to a certain degree. The definition of “useful” or “needed” energy has to be adjusted to the underlying system which is to be evaluated. When dealing with energy streams from the technical point of view, energy quality must be considered. This is the reason why the concept of exergy was introduced in evaluating thermodynamic systems [Kotas T.J. (1995)]. The concept implicitly assumes the stated interdependency of the quality problem and introduces the working potential as the useful part of an energy stream. However, the concept of exergy or the evaluation through a comparison with an ideal reference state are broadly accepted and applied in energy efficiency evaluations [Rosen M.A.; et.al. (2008)].

A more practical way to deal with the boundary problem is to use cost-benefit analysis. Through a cost-benefit analysis the level of detail for a certain boundary can be estimated. It is meaningless to f.e. account for the solar radiation driving humidity of combustion air for a gas-fired melting furnace. If adjustments for boundary setting or energy quality differences have to be made, the quality equivalent method can be used [Patterson M.G. (1996)].

When dealing with complex industrial processes, the partitioning problem is of crucial interest. One way of solving this problem is to simple avoid it through the modeling of the system. This means that f.e. energy contents of different products are not allocated through any arbitrary unit based on the energy balance but are estimated through a valid model which describes the system’s transformation process. If the modeling of the considered system is possible, partitioning problems vanish.

The theoretical discussion on energy efficiency, the evaluation through indicators and their corresponding problems is finished. The last step is to define proper indicators, which are used for the model approach in this work.

A very detailed analysis of energy efficiency indicators is given by [Phylipsen G.J.M. (2010)]. This work describes energy efficiency indicators and how they can be applied. Indicators are classified for different system boundary levels, resulting in the energy efficiency indicator pyramid shown in Figure 2 [Phylipsen G.J.M. (2010), p.14].

This pyramid shows a Top-down and Bottom-up approach for indicators on different level. While on production process-and company level thermodynamic and technological indicators are used, sub-sectoral and sectoral indicators mainly use economic indicators to measure energy efficiency. Due to the fact that this works deals with three different level, production unit, process- and company level, technological as well as economic indicators can be used.

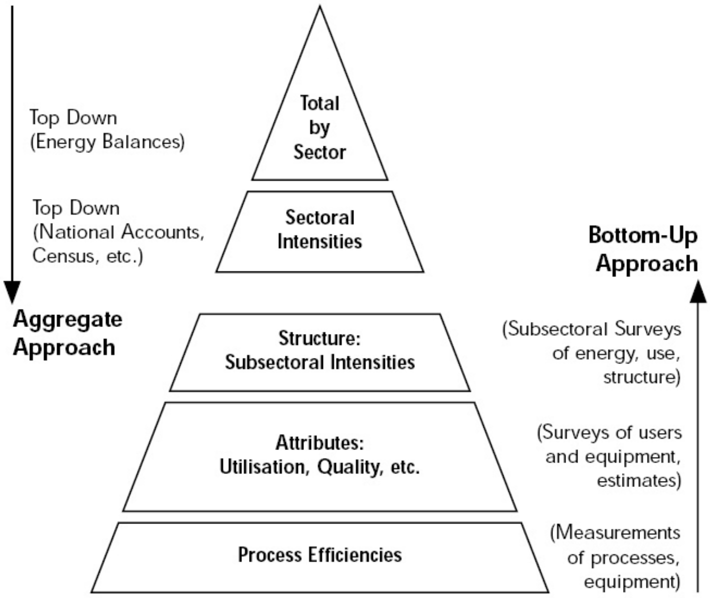


Figure 2: Energy efficiency indicator pyramid

According to the theoretical analysis of energy indicators, the following use of indicators can be concluded. This summary also includes non-energy indicators like material flow indicators, which are relevant to measure material usage.

Indicators on production unit level:

- Thermal efficiency
- Specific energy consumptions and heat recovery potentials
- Material loss ratios

Indicators on process level

- Specific energy consumptions
- Primary-and recirculation material input ratio

Indicators on company level

- Specific energy consumptions
- Primary-and recirculation material input ratio
- Specific energy carrier costs

## 2.3 Thermodynamic basis

This section provides the thermodynamic basis which is needed for thermodynamic calculations in this thesis. Only the most important equations are described, thus no discussion on thermodynamic basics such as system boundaries, laws of thermodynamics or other principles will be made.

In order to calculate energy content of various material and energy carrier streams, some basic calculation principles are defined. The energy content of a material or energy carrier stream is its enthalpy. Specific enthalpy, thus enthalpy per mass, is calculated through [Baehr H.; Kabelac S. (2009), p.88]:

$$\Delta h_s = c_p(T - T_0)$$

Equation 2.1: Calculation of specific enthalpy

The specific enthalpy is the specific heat capacity times the temperature difference between the two states. The subscript $s$ indicates that the enthalpy only includes the sensible heat content. There is another part of the energy content, which must be considered, namely the latent heat. This part occurs if there is a phase change of the material stream, which, of course, happens during the melting processes in foundry companies. The specific energy of any material stream including a phase change is therefore:

$$e = \Delta h_s + h_{ph}$$

Equation 2.2: Calculation of specific energy

where $h_{ph}$ is the enthalpy or specific latent heat during phase change. For foundry companies the phase change is considered from the solid to the liquid phase of the metal. Typical values range between 250 and 270 kJ/kg, depending on the metal.

The specific heat capacity must be also considered for different material and energy carrier types. The specific heat capacities for different materials like aluminum and steel with different alloys were calculated in detail using the JANAF tables [JANAF tables (1974)].

The combustion calculation was also carried out after [Baehr H.; Kabelac S. (2009), p.445 ff] to calculate all relevant properties of natural gas combustion and flue gas streams. However the detail description of these calculations is not task of this work.

# 3 Model development

In this chapter the model development is carried out. The model is derived based on the objective of this work, described in section 1.2. First, the overall model approach is outlined. As it was stated before, this thesis contents the results of the project "Energy efficiency in the foundry industry" of the first project year. Since this period covered only the first part of the model, the objective of the whole three-year project is briefly given.

In short, the objective of this project was to develop an approach which is able to benchmark foundry companies, meaning that foundry products or processes can be compared to each other as well as to substitution products using energy efficiency indicators. Therefore, the approach includes three different possibilities for benchmarks:

- Process benchmark
- Product benchmark
- Life-cycle benchmark

The Process benchmark offers the possibility to compare different foundry processes between different companies. The second benchmark compares foundry products with their substitution products, while the third benchmark deals with the analysis of the whole life-cycle of a specific foundry product. Since the last two were not part of the first project year, they are not fully developed and therefore not covered in this thesis. Nevertheless, it will be shown that the model is also preparing the basis for those benchmarks.

For this purpose it was necessary to first develop the model itself and second to implement the model as an analysis tool, which can be used by a foundry company for dealing with the challenges previously describes in the problem setting.

The model development contains five main steps, which are described in this chapter:

1. Definition of data acquisition methodology
2. Hierarchical model composition
3. Model design
    a. Top-down approach
    b. Bottom-up approach
4. Indicator summary
5. Comparison/Benchmark

In the beginning the data acquisition methodology is described. A questionnaire and data sheets are developed to gather technological and economic data. Then the model development is described, where first the hierarchical model composition is deployed. The main part is the model design, which is divided into two parts, dealing with two different approaches for the analysis of energy-consumption and efficiency. The last two parts summarize all relevant parameters and indicators and define which indicators can be used for different comparison-or benchmarking purpose.

## 3.1 Definition of the data acquisition methodology

Figure 3, cited from [Coss S. et.al. (2015)], shows the data acquisition methodology graphically, which is described in this section. The first step in developing the data acquisition methodology is the literature review of relevant articles and papers focusing on the foundry industry. Since the purpose is to quantify energy efficiency potentials, the research focus lies on the processes and production units actually used during operation. After that two templates for data acquisition were developed in parallel:

- The questionnaire
- The data sheets

The purpose of the questionnaire is to gain a first brief insight into the company's processes, production units and their corresponding energy utilization. The data sheets are used for further data acquisition on a lower level dealing with technical-and thermodynamic data. The questionnaire deals with the data acquisition on company or process level, while the data sheets are designed to gather specific technological data of production units. The questionnaire, which was developed for the application of the foundry industry, can be found in Annex A. It contains three sections of questions containing general information on the company, energy carriers and overall energy consumption and the related products and production processes.

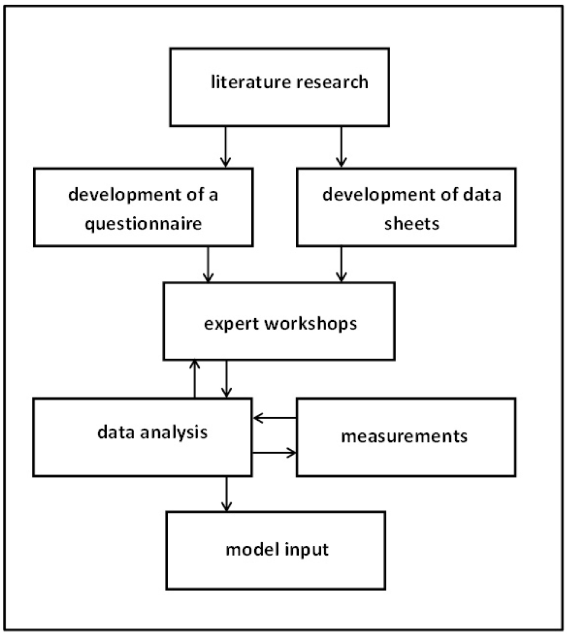


Figure 3: Data acquisition methodology

As mentioned before, the purpose of the questionnaire is to gain general, overall information of the company site. In order to acquire further relevant technological data on production unit level, data sheets were developed in parallel. An example of a data sheet for a shaft furnace is presented after the questionnaire in Annex A, which covers important technological-and thermodynamic properties for the requirements of the model input. It can be seen, that literature review is crucial in order to create proper data sheets for the foundry production units. The reason why the questionnaire and the data sheets are said to be developed in parallel is, because they provide data for two different evaluation approaches. This will be further discussed in the model design section.

After the preparation of the data of the questionnaire and the data sheets, expert workshops are carried out to aggregate the available data. Furthermore, a process landscape is drawn, which contains the graphical representation of material-and energy flows of the production process..

At this step it is most important to define which kind of data is available, if necessary data is missing and how it can be acquired. Therefore further data analysis and measurements are implemented in order to derive relevant missing data.

If all relevant information is available and checked for data quality it can be used as model input data.

## 3.2 Hierarchical model composition

As previously mentioned, the model development is the first step for the creation of an analysis tool, which can be used by foundry companies to evaluate their energy performance. Due to that, the model composition is defined to be hierarchical and modular. This concept is shown in Figure 4 cited from [Coss S. et.al. (2015)]:

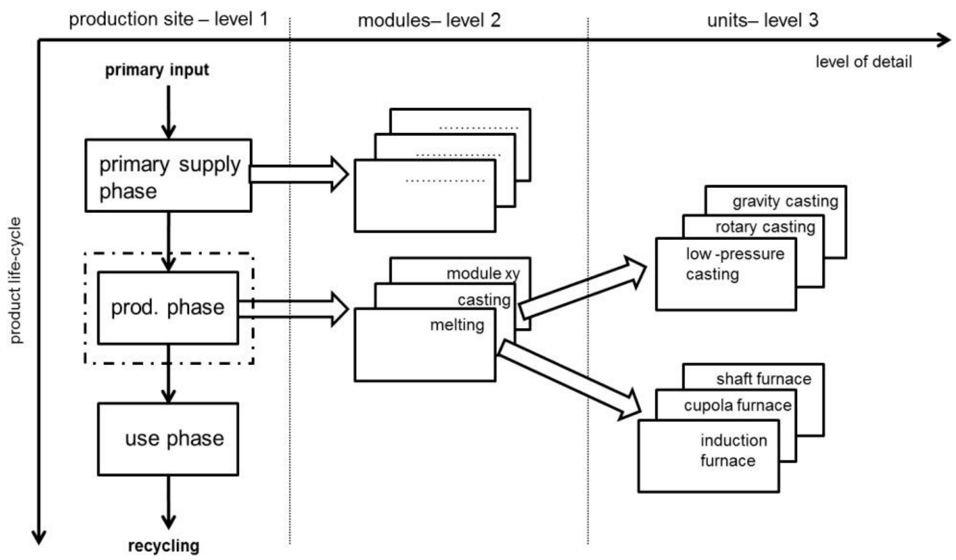


Figure 4: Model composition

The horizontal axis shows the system boundary level, from the company's fence to the main processes, called modules, till the production unit level. On the vertical axis the product life-cycle is represented, a cradle-to-grave approach. The level of lower detail are hierarchically depended on the levels of higher detail, and depending on the approach, vice-versa. However, these different levels are strictly connected through several indicators. The reason why the main processes are called "modules" is that the flexibility and comparability of different processes should be given throughout the foundry industry. Those main processes are standardized through the module approach. There are several main processes which occur in every foundry industry, but there are also company and product specific processes. Examples for main processes (modules) which occur in almost every foundry, in this or in a similar order, are:

- Melting
- Casting
- Unpacking
- Heat treatment
- Mechanical treatment and finishing

Those can be defined as the main processes of a foundry and are therefore defined as main modules.

This definition of the model composition is crucial for the evaluation process, because it provides the basis for energy efficiency analysis throughout different levels of the foundry company. Careful attention should be given to the definition of parameters and indicators connecting both the different level and the product-(life)cycle.

## 3.3 Model design

Based on the requirements of the project design and the hierarchical model composition, the definition of the model design is carried out. The model design can be seen in Figure 5, which is slightly changed to the original version published in [Coss S. et.al. (2015)]:

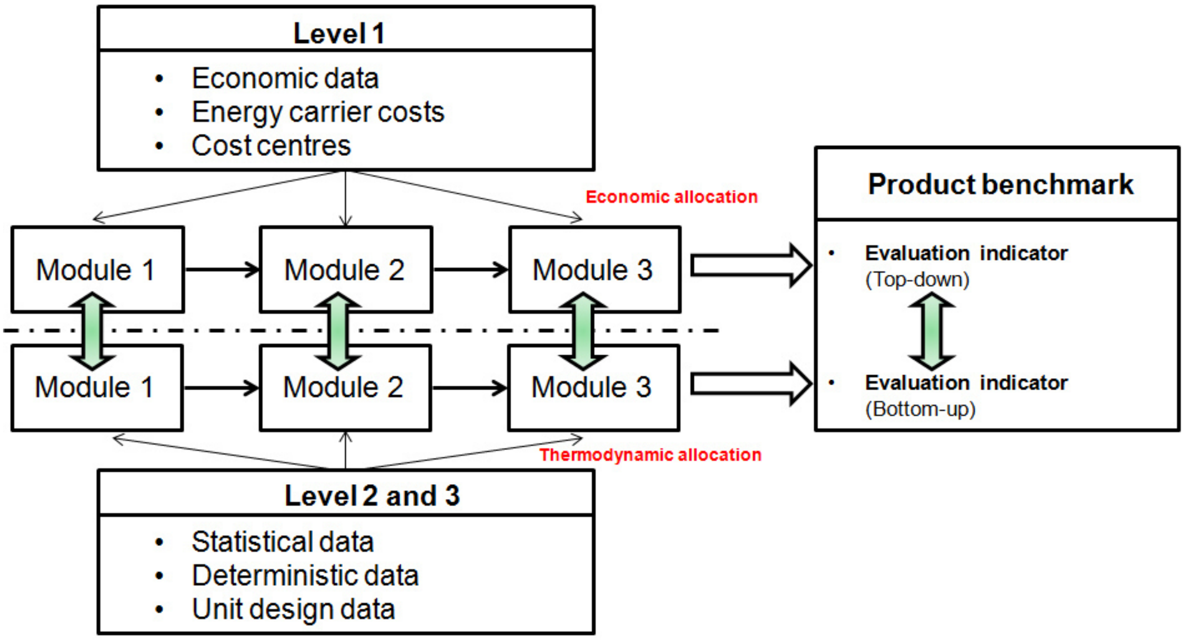


Figure 5: Model design representation

The model design contains two different areas representing two different approaches of analysis techniques. Those two different approaches are called the

- Top-down and the
- Bottom-up

approaches, respectively.

The Top-down approach uses data of high aggregation, like economic data from controlling departments, to determine energy consumption based on economic allocations of the energy carrier costs. It is important to note, that economic data is dealing with energy carrier costs arranged in cost centre systems. Those energy carrier costs should not be mixed up with the corresponding physical energy consumption of a given process. Anyway, the Top-down analysis is using data of energy carrier costs, cost-centre costs and data of high aggregation like yearly or monthly energy consumption in its analysis.

The Bottom-Up approach on the other hand uses physical, thermodynamic and general technological data in order to determine energy consumption through thermodynamic calculations of a given process.

Thus, the Bottom-up approach determines “real” energy consumption while the Top-down approach determines allocated energy carrier costs. The results may differ from each other. The important point is, that if the difference between the “allocated energy consumption” (Top-down) and the “real energy consumption” (Bottom-up) can be quantified, a first insight into inefficiencies is given.

It is clear that the developed questionnaire is providing the data for the Top-down approach, while the data sheets provide it for the Bottom-up approach. Those two approaches are finally compared to each other through the use of evaluation indicators. The green arrows in Figure 5 indicate that a comparison can be made between the modules as well as for a combination of modules, which represent the whole company’s process, if all modules are considered. Theoretically it is also possible to even compare single devices to each other. However, due to simplicity this is not represented in Figure 5 and it is not assumed that economic data is available on production unit level.

The overall description of the model design is finished. The next sections develop the two approaches, which are the core part of the model.

### 3.3.1 Top-down approach

The theoretical description of the Top-down approach, described in this section, was already published in [Coss S. et.al. (2015)]. As briefly mentioned before, the objective of this approach is to transfer energy carrier costs from the functional view of cost-centres to a process-based view through a module representation. To achieve this goal, matrix representation is used in order to show the steps of transformation.

The Top-down approach consists of five steps which are carried out chronologically:

1. Economic data acquisition
2. Allocation of the cost centres to the modules
3. Calculation of the corrected energy consumptions
4. Calculation of energy consumption for each module and cost unit
5. Calculation of energy indicators

This approach consists of five steps, which are carried out chronologically. The first step is the application of the data acquisition methodology previously shown in Figure 3. Through this methodology, economic and aggregated data on energy carrier costs, cost centers and overall energy consumptions are gathered. The result of this step is the aggregated information on the cost centres of the company, their allocated energy carrier costs as well as their quantity e.g. in MWh/a or €/a. Since several energy carriers can be allocated to one cost centre, or one energy carrier is used in several cost centres, the result can be represented in matrix form, which is called the cost centre matrix.

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & c_{re} & \vdots \\ c_{m1} & \cdots & c_{mn} \end{bmatrix} (m \ \times n)$$

Equation 3.1: Cost centre matrix

The matrix $(C)$ has $(m)$ rows and $(n)$ columns, representing $m$ cost centres and $n$ energy carriers. The element $(c_{re})$ is then the cost of the $e^{th}$ energy carrier allocated to the $r^{th}$ cost centre. Note, that the nomenclature always uses energy carrier costs for the unit in the Top-down analysis. Beside that, it is also possible that energy consumptions are directly allocated in energy units by the company, but those energy consumptions are usually derived from energy costing in the controlling department. Attention should be therefore given to the used allocation method. From the proposed method of the Top-down approach either costs or consumptions can be used in the cost centre matrix.

As stated before, the functional view of the cost centres have to be transferred to a process-based view. This is done in step two, where the cost centres are allocated to the modules. This means, that first a definition has to be made on how the cost centres are to be allocated to the modules. A problem occurs from that, because the costs of one cost centre are not the same as for the process since different allocation methods were used. This problem is called the “allocation problem” and will be discussed after the formulation of the allocation matrix $(I)$, which will do the transformation.

$$I = \begin{bmatrix} i_{11} & \cdots & i_{1n} \\ \vdots & i_{rj} & \vdots \\ i_{m1} & \cdots & i_{mn} \end{bmatrix} (m \times k)$$

Equation 3.2: Allocation matrix

The matrix $(I)$ represents the allocation of the $r^{th}$ cost centre to the $j^{th}$ module. Note, that the rows of matrix $C$ and matrix $I$ must be of equal size. The matrix element $(i_{rj})$ can only be either zero or one, corresponding to no allocation or to a full allocation of a cost centre to a module, respectively. Attention should be given, that the sum of all elements of one row in $C$ equals one, which secures that one cost centre is allocated only one time. The sum of one column in $C$ does not face restrictions, because one module can contain one or several cost centres. Before the transformation of the cost centre view to the process-based view is carried out, the "allocation problem" is briefly discussed. Figure 6 shows the graphical representation of the allocation problem.

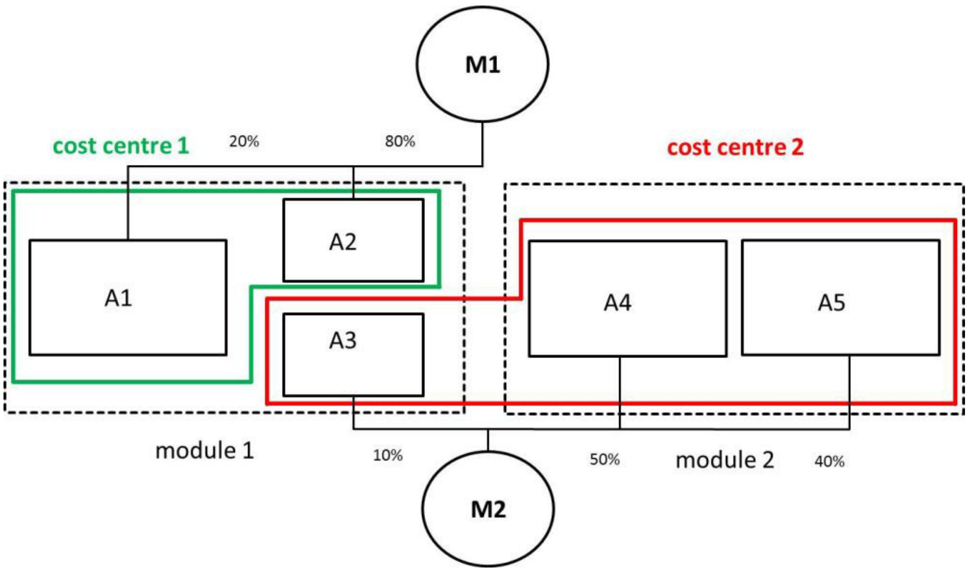


Figure 6: Graphical representation of the "allocation problem"

The aim of this transformation is to allocate all energy carriers from the cost centres to the modules. Problems occur if the cost centres are not physically the same as the modules. Figure 6 shows the situation where two measuring points measure a certain amount of energy and allocate this energy to different production units in their cost centres.

For the cost centre 1, this procedure does not create a problem, because the cost centre is fully part of module 1. In contrast to that, it would be wrong to allocate the whole result of measurement 2 from cost centre 2 to module 2. It can be seen that production unit A3 is not part of cost centre 2 but of cost centre 1, and must be therefore allocated to cost centre 1.

The cost centres must be carefully examined and it has to be discovered, which production units are measured within each cost centre. If a cost centre includes a production unit from a different module, this energy carrier value must be corrected. A new corrected matrix $(C_c)$ can be derived, which contains the corrected values.

$$C_c = \begin{bmatrix} c_{c,11} & \cdots & c_{c,1n} \\ \vdots & c_{c,re} & \vdots \\ c_{c,m1} & \cdots & c_{c,mn} \end{bmatrix} (m \times n)$$

Equation 3.3: Corrected cost centre matrix

Each element $c_{c,re}$ now represents the corrected values of energy costs between the cost centres and the modules, assuming that the allocation of cost centres is simply done by a boolean allocation.

Now step 4 can be executed, where the transformation from cost centres to modules is done. This is carried out through the following matrix operation in which the module-energy matrix is generated.

$$M = C_c^T \cdot I \ (n \times k)$$

Equation 3.4: Module-energy matrix

$(M)$ is called the module-energy matrix, where every element $\widehat{m}_{ej}$ quantifies the energy cost of the $e^{th}$ energy carrier corresponding to the $j^{th}$ module. If the entries of the corrected cost centre matrix have been energy consumptions, energy carrier costs can be generated through simply multiplying every row of matrix $M$ with its specific energy costs, and vice versa if energy costs have been used.

The last step of the Top-down analysis is the preparation of relevant energy indicators. For this reason two indicators are defined which can be directly calculated from the module-energy matrix. Those are called the “energy carrier intensity” and the “module intensity”. The energy carrier intensity is defined as follows.

$$eci_{ej} = \frac{\widehat{m}_{ej}}{\sum_e \widehat{m}_{ej}}$$

Equation 3.5: Definition of energy carrier intensity

The element $(eci_{ej})$ describes the energy carrier intensity of the $e^{th}$ energy carrier in the $j^{th}$ module. This indicator describes the ratio of different energy carriers in one module and can be used for analyzing the composition of energy carriers in a module. In order to gain more information on which energy carrier is preferably used in a certain module, an ABC-analysis can be carried out. With this approach it is possible to derive certain information about possible energy efficiency potentials for a specific module.

The second indicator, which is also derived from the module-energy matrix, is the module intensity and is calculated through the next equation.

$$mi_{ej} = \frac{\hat{m}_{ej}}{\sum_j \hat{m}_{ej}}$$

Equation 3.6: Definition of module intensity

The module intensity $(mi_{ej})$ shows how intensive an energy carrier is used by a certain module. The module intensities of f.e. the energy carrier “electricity” would provide insight in which processes electricity is mainly used. Note, that both indicators use the module-energy matrix as a basis and that both are calculated very similar using the sums of rows and column as denominator. However, the meaning of them is quite different and the purpose of their usage also differs. If a certain process is to be optimized, energy carrier intensity can be taken as an evaluation indicator, because it provides insight on which energy carriers optimization should focus. On the other hand side, if a certain energy carrier is getting more expensive over time, the focus of optimization will be on reducing usage of it. In this case, module intensity can evaluate on which processes energy efficiency potential analysis should focus on.

The development of the Top-down analysis is finished. The chronological steps were explained in detail and its application is carried out in chapter 4.

### 3.3.2 Bottom-up approach

As described in Figure 5, the model contains two approaches using economic as well as thermodynamic-and technological data in order to determine actual energy consumption and energy efficiency potentials. In this section the Bottom-up analysis is developed and the corresponding methodological steps are presented.

As in the economic approach, the Bottom-up analysis is developed through chronological step.

The procedure is as follows:

1. Assignment definition of the production units to the modules
2. Modeling of the production units
3. Determination of key indicators and parameters of the units
4. Linking of production units to calculate the corresponding modules
5. Determination of key indicators and parameters of the modules
6. Linking of modules to calculate the whole production site

Similar to the first step in the Top-down analysis, the Bottom-up approach seeks a definition of which production units are connected to which modules. Through the former analysis of cost centres, measuring units and modules the system borders were already set up. Those can be also used in the Bottom-up approach.

The second step is the modeling of the production unit, based on actual data from the data sheets. For this, a simple model definition is used, which is shown in Figure 7 [Coss S. et.al. (2015)].

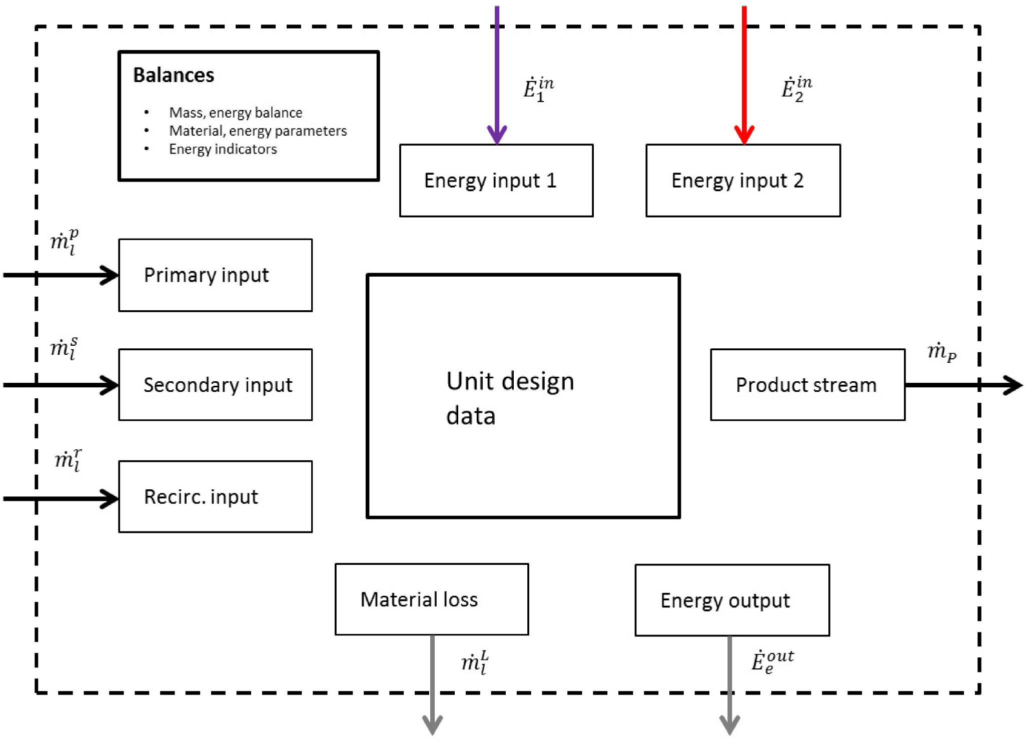


Figure 7: Model approach for a production unit

In this approach all production units are modeled based on mass-and energy flows and their corresponding losses of material and energy. Based on those mass-and energy balances all relevant information for the further calculation is derived. The result of the modeling and the calculation of the mass-and energy balances is represented as “balances” in Figure 7.

Note, that the production unit model contains only one product outflow, which represents the desired product flow. All further calculations will be based on those product stream, which allows calculating indicators based on product-cycles including internal material backflow and wastage recirculation.

Due to the reason that production should not only be analyzed but as well be optimized at a later stage, a black box model of the production unit is not sufficient. In fact, the thermodynamic behavior of the production must be modeled. As an example, the modeling of a furnace production unit is shown. Such furnaces are used in every foundry company where melting operation is carried out. The optimization of such a production unit is crucial for energy efficiency.

Suppose thermodynamic information of a furnace melting any metal is available. If thermodynamic properties of the process like temperature, melting time and mass inflows are given, one can determine the overall heat transfer from the furnace to the input material with the help of a heat transfer model. The generation of such a model for this furnace would be the so called deterministic or analytical approach. Another approach would include the determination of the parameters through statistical analysis. Both approaches can be used in order to describe a certain production unit, which was outlined in [Giacone E.; Manco S. (2012)]. However, the actual application of the approach is dependent on data availability.

For this work data is very limited, because statistical values are not available. Due to that, analytical modeling is preferred. It should be mentioned, that there is also the possibility of numerical simulations to determine heat transfer, but this is, of course, out of the scope of this thesis. Figure 8 shows the approach for the analytical heat transfer model of such a furnace.

Suppose there is a material flow of aluminum into a gas-fired melting furnace. The heat of the burned natural gas is transferred to the material input till a certain extraction temperature is reached. The question is how the melting time varies with varying model parameters like the furnace temperature? In other words, what is the functional dependeny between furnace temperature and melting time?

The assumption is, that higher temperatures in the furnace ($T_F$), which can be calculated from the combustion analysis will lead to faster melting times, resulting in lower natural gas consumption. ($T_M$) is the temperature of the material input, ($T_A$) is the ambient temperature,

$(q_M)$ is the specific heat content of the material input and $(\dot{q}_M)$ is the heat flow from the furnace, or better the combustion gases, to the melting material.

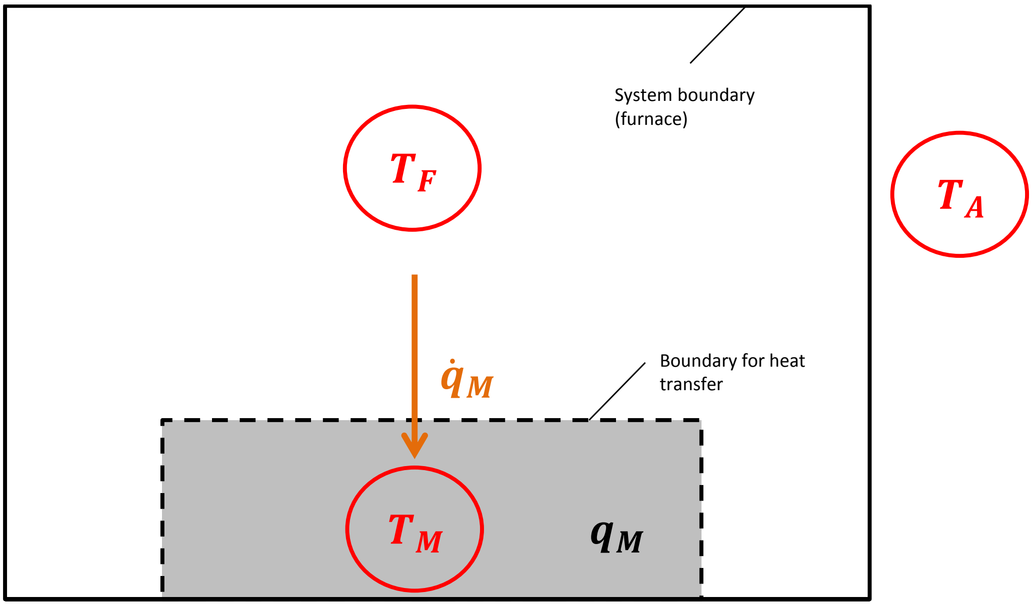


Figure 8: Analytical heat transfer model of a furnace

The heat transfer from the furnace to the material input can be described through

$$\dot{q}_M = \alpha(T_F - T_M)$$

Equation 3.7: Heat transfer equation approach

where $(\propto)$ describes a fictive heat transfer coefficient and $(T_B - T_M)$ is the difference between the furnace temperature and the material temperature, which is the driving force of the heat transfer.

The heat content of the material is rising due to the heat transferred, which then results in rising material temperatures. This is described through the specific heat content of the material through

$$q_M = c_p(T_M - T_A)$$

Equation 3.8: Specific heat content

which is simply the calculation of enthalpy of the material relative to ambient reference state at constant pressure [Baehr H.; Kabelac S. (2009), p.88].

The next step is to insert Equation 3.8 into Equation 3.7 resulting in Equation 3.9

$$\dot{q}_M = \alpha \left[ T_F - \left( \frac{q_M}{c_p} + T_A \right) \right]$$

Equation 3.9: Combining (3.7) and (3.8)

which describes the heat transfer as a differential equation of first order through

$$\dot{q}_M + \frac{\alpha}{c_p} q_M = T_F - T_A$$

Equation 3.10: Differential equation of the heat transfer

which is solved using an exponential approach, resulting in

$$q_M(t) = c_p(T_F - T_A)\left(1 - e^{-\frac{\alpha}{c_p}t}\right)$$

Equation 3.11: Solution of (3.10)

describing the heat content of the input material after a given melting time $(t)$ . If the melting time as well as the extraction temperature is known, which is usually the case in a foundry company, the fictive heat transfer coefficient can be estimated. Assuming this coefficient to be constant for different temperature ranges, a dependency of the melting time $(t)$ and the furnace temperature $(T_F)$ is found.

$$t(T_B) = -\frac{c_p}{\alpha} ln\left(1 - \frac{(T_M - T_A)}{(T_0 - T_A)}\right)$$

Equation 3.12: Functional dependency of the melting time

This equation looks similar to the heat transfer in a direct current heat exchanger. However this is true, because the approach is quite similar. Through that approach, a direct dependency of the melting time and the furnace temperature is found. Therefore, future optimizations can use higher furnace temperatures resulting in decreasing melting times and therefore decreasing natural gas consumption. This analytical approach is used for modeling of a melting furnace in the Bottom-up approach.

The third step is the determination of key parameters and indicators of the production unit based on the modeling results. The objective of this step is to define and calculate relevant parameters and indicators evaluating the production unit's performance, but furthermore provide the basis for the linking of the production units and the modules throughout the foundry processes. Due to that reason, the overall balance indicated in Figure 7 contains two balances and three parameter and indicator summaries, which are:

- Mass- and energy balance
- Material-and energy parameter summary
- Energy indicator summary

The mass-and energy balances contain the input and output values of the production unit. The material-and the energy parameter summary contain parameters calculated on the basis of the balances to create indicators for the module calculation as well as for the evaluation of the unit. Examples for material parameters are:

- Primary, secondary and recirculation material input ratio
- Turnout
- Material loss ratio

The first three describe the amount of primary, secondary-and recirculation material which is needed to produce the desired output product stream. The turnout describes the overall “material efficiency”, thus the ratio between the product output to all input flows, while the material loss ratio gives insight into material losses throughout the process. Examples of energy parameters include:

- Specific energy carrier consumption (e.g. electricity or natural gas)
- Specific flue gas losses
- Specific dissipative heat loss

Note, that the term “specific” refers to the issue that all energy carrier flows are referenced to the product output. Specific natural gas consumption therefore quantifies natural gas consumption per unit of product output.

Finally, the energy indicator summary includes energy indicators, which are used as evaluation indicators of the process. Some examples include:

- Specific energy carrier consumption
- Specific theoretical heat recovery potential
- Production unit efficiency
- Flue gas energy loss ratio

Those indicators are mainly drawn from the energy parameter summary, but also use information of the mass-and energy balances. The overall purpose of separating those parameters through different summary tables is to create “high-level parameters” based on "low-level parameters" of the balances, so that consistency is assured throughout the different system level.

The whole algebra of the Bottom-up analysis is presented as follows. At first, a proper notation must be defined to ensure that different production units and modules can be represented. At first, the mass balance of a production unit has to be discussed. Let $(\dot{m})$ indicate the mass flow, two indices are needed to indicate module and production unit and one indicating the specific material-or energy mass flow. This results for a mass stream in the general notation$(\dot{m}_{jl,m})$, which represents the $m^{th}$ mass stream of the $l^{th}$ production unit in the $j^{th}$ module. The mass flow of an energy carrier stream is notated through$(\dot{m}_{jl,e})$. With the help of this notation the general mass balance of a production unit $(U_{jl})$ can be formulated through

$$\sum_{m} \dot{m}_{jl,m} + \sum_{e} \dot{m}_{jl,e} = 0$$

Equation 3.13: General mass balance

stating that the sum of all in-and out flowing mass streams must be zero. In general, incoming streams are calculated positively, while exerting streams have a negative sign.

The next step is the development of all relevant parameters and indicators. For that reason a proper notation should be followed. It is assumed that all equations are written for an arbitrary production unit $U_{jl}$, but to simplify the demonstration the indices are removed.

In order to further differentiate between different kinds of mass flows some more notation is needed. It has to be differentiated between the inflows and the outflows as well as between different kinds of input material streams and energy carrier streams. Three different kinds of input material streams are defined:

- Primary input material
- Secondary input material
- Recirculation input material

A primary input material stream, indicated by the superscript $(p)$, is a material stream which is a direct input flowing through the company boundaries. A secondary input stream, shown as superscript $(s)$, is a stream coming from any upstream production unit, while the recirculation input material, using the superscript $(r)$, is an internal waste stream. This distinction is crucial for the evaluation of material flows, because it allows the exact quantification of material usage of every production unit.

With this definition of different material streams it is possible to develop the following material parameters. The primary input material ratio $(r_p)$ is calculated through

$$r_p = \frac{\sum_m \dot{m}_m^p}{\dot{m}_P}$$

Equation 3.14: Definition of the primary material input ratio

where $(\sum_m \dot{m}_m^p)$ is the sum of all primary input material streams of a production unit divided by the product output stream $(\dot{m}_P)$. Note, that since the definition of the production unit was to have one single output, there is only one output stream to which all streams are referenced. The secondary-and recirculation material ratios are calculated similar through the next two equations.

$$r_s = \frac{\sum_m \dot{m}_m^s}{\dot{m}_P}$$

Equation 3.15: Definition of the secondary material input ratio

$$r_r = \frac{\sum_m \dot{m}_m^r}{\dot{m}_P}$$

Equation 3.16: Definition of the recirculation material input ratio

The turnout $(To)$ of a production unit is calculated through:

$$To = \frac{1}{r_p + r_s + r_r}$$

Equation 3.17: Calculation of the turnout

The turnout is a number between zero and one indicating the material usage in the production unit.

The material loss ratio, indicated by the subscript $(L)$, gives insight how much material is lost through the process and is determined through:

$$r_L = r_p + r_s + r_r - 1$$

Equation 3.18: Calculation of the material loss ratio

Using this notation the material mass balance, which corresponds to the first term in Equation 3.13, can be written in detail as follows:

$$\sum_p \dot{m}_m^p + \sum_s \dot{m}_m^s + \sum_r \dot{m}_m^r + \sum_L \dot{m}_k^L + \dot{m}_P = 0$$

Equation 3.19: Detailed material mass balance

All input material streams must be equal to the sum of the material losses and the output stream. The mass balance in Equation 3.13 also includes the mass flows of the energy carriers. The material-and energy carrier mass flows are considered to be equal to zero separately, assuming no mass transfer between the energy carriers and the product flow. The energy carrier mass balance can therefore be written as

$$\sum_e \dot{m}_e^{in} + \sum_e \dot{m}_e^{out} = 0$$

Equation 3.20: Energy carrier mass balance

where $\left(\sum_e \dot{m}_e^{in}\right)$ represents the sum of all energy carrier mass inflows and $(\sum_e \dot{m}_e^{out})$ account for all energy carrier mass outflows.

The discussion of mass balances and their derivate parameters is finished. The next step is the development of the detailed energy balance and its derivate parameters and indicators.

The general energy balance of a production unit is expressed through

$$\sum_m \dot{E}_m + \sum_e \dot{E}_e = 0$$

Equation 3.21: General energy balance

where $\left(\sum_m \dot{E}_m\right)$ is the sum of all energy streams corresponding to material streams and $\left(\sum_e \dot{E}_e\right)$ corresponding to those of the energy carriers. Note that in contrast to the mass balances, the energy balance can only be written including both material and energy carrier flows, because energy is transferred between those streams and thus material- and energy carrier energy balances are separately not equal to zero. Examples for energy streams, flowing into the system are

- Natural gas
- Combustion air
- Electricity
- Enthalpy of any input material stream

while examples of out flowing streams include:

- Flue gas losses
- Dissipative heat losses
- Enthalpy of any output material stream

A more detailed energy balance can therefore be written as:

$$\left[\sum_{m} \dot{E}_{m}^{in} + \sum_{m} \dot{E}_{m}^{out}\right] + \left[\sum_{e} \dot{E}_{e}^{in} + \sum_{e} \dot{E}_{e}^{out}\right] = 0$$

Equation 3.22: Detailed energy balance

The first term is the part which includes the material streams, while the latter one is representing the energy carriers.

As it was stated before, the development of relevant energy parameters is crucial for the further analysis in this approach. The overall goal is to analyse energy consumption and to determine possible efficiency potentials. The following description develops these parameters.

The specific energy flow of an energy carrier is obtained through

$$\dot{e}_{e} = \frac{\dot{E}_{e}}{\dot{m}_{P}}$$

Equation 3.23: Definition of specific energy flow

where $(\dot{e}_{e})$ corresponds to the specific energy flow. Supposing that the energy stream is taken to be natural gas, this parameter calculates the natural gas energy flow which is needed to produce one unit of product output. Two other important energy parameters should be mentioned. First the specific flue gas loss in Equation 3.24 and second the specific dissipative heat loss in Equation 3.25.

$$\dot{e}_{fg} = \frac{\dot{E}_{fg}}{\dot{m}_{P}}$$

Equation 3.24: Specific flue gas loss

$$\dot{e}_{hl} = \frac{\dot{E}_{hl}}{\dot{m}_{P}}$$

Equation 3.25: Specific dissipative heat loss

Those two parameters are not directly needed for determination of energy consumption, but are furthermore used for efficiency potential quantification, because they quantify how much energy can possibly be recovered or is irretrievably lost.

The definition of mass- and energy balances including their derivative parameters is finished. The next step is the definition of the relevant energy indicators.

Two indicators where already defined in Equation 3.23 and Equation 3.24. The first one is the specific energy consumption of an energy carrier, the second one is equal to the theoretical heat recovery potential $(\dot{e}_{hr,th})$, because flue gas streams can be used for heat recovery. The overall specific energy consumption $(\dot{e})$ is calculated through:

$$\dot{e} = \sum_{e} \dot{e}_e$$

Equation 3.26: Overall specific energy consumption

The definition of the specific heat recovery potential is:

$$\dot{e}_{hr,th} = \dot{e}_{fg}$$

Equation 3.27: Specific theoretical heat recovery potential

Two other relevant indicators are the thermal efficiency in Equation 3.28 and the flue gas loss ratio in Equation 3.29.

$$\eta_{th} = \frac{\dot{E}_P}{\sum_m \dot{E}_m^{in} + \sum_e \dot{E}_e^{in}}$$

Equation 3.28: Definition of the thermal efficiency

$$\vartheta = \frac{\dot{E}_{fg}}{\dot{E}_{fuel} + \dot{E}_{cair}}$$

Equation 3.29: Definition of the flue gas loss ratio

$(\dot{E}_{fuel})$ is corresponding to the fuel energy input, like f.e. natural gas energy input, and $(\dot{E}_{cair})$ is the combustion air energy input.

All parameters and indicators are now developed on the lowest level of this model approach, thus on the production unit level. In order to determine energy consumption-and efficiency for a specific product, it is necessary that different production units are connected together to form the characteristic process of a product. On the basis of such a process, the product must be evaluated based on its energy consumption. For that, it is necessary to develop proper indicators also on module-and company level. This is now carried out, corresponding to step 4 of the Bottom-up approach.

Step 4 carries out the “summation” of different production units to whole processes or modules. Two production units are connected in order to calculate the relevant parameters and indicators corresponding to the production process of a certain product. Figure 9 shows the idea of linking two production units to create a process or a module.

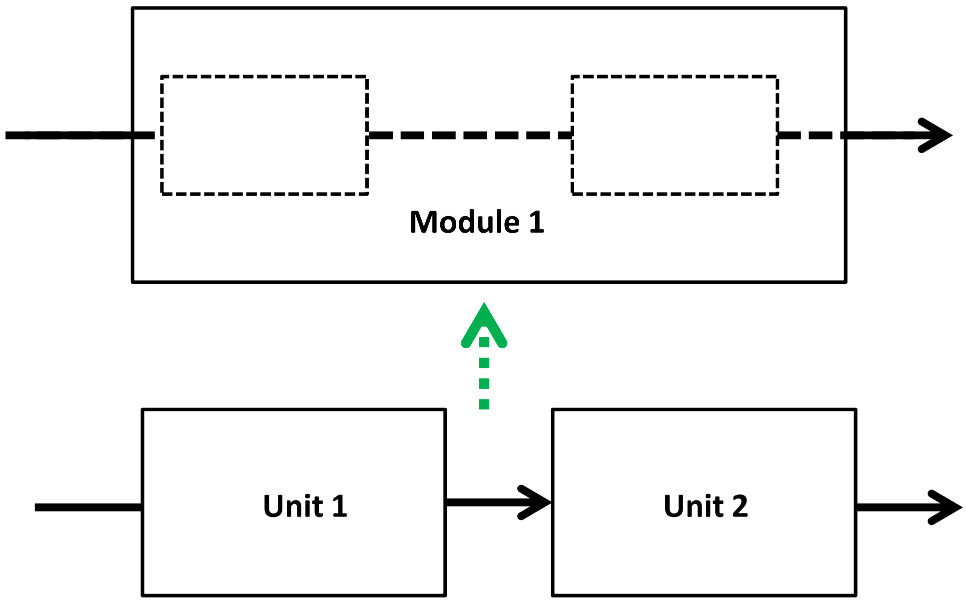


Figure 9: Idea of production unit linking

Till now, the production units are calculated based on separate and independent balances. To achieve the objectives of the model design, whole processes or modules must be determined. This is done through the linking of production units corresponding to the desired process or product. The next step is therefore to describe the linking algebra of this “summation”.

The linking of the production units are always based on the product flow between them. Figure 9 shows that a certain product flows through two production units 1 and 2. Separate balances and summary tables are calculated, which now have to be connected. Assuming that only those two units are part of module 1, the characteristic balances and tables can be calculated on the module level as follows.

One specific product is processed through module 1. It is important to understand, that all calculations are carried out from the end to the beginning of the process, because, in general, the properties of the end product are well known. Thus, mass of the product output is usually known. It is now crucial that all specific parameters and indicators of the production units are now allocated to the product.

The mass product outflow of production unit 2 is equal to the mass of the end product of module 1, which is a given value. First the mass flows of unit 2 must be determined. This is done through the material input ratios of production unit 2:

$$\dot{m}_{12}^{p} = r_{12,p} * \dot{m}_{1,P}$$

Equation 3.30: Calculation of the primary input material flow from the module

Equation 3.30 shows that the primary material input of production unit 2 equals its material ratio times the product outflow of module 1. This is possible, because, as stated before, product outflow of module 1 is equal to product outflow of production unit 2.

The indices are needed in order to indicate on which level the parameter is located. Subscripts like $11$ in $(r_{12,p})$ always indicate a production unit, while only one subscript e.g. in $(\dot{m}_{1,P})$ indicates a module parameter. The result of this calculation is the transformation of the material input based on the production unit balance, to the material input referenced on the product. This procedure is similarly carrier out for all material streams, which result is the complete determination of the material streams referenced to the product.

The energy streams must be also allocated to the product output of module 1. The specific energy streams are calculated through:

$$\dot{e}_{11,e}^{*} = \dot{e}_{11,e} * \dot{m}_{1,P}$$

Equation 3.31: Calculation of the specific energy stream

Through this calculation it is possible to correctly allocate the energy consumption to a specific product. The star is indicating that the specific energy consumption is now referenced to the product. If all material-and energy carriers are referenced to the product, the production units 1 and 2 are connected, based on the underlying production process.

In step 5 the relevant parameters and indicators are calculated on module level. The calculation of the module parameters and indicators is similar to those on the production level. The primary material input ratio of module 1 is calculated through

$$r_{1,p} = \frac{\sum_m \dot{m}_{1,m}^{p}}{\dot{m}_{1,P}}$$

Equation 3.32: Primary material input ratio (module level) where, $(\sum_m \dot{m}^p_{1,m})$ is the sum of all primary material input streams into the module, which is equal to all material input streams of production units 1 and 2. The secondary-and the recirculation material ratios as well as the turnout and the material loss ratio are calculated similarly to the production units. The material parameters are fully determined through this procedure. Since the product is flowing through all connected production units and the specific energy streams are consequently calculated based on their output, the specific energy consumption of an energy carrier is simply calculated through:

$$\dot{e}^*_{1,e} = \sum_e \dot{e}^*_{11,e}$$

Equation 3.33: Specific energy stream (module level)

Through the presented equations, all relevant parameters and indicators can be calculated on the module level. The indicators like theoretical heat recovery or thermal efficiency are not presented again since their calculation is again equal to those on production unit level.

The last step in the Bottom-up analysis is the calculation of the company level based on the modules of the production process. The procedure of combining modules is the same like for combining production units. However, there are some differences on the company level. First there are no secondary material streams, due to the fact that all modules are connected to each other. Only primary-and recirculation material streams are left, which was the initial objective of defining primary-and recirculation material flows. Second, one new factor is introduced, which is called the “wastage factor”. This factor determines how much wastage is produced in the company’s operation. The higher the wastage factor, the higher is also the recirculation material flow.

The primary-and recirculation material ratios on the company level are:

$$r_p = \frac{\sum_j \dot{m}^p_j}{\dot{m}_P}$$

Equation 3.34: Primary material input factor (company level)

Note that this equation looks quite similar to Equation 3.14, but in this case used material streams are added up from the module level.

$$r_r = \frac{\sum_j \dot{m}^r_j}{\dot{m}_P}$$

Equation 3.35: Recirculation material input factor (company level)

The specific energy carrier consumptions of the modules can be simply added up through:

$$\dot{e}_e^* = \sum_j \dot{e}_{j,e}^*$$

Equation 3.36: Specific energy carrier consumption (company level)

The wastage factor is defined through

$$f_{1,w} = 1 + \frac{\dot{m}_P}{\dot{m}_{P'}}$$

Equation 3.37: Definition of the wastage factor.

where $(f_{1,w})$ is the wastage factor of module 1 and $\left(\frac{\dot{m}_P}{\dot{m}_{P'}}\right)$ is the ratio of the material output with $(\dot{m}_P)$ and without $(\dot{m}_{P'})$ wastage. The wastage factor can then be multiplied by the recirculation material ratio in order to determine overall recirculation material. The wastage factor is larger than one and recirculation material stream is rising if the wastage factor grows. It is also important to calculate material inputs of downstream modules, because it calculates the module's "real" output.

The development of the theoretical concept of the Bottom-Up analysis is finished. Through the consequent notation of material and energy carrier streams, it is possible to derive important parameters on unit, module and company level. The next section summarizes all mentioned parameters and indicators and shows them graphically in Figure 10.

## 3.4 Parameter and indicator summary

In this section a parameter-and indicator summary is given for a better understanding of the calculation framework of the Bottom-up analysis. First, a graphical representation of the mass flows of all three levels is shown in Figure 10. There it can be seen, how the different mass flows add up together from the bottom (production unit level) to the higher module level and finally to the top level (company level). All material-and energy carrier mass streams are shown. The energy streams are not explicitly presented, however they are all derived from the mass streams. Note that it was resigned to use a star as a superscript to indicate that all streams are referenced to the final product.

Table 2 finally summarizes all variables used to calculate the mass-and energy balance as well as the corresponding parameters and indicators on the production unit level. As an example, production unit 2 as shown in Figure 10 is used. Four indicators are derived, which evaluate the production unit. Thermal efficiency can be used to evaluate the efficiency of a furnace while the specific theoretical heat recovery potential can be used for further optimization. An example for that is Pinch-Analysis, which optimizes heat flows between production units. The specific energy consumption is used to quantify energy consumption of each energy carrier.

A detailed table on the module level is disclaimed, because it is similar to Table 2 since only the subscripts are changed. However, the analysis of the indicators is equally crucial, because it provides the basis for a comparison of (main) processes throughout different companies.

Highly important is the summary of the company level, because it provides the basis for the evaluation of the company's performance and enables the possibility for a further LCA. Table 3 summarizes the mass- and energy balances as well as the parameter and indicators on company level. Note that there are no secondary material streams, because they only occur between production units or modules. Four main indicators can be established; where the turnout measures the overall material output and gives insight into efficiency of material usage. The two material input ratios measure the need of primary resources and the material circulation in the company. Specific energy consumptions again measure overall energy utilization on company level.

The development of the Bottom-up analysis is finished. The next section discusses the derived indicators and how they can be used for benchmarking purposes.

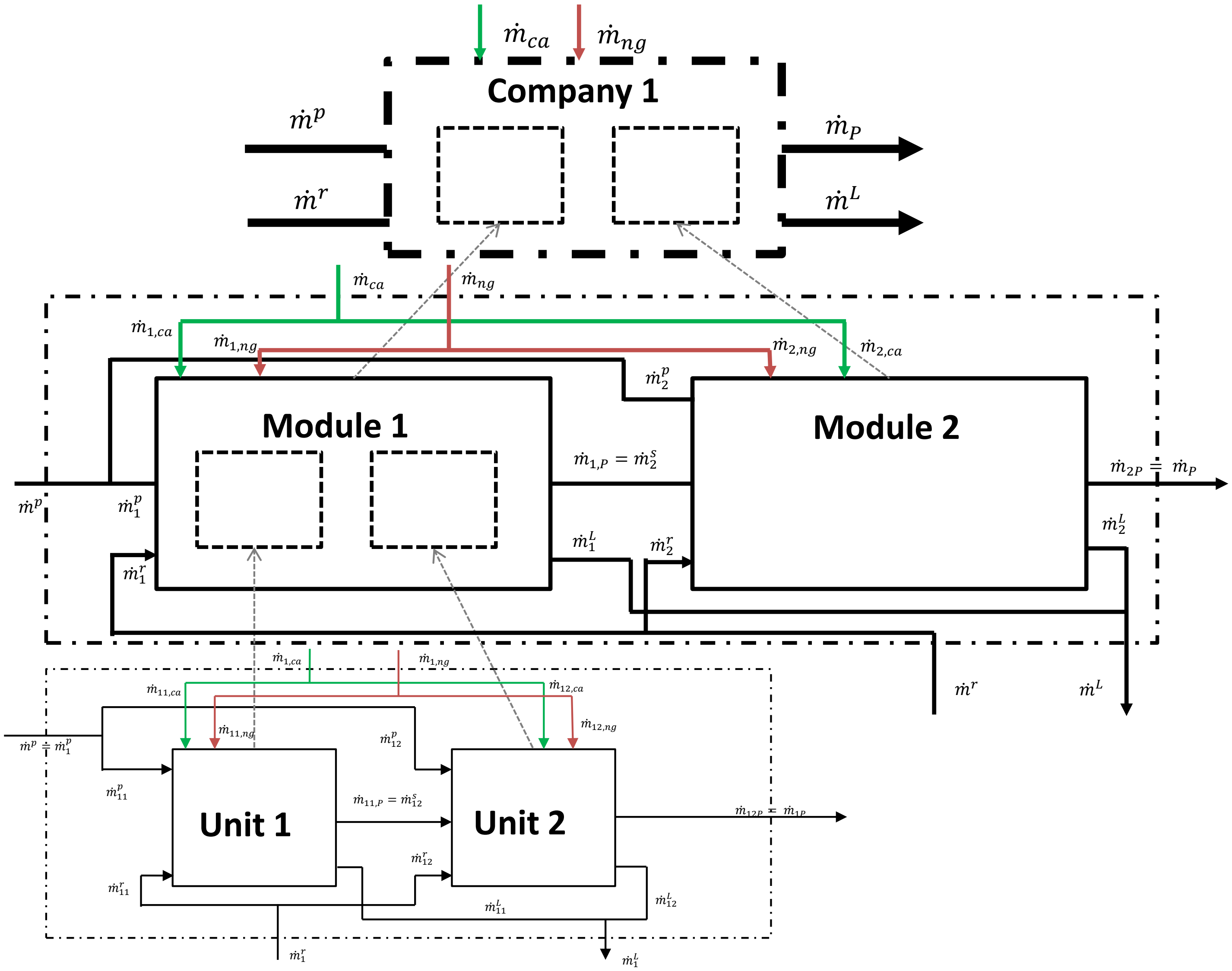


Figure 10: Graphical representation of the Bottom-up analysis

Table 2: Production unit framework summary

| Material-energy carrier balances | | | | Parameter-and indicator summary | | |
|---|---|---|---|---|---|---|
| | | Mass flows | Energy flows | Parameters | Indicators | |
| Material streams | Inflow | $\dot{m}_{12}^{p}$ | $\dot{E}_{12}^{p}$ | $r_{12,p}$ | Flue gas loss ratio | $\vartheta_{12}$ |
| Material streams | Inflow | $\dot{m}_{12}^{s}$ | $\dot{E}_{12}^{s}$ | $r_{12,s}$ | Specific compressed air consumption | $\dot{e}_{12,ca}$ |
| Material streams | Inflow | $\dot{m}_{12}^{r}$ | $\dot{E}_{12}^{r}$ | $r_{12,r}$ | Specific natural gas consumption | $\dot{e}_{12,ng}$ |
| Material streams | Outflow | $\dot{m}_{12}^{L}$ | $\dot{E}_{12}^{L}$ | $r_{12,L}$ | Specific theoretical heat recovery potential | $\dot{e}_{12,hr,th}$ |
| Material streams | Outflow | $\dot{m}_{12P}$ | $\dot{E}_{12P}$ | (Allocation reference) | Thermal efficiency | $\eta_{th}$ |
| Energy carrier streams | Inflow | $\dot{m}_{12,ca}$ | $\dot{E}_{12,ca}$ | $\dot{e}_{12,ca}$ | | |
| Energy carrier streams | Inflow | $\dot{m}_{12,ng}$ | $\dot{E}_{12,ng}$ | $\dot{e}_{12,ng}$ | | |
| Energy carrier streams | Outflow | $\dot{m}_{12,fg}$ | $\dot{E}_{12,fg}$ | $\dot{e}_{12,fg}$ | | |
| Energy carrier streams | Outflow | --- | $\dot{E}_{12,hl}$ | $\dot{e}_{12,hl}$ | | |

Table 3: Company level framework summary

| Material-energy carrier balances | | | | | Parameter-and indicator summary | | |
|---|---|---|---|---|---|---|---|
| | | Mass flows | Energy flows | Parameters | Indicators | |
| Material streams | Inflow | $\dot{m}^p$ | $\dot{E}^p$ | $r_p$ | Turnout | $To$ |
| | | --- | --- | --- | Primary material input ratio | $r_p$ |
| | | $\dot{m}^r$ | $\dot{E}^r$ | $r_r$ | Recirculation material input ratio | $r_r$ |
| | Outflow | $\dot{m}^L$ | $\dot{E}^L$ | $r_L$ | Specific energy carrier consumption | $\dot{e}_e$ |
| | | $\dot{m}_P$ | $\dot{E}_P$ | --- (Allocation reference) | | |
| Energy carrier streams | Inflow | $\dot{m}_{ca}$ | $\dot{E}_{ca}$ | $\dot{e}_{ca}$ | | |
| | | $\dot{m}_{ng}$ | $\dot{E}_{ng}$ | $\dot{e}_{ng}$ | | |
| | Outflow | $\dot{m}_{fg}$ | $\dot{E}_{fg}$ | $\dot{e}_{fg}$ | | |
| | | --- | $\dot{E}_{hl}$ | $\dot{e}_{hl}$ | | |

## 3.5 Indicator analysis for comparison/benchmark

Recollecting the topic and objectives of this work, the model should provide the basis for a benchmark of the production process, the whole life-cycle and the product itself. It should furthermore determine and analyze the actual energy consumption of the company, evaluate the energy efficiency and gather information on possible energy efficiency potentials. This section will answer the question, which indicators can be used for which purpose.

The Top-down analysis provides indicators on company and module level. There, actual energy consumptions of the energy carriers are available on company-and module level, while two characteristic indicators where developed. The Bottom-up analysis also provides these energy consumptions based on the corresponding production units including a thermodynamic analysis. The comparison of the indicators from the two approaches will therefore determine the difference between the allocated energy carrier consumption based on cost centres and the “real” physical energy consumption of the modules. Through this comparison, the differences between the results evaluate the accuracy of the cost allocation itself and determine its intransparency.

Figure 5 shows that the product benchmark is done through the comparison of the results of the two approaches. The indicators derived through Equation 3.4, Equation 3.5 and Equation 3.6 can be directly compared with the energy consumptions established through the module calculation, see Figure 10. Note that in the Top-down approach all energy values are absolute values, meaning that energy consumption is determined on a yearly production basis. Therefore those values should be first converted into specific consumptions by dividing them by the yearly product production. This comparison can be done on module and company level, using the indicators derived in Table 3. The comparison of the results also gathers information on possible energy efficiency potentials.

The module indicators can be furthermore used for the production benchmark. Through the tight definition of the modules as main processes, a comparison between main processes throughout different companies is possible. It should be mentioned that company processes are in most cases quite different. Therefore attention should be given to the comparability of the companies. However, if a comparison seems meaningful, module indicators can be used.

The model also provides the basis for a downstream analysis within the life-cycle analysis. While the turnout on company level determines the overall material use efficiency, the primary-and recirculation material input ratios give insight on how much primary material is actually used to produce one unit of product and how much material is circulating inside the company. The higher the circulation rate, the higher the energy consumption and therefore the lower the energy efficiency. This ratio should be considered as a crucial indicator in further optimization procedures. If life-cycle analysis is carried out for a company, the indicators on company level can be used to link the company to its up-and downstream life-cycle processes.

The main purpose of this work is the analysis of energy consumption and the evaluation of energy efficiency. The actual energy consumption can be determined both through the Top-down analysis and the Bottom-up analysis. The energy efficiency can be calculated on the production unit level, through the indicators in Table 2. The indicators on production unit level also provide the basis for optimization procedures like heat integration through Pinch-analysis. Thermal efficiency can be taken to evaluate the thermodynamic performance of a production unit, while the material input ratios show the composition of the material input streams. An evaluation of energy efficiency can be therefore carried out on all three system levels.

Finally, Table 4 summarizes the discussed evaluation methods and shows which indicators are used in different evaluation purposes.

Table 4: Indicator summary for comparison/benchmark

| | | **Top-Down** | | **Bottom-Up** | | |
|---|---|---|---|---|---|---|
| | Evaluation purpose | Company level | Module level | Company level | Module level | Unit level |
| Benchmark | Product | $E_e$ | • $mi_{ej}$<br>• $eci_{ej}$ | $\dot{E}_e$ | $\dot{E}_{j,e}$ | --- |
| Benchmark | Production | --- | • $mi_{ej}$<br>• $eci_{ej}$ | --- | • $\dot{E}_{j,e}$<br>• $To_j$<br>• $r_{j,p}$<br>• $r_{j,r}$ | --- |
| Benchmark | Life-cycle | --- | --- | • $\dot{E}_e$<br>• $To$<br>• $r_p$<br>• $r_r$ | --- | --- |
| General evaluation | Energy consumption | $E_e$ | • $mi_{ej}$<br>• $eci_{ej}$ | $\dot{E}_e$ | $\dot{E}_{j,e}$ | $\dot{e}_{jl,e}$ |
| General evaluation | Energy efficiency | $e_e$ | --- | --- | --- | • $\eta_{jl,th}$<br>• $\dot{e}_{jl,e}$<br>• $\vartheta_{jl}$ |
| General evaluation | Intransparency | $E_e$ | • $mi_{ej}$<br>• $eci_{ej}$ | --- | • $\dot{E}_{j,e}$<br>• $To_j$<br>• $r_{j,p}$<br>• $r_{j,r}$ | --- |
| General evaluation | Optimization | --- | • $mi_{ej}$<br>• $eci_{ej}$ | • $To$<br>• $r_p$<br>• $r_r$ | --- | • $\dot{e}_{jl,hr}$<br>• $\vartheta_{jl}$ |

# 4 Application of the model

The theoretical basis for the model was developed throughout the last chapters of this thesis. This chapter deals with the application of the model on a typical foundry process, which objective is to show, how the model is applied and which results can be generated. Furthermore, the application of the model will prove the applicability of the model approach to the foundry industry.

During the first year of the project “Energy efficiency in the foundry industry”, several foundry companies where analyzed. One specific foundry company is chosen for the application of the model. Since all used information and data is confidential, no names or representative data is shown. The whole model will be applied to two main processes of this company, namely the modules “melting” and “casting”. Those two modules can be seen as the core part of any foundry company, so the results of the application are assumed to be representative. The application consists of all steps previously developed in chapter 3.

## 4.1 Application of the Top-down analysis

In this section the Top-down procedure is carried out for the two modules of the foundry company. The general information on cost centres, modules and the corresponding energy consumptions were gathered through the questionnaire and the data sheets, see Annex A.

With the help of the data acquisition methodology, it is possible to derive the cost centre matrix of Equation 3.1, which allocates the energy costs-or consumptions to the corresponding modules. It was found, that mainly two energy carriers are used in the foundry; electricity and natural gas.

The result of the cost centre matrix determination is presented in Table 5.

Table 5: Cost centre matrix $(C)$

| Cost centre number | Electricity [kWh] | Natural gas [Nm³] |
|---|---:|---:|
| 1 | 141,858 | 8,023,753 |
| 2 | 15,104,289 | 40,508 |
| 3 | 804,816 | --- |
| 4 | 5,987,520 | 1,945,045 |
| 5 | 534,600 | --- |
| 6 | 544,320 | --- |
| 7 | 12,312,000 | --- |
| 8 | 3,240,000 | --- |
| 9 | 5,617,447 | 3,191,064 |
| 10 | 777,600 | --- |
| 11 | 13,893,768 | --- |
| 12 | 39,700 | --- |
| 13 | 177,226 | --- |
| 14 | 844,668 | 422,302 |
| 15 | 3,990 | --- |
| 16 | 3,672 | --- |
| 17 | 5,453 | --- |
| 18 | 114,422 | --- |

The entries of matrix $C$ contain energy consumption values per production year, because they are based on nominal power of the production units. The consumption values were simply derived from the nominal power using an average operation time per year. It can be implicitly seen, that those consumption values may not be equal to the real physical consumption, because they are based on average values.

The next step is the allocation of the cost centres to the modules, which is done through the allocation matrix $I$ in Equation 3.2. For that, all production units were examined and their corresponding modules were defined. The results are shown in Table 6.

Cost centre 1 f.e. is allocated fully to the module melting, while cost centre 2 is allocated to casting. Every cost centre is allocated to a certain module, while a differentiation is made between main modules and support modules. It is assumed that main modules can be found in most of the foundry companies, so that a certain comparability should be given between them. The specialization of the foundry, depending on its products, is taken into account through support modules.

Table 6: Allocation matrix $(I)$

| | Main processes/modules | | | | | | Support processes/modules | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cost centre | Melting | Casting | Unpacking | Heat treatment | Mechanical treatment | Finishing | Painting shop | Air pressure supply | Buildings | Auxiliaries |
| 1 | 1 | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 2 | --- | 1 | --- | --- | --- | --- | --- | --- | --- | --- |
| 3 | --- | --- | 1 | --- | --- | --- | --- | --- | --- | --- |
| 4 | --- | --- | --- | 1 | --- | --- | --- | --- | --- | --- |
| 5 | --- | --- | --- | --- | 1 | --- | --- | --- | --- | --- |
| 6 | --- | --- | --- | --- | 1 | --- | --- | --- | --- | --- |
| 7 | --- | --- | --- | --- | 1 | --- | --- | --- | --- | --- |
| 8 | --- | --- | --- | --- | 1 | --- | --- | --- | --- | --- |
| 9 | --- | --- | --- | --- | --- | --- | 1 | --- | --- | --- |
| 10 | --- | --- | --- | --- | --- | 1 | --- | --- | --- | --- |
| 11 | --- | --- | --- | --- | --- | --- | --- | 1 | --- | --- |
| 12 | --- | --- | --- | --- | --- | --- | --- | --- | --- | 1 |
| 13 | --- | --- | --- | --- | --- | --- | --- | --- | --- | 1 |
| 14 | --- | --- | --- | --- | --- | --- | --- | --- | 1 | --- |
| 15 | --- | --- | --- | --- | --- | --- | --- | --- | --- | 1 |
| 16 | --- | --- | --- | --- | --- | --- | --- | --- | --- | 1 |
| 17 | --- | --- | --- | --- | --- | --- | --- | --- | --- | 1 |
| 18 | --- | --- | --- | --- | --- | --- | --- | --- | --- | 1 |

Table 7: Results of the Module-energy matrix $(M)$

| Energy carrier | Melting | Casting | Unpacking | Heat treatment | Mechanical treatment | Finishing | Painting shop | Air pressure supply | Buildings | Auxiliaries |
|---|---|---|---|---|---|---|---|---|---|---|
| Electricity [GWh] | 0.14 | 15.10 | 0.80 | 5.99 | 16.63 | 0.78 | 5.62 | 13.89 | 0.84 | 0.34 |
| Natural gas [GWh] | 88.42 | 0.45 | 0.00 | 21.43 | 0.00 | 0.00 | 35.17 | 0.00 | 4.65 | 0.00 |

During the examination it was found out, that no allocation problem derive from the production units to the modules. All cost centres can be allocated as a whole to a specific module, which makes the calculation of corrected consumptions unnecessary.

Before the calculation of the energy indicators can be carried out, the energy carrier units must be transferred into a standard unit. This is chosen to be kWh. While electricity does not need to be converted, the volume consumptions of natural gas must be multiplied by 11.02 kWh/ Nm$^3$, which corresponds to the lower heating value of natural gas.

The energy consumptions of the energy carriers are now calculated for all assigned modules through Equation 3.4, resulting in the module-energy matrix shown in Table 7. It represents the energy carrier consumptions throughout the modules of the company. Thus, the company's energy consumption can be presented for each module in Figure 11.

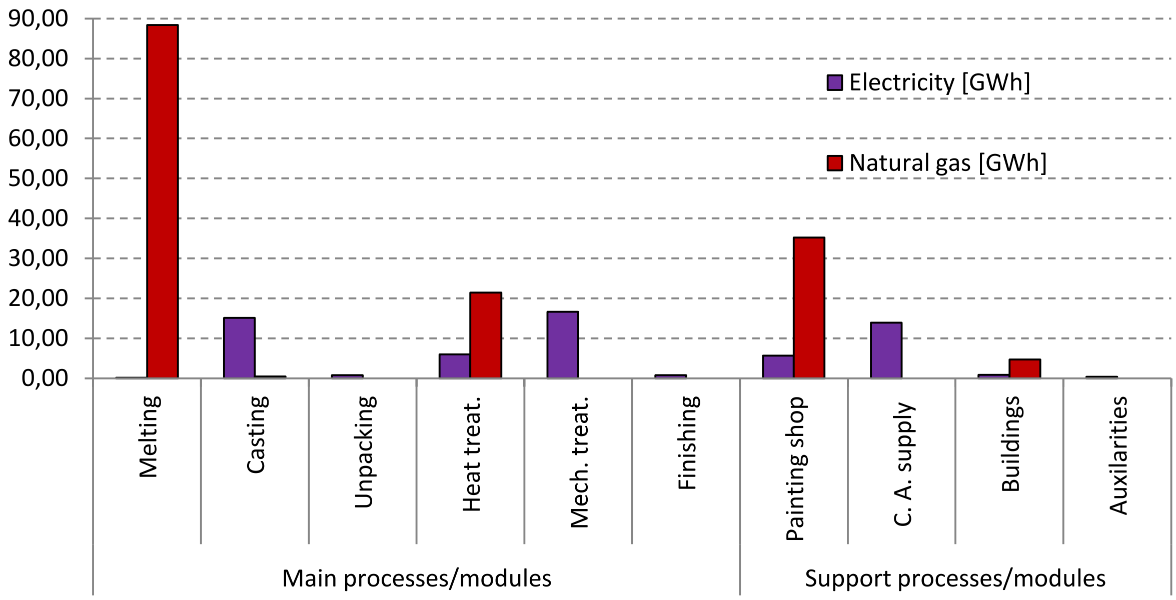


Figure 11: Energy carrier consumptions in the company

Natural gas is mainly used in the melting, the heat treatment and the painting shop, with consumptions of approx. 90, 21 and 35 GWh, respectively. Those consumptions result in 145 GWh, which correspond to 96,6 % of the overall natural gas consumption or 68 % of the overall energy consumption. Electricity consumption result in 60 GWh and is mainly used by the modules casting (15 GWh), mechanical treatment (17 GWh) and compressed air supply (14 GWh).

To study the results of the energy consumptions in more detail, the two characteristic indicators, energy carrier intensity and module intensity are calculated through applying Equation 3.5 and Equation 3.6, respectively. The energy carrier intensities are shown in Figure 12.

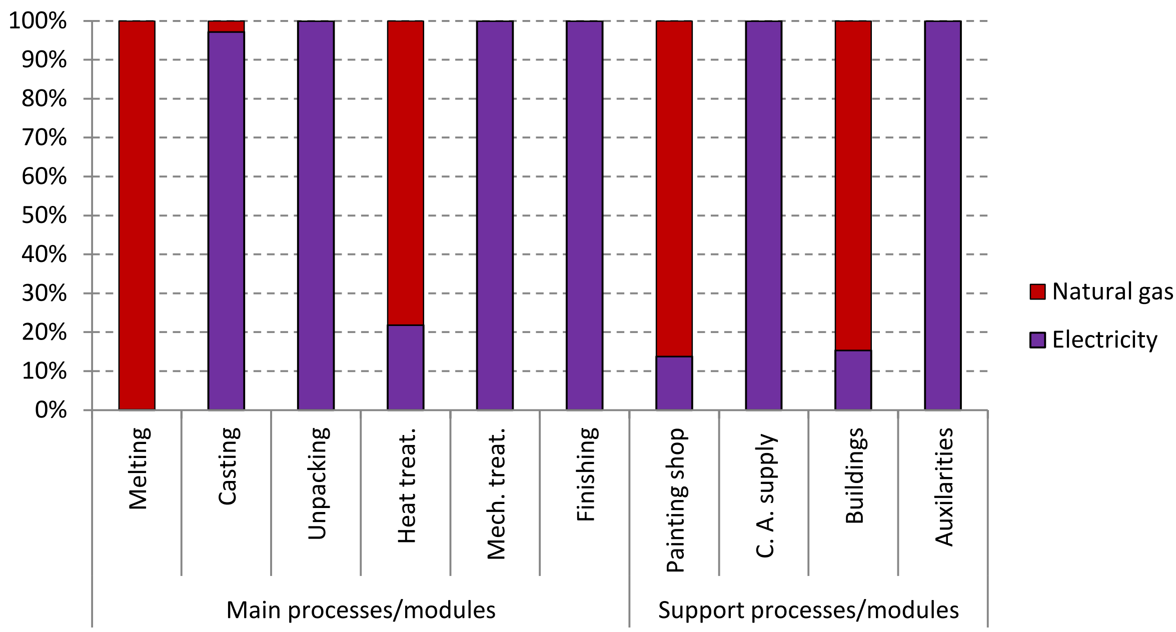


Figure 12: Energy carrier intensities

It can be seen that the melting shop uses nearly only natural gas, while heat treatment, the painting shop and the buildings, which major energy carrier is natural gas, also use some amount of electricity. All other modules use electricity as their main energy source. Note, that if a lot of different energy carriers are used in the company, this indicator enables to know on which energy carrier a potential process optimization should focus. In this case the situation is quite clear, due to the use of “only” two energy carriers.

If optimization focus lies on reducing a specific energy carrier, because of f.e. rising energy carrier costs, module intensity can be used.

Figure 13 shows the module intensity for electricity, while Figure 14 shows the result for natural gas. Again, it can be seen that electricity is mostly used in casting, mechanical treatment and compressed-air production. Natural gas in contrast is mainly used during melting, heat treatment and in the painting shop. If the focus of optimization lies on reducing natural gas consumption, due to higher market prices or environmental considerations, this indicator clearly determines the modules where an optimization should focus on.

In the last step, the energy carrier costs are calculated based on the results of Figure 11. The cost for electricity is taken to be 0.06 €/kWh, while natural gas costs are 0.029 €/kWh. The result is shown in Figure 15. Due to the fact that energy carriers have different specific costs, the relation between electricity and natural gas consumption change.

If preferred, energy carrier intensity and natural gas consumptions can be also calculated based on energy carrier costs.

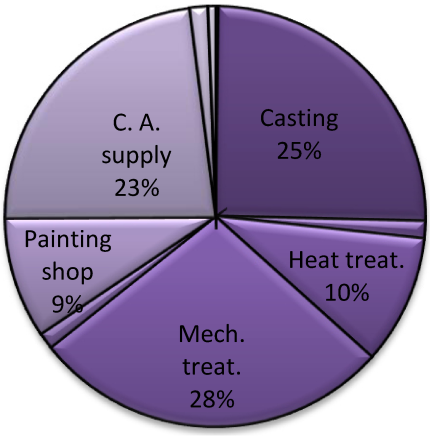


Figure 13: Module intensity for electricity

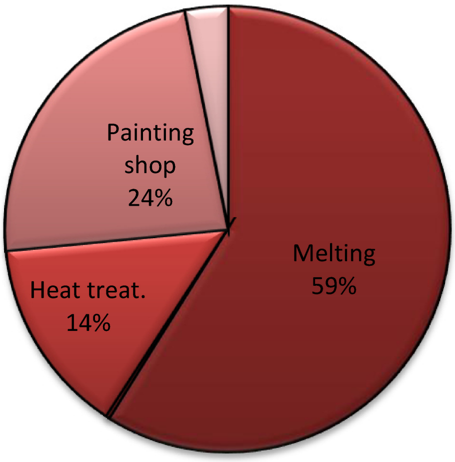


Figure 14: Module intensity for natural gas

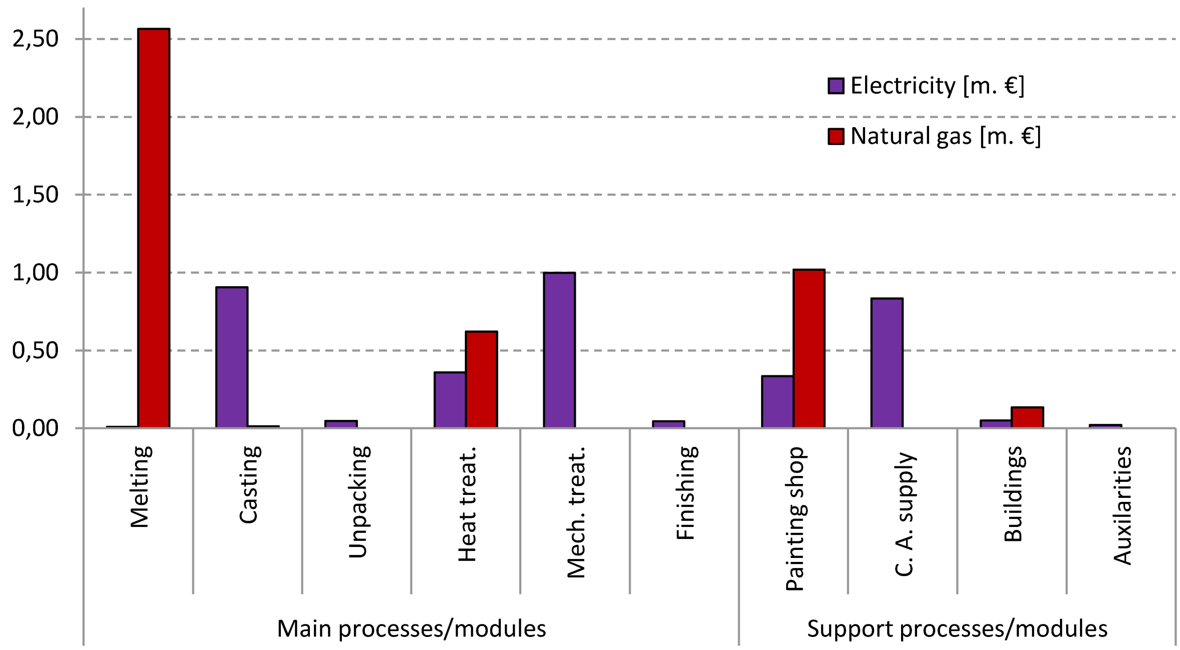


Figure 15: Energy carrier costs for the modules

## 4.2 Application of the Bottom-up analysis

In this section the Bottom-up analysis is carried out. For that, all steps previously shown are executed. Step 1 is the definition of the production units to the modules. As mentioned before, the Bottom-up analysis is applied to the modules melting and casting. Several different production units are identified in those two modules. In order to guarantee confidentially, no names or representing data is shown. The definition of the production units to the modules is as follows:

- Module 1: Melting
    - Production unit 1.1
    - Production unit 1.2
    - Production unit 1.3
    - Production unit 1.4
- Module 2: Casting
    - Production unit 2.1
    - Production unit 2.2

The module melting consists of four production units, while the module casting consists of only two. For the presented units, only electricity and natural gas are considered as energy carriers, because they are found to be the main energy sources of the production process.

The next step is the modeling of the production units in order to calculate their mass-and energy balances. The modeling is shown as an example for production unit 1.3. At first all relevant data must be available from the data sheets. The results of the data sheet for U 1.3 are shown in Table 8.

Table 8: Data sheet results for U 1.3

| | Material input [kg/batch] | Input temperatures [°C] |
|---|---|---|
| Primary material input | 977 | 25 |
| Secondary material input | 635 | 770 |
| Recirculation material input | 259 | 25 |
| General U 1.3 data | | |
| Material losses | 0.01 | [1] |
| External wall surface | 30 | [m²] |
| External wall temperature | 150 | [°C] |
| Natural gas consumption | 48.35 | [Nm³/T] |
| Combustion air temperature | 25 | [°C] |
| Lambda | 1.2 | [1] |
| Extraction temperature | 762.5 | [°C] |
| Flue gas temperature | 891.4 | [°C] |

The information of the data sheets were generated through the first project year. The top of the table shows the material input data, which consist of the mass flow and the corresponding input temperatures. The mass flow is given for the specific batch time of the production unit in order to gain flexibility of calculating units of different time frames.

The general data consist of loss parameters like material losses, external wall temperature-and area. Furthermore, natural gas consumption is given as average parameter, which was calculated from a previous analysis. Combustion air temperature and lambda are important to calculate flue gas streams. The extraction temperature is relevant for the enthalpy of the product outflow, while the flue gas temperature determines the energy content of the flue gases and therefore the heat recovery potentials.

Based on the data presented in the data sheets, all mass- and energy streams can be calculated. The mass-and energy balances are obtained through thermodynamic calculations. For both the material streams as well as for the energy carriers four parameters are calculated:

- Mass flow
- Energy flow
- Power
- Specific energy

The calculation of the mass-and energy flows are carried out for all entering and exerting streams and provide the basis for the balances. If batch time is not equal to one hour, the calculation of power can be used to compare energy flows of systems with different time frames. Specific energy is the specific enthalpy of f.e. a flue gas stream. Note that in this case the reference is not taken to be the product output stream but the mass of the stream itself. Table 9 shows the results of the calculation of all inflow-and outflow streams of the production unit.

The production unit inflows are primary material of 977 kg, secondary material from an upstream unit of 635 kg and recirculation input of 259 kg. The batch time is one hour. Only the secondary input has a specific enthalpy greater than zero, because the other two streams are entering at ambient condition. As given from the data sheets, an average natural gas consumption of 48.35 $Nm^3$ per year results in 986 kWh/batch of energy carrier consumption for the specific batch time frame. No electricity is used in this unit. The product output is the sum of all inflow material streams minus the material losses. The specific energy is calculated as enthalpy including latent heat if necessary. Flue gas mass-and energy flows are calculated based on a combustion calculation.

Table 9: Mass-and energy balance U 1.3

| | | Mass flow [kg/batch] | | Energy flow [kWh/batch] | | Power [kW] | spec. Energy [kWh/T] |
|---|---|---|---|---|---|---|---|
| Input streams | Primary material input | $\dot{m}_{13}^{p}$ | 977.46 | $\dot{E}_{12}^{p}$ | 0.00 | 0.00 | 0.00 |
| | Secondary material input | $\dot{m}_{13}^{s}$ | 635.26 | $\dot{E}_{12}^{s}$ | 182.22 | 182.22 | 286.84 |
| | Recirculation material input | $\dot{m}_{13}^{r}$ | 259.33 | $\dot{E}_{12}^{r}$ | 0.00 | 0.00 | 0.00 |
| | Combustion air | $\dot{m}_{12,cair}$ | 1.805.01 | $\dot{E}_{12,ca}$ | 0.00 | 0.00 | 0.00 |
| | Natural gas | $\dot{m}_{12,ng}$ | 71.63 | $\dot{E}_{12,ng}$ | 986.67 | 986.67 | 13.775.00 |
| | Electricity | --- | --- | $\dot{E}_{12,el}$ | 0.00 | 0.00 | --- |
| Output streams | Product output | $\dot{m}_{13P}$ | 1.851.88 | $\dot{E}_{12P}$ | 526.32 | 526.32 | 284.21 |
| | Flue gas | $\dot{m}_{12,fg}$ | 1.876.63 | | 268.24 | 268.24 | 142.94 |
| | Material loss | $\dot{m}_{13}^{L}$ | 20.18 | $\dot{E}_{12}^{L}$ | 5.86 | 5.86 | 290.37 |
| | Dissipative heat loss | --- | --- | $\dot{E}_{12,hl}$ | 368.46 | 368.46 | --- |

Dissipative heat loss is quantified as the rest of the energy input, which is not part of the material-or the flue gas stream.

After the calculation of the mass-and energy balances in Table 9, the next step is the calculation of the characteristic parameters and indicators of this unit, described in section 3.3.2. The result of this step is given in Table 10.

Table 10: Results of the parameter and indicator calculation

| | Parameters [kWh/T] | | Indicators [kWh/T] | |
|---|---|---|---|---|
| Primary material input ratio | $r_{13,p}$ | 0.53 | $\vartheta_{13}$ | 0.27 |
| Secondary material input ratio | $r_{13,s}$ | 0.34 | $\eta_{13,th}$ | 0.45 |
| Recirculation material input ratio | $r_{13,r}$ | 0.14 | $\dot{e}_{13,ng}$ | 532.79 |
| Material loss ratio | $r_{13,L}$ | 0.01 | $\dot{e}_{13,hr,th}$ | 144.85 |
| Specific natural gas consumption | $\dot{e}_{13,ng}$ | 532.79 | | |
| Specific combustion air consumption | $\dot{e}_{13,cair}$ | 0.00 | | |
| Specific electricity consumption | $\dot{e}_{13,el}$ | 0.00 | | |
| Specific flue gas loss | $\dot{e}_{13,fg}$ | 144.85 | | |
| Specific dissipative heat loss | $\dot{e}_{13,hl}$ | 198.97 | | |

All indicators and parameters, excluding the material ratios, are given in kWh/T. The reference is the product output of this production unit. All values are derived through the equations in section 3.3.2. The results show that 532.79 kWh of natural gas per ton of final product is consumed in this unit. The thermal efficiency is 45 %, while the flue gas loss ratio is 27 %. A theoretical heat recovery potential of nearly 145 kWh/T can be quantified. This procedure is similarly carried out for all production units, which lead to the calculation of the modules.

The relevant indicators are calculated for every production unit used in the production process. Table 11 shows the result for the production units in the module melting, while Table 12 summarizes the results for the module casting.

Table 11: Results module melting

| | $\dot{e}_{1i,ng}$ | $\dot{e}_{1i,el}$ | $\dot{e}_{1i,hr,th}$ | $\eta_{1i,th}$ | $\vartheta_{1i}$ |
|---|---|---|---|---|---|
| Unit 1.1 | 679.28 | --- | 132.40 | 0.40 | 0.19 |
| Unit 1.2 | 881.60 | --- | 259.33 | 0.31 | 0.29 |
| Unit 1.3 | 532.79 | --- | 144.85 | 0.45 | 0.27 |
| Unit 1.4 | --- | 1.14 | --- | --- | --- |

Table 12: Results module casting

| | $\dot{e}_{1i,ng}$ | $\dot{e}_{1i,el}$ | $\dot{e}_{1i,hr,th}$ | $\eta_{1i,th}$ | $\vartheta_{1i}$ |
|---|---|---|---|---|---|
| Unit 2.1 | --- | 6.87 | 0 | --- | 0 |
| Unit 2.2 | --- | 292.10 | 0 | --- | 0 |

The production units of the module melting show different specific energy consumptions ranging from 532 to 881 kWh/T. The higher the specific energy consumption the higher as well the theoretical heat recovery potential. The thermal efficiencies also correspond to the energy consumptions. From that point of view, energy efficiency can be clearly quantified by using the specific energy consumption. It can be seen that U 1.3 is more energy efficient than unit 1.2.

Now the combination of the production units to calculate the corresponding module and afterwards the company's balance is carried out. The chronology of the process is outlined through the numbering of the units. It is assumed that a product of 20 kg/piece is processed through the production units.

The results of the two modules are shown in Table 13. The primary material usage during melting is 60 while recirculation accounts for 45 %. This means that 45 % of the material output of this module was already melted before. Reducing this amount will lead to a tremendous increase in efficiency. Specific energy consumptions are calculated for both modules. The result shows 21 kWh/p. of natural gas in melting and 6.58 kWh/p. of electricity while casting. Those values can be compared with values of different companies to have a process benchmark.

Table 13: Module indicator results

| | Module 1 | Module 2 | Unit |
|---|---|---|---|
| $r_{j,p}$ | 0.60 | 0.00 | [1] |
| $r_{j,s}$ | 0.00 | 1.06 | [1] |
| $r_{j,r}$ | 0.45 | 0.00 | [1] |
| $r_{j,L}$ | 0.05 | 0.06 | [1] |
| $\dot{e}_{j,ng}$ | 21.01 | --- | [kWh/p.] |
| $\dot{e}_{j,el}$ | 0.03 | 6.58 | [kWh/p.] |

The final step is the calculation of the indicators on company level, which are given in Table 14.

Table 14: Company results

| | Company level | Unit |
|---|---|---|
| $r_p$ | 0.64 | [1] |
| $r_r$ | 0.48 | [1] |
| $r_L$ | 0.12 | [1] |
| $\dot{e}_{ng}$ | 21.01 | [kWh/p.] |
| $\dot{e}_{el}$ | 6.61 | [kWh/p.] |

64 % of the final product output is supplied through primary material, 48 % is coming from recirculation material. The overall material losses account for 12 %, while the energy carrier consumptions are 21.01 and 6.61 kWh per final product output. 48 % of the material is recirculated in between the company which leads to lower energy efficiency.

If overall energy consumption should be considered, the average amount of final products must be known. Since information on this is rare, it is assumed that 2.7 million final products are produced in one year. This results in overall natural gas consumption of 56.72 GWh and 17.84 GWh of electricity consumption. The costs of energy carriers for the company based on the Bottom-up approach result in 1.64 m. € for natural gas and 1.07 m. € for electricity.

The application of the Bottom-up analysis is finished. In the next chapter, the results of the model application are finally analyzed.

## 4.3 Comparison and results of the model application

The application of the model showed that all necessary results can be obtained by the execution of the Top-down and the Bottom-up approaches and their characteristic steps.

The results of the whole model approach can be used for different benchmarking or general evaluation purpose described in Table 4.

The product benchmark compares foundry products throughout different companies. For that, overall energy consumptions on company-and module level are needed. The Top-down indicators for this benchmark are taken from Figure 11 to Figure 14. Bottom-up indicators are taken from Table 13.

Since no other product was studied in this thesis, the product benchmark is disclaimed. However, the results can be taken directly for the evaluation of intransparency in the company, because the economic and the thermodynamic approaches are compared. Figure 16 compares the results of the energy consumptions for both approaches of the two modules.

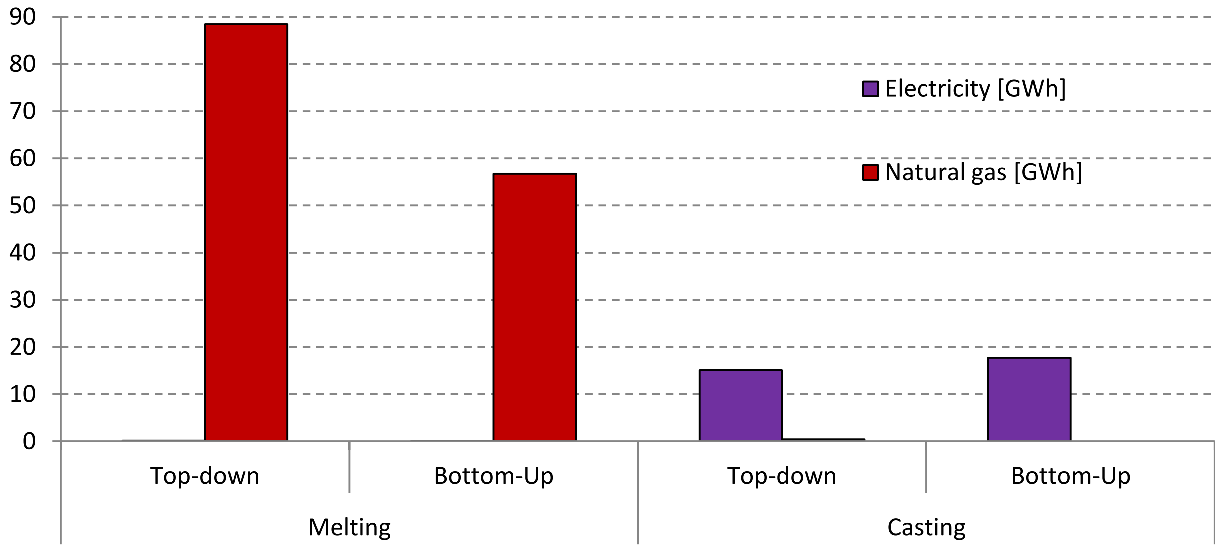


Figure 16: Comparison of Top-down and Bottom-up results

It can be seen that in melting module, the natural gas consumption is underestimated in the Bottom-up analysis compared to the results of the Top-down analysis. The electricity consumption is negligible for both. Contradictory, electricity consumption shows higher values in the casting module.

These contradictory results may have several reasons, which could be:

- Incorrect economic allocation of energy consumptions
- Bottom-up modeling based on average values
- Bottom-up modeling does not take auxiliary units into account

The difference between the two approaches is a mixture of those three issues. However, further analysis on which issues do have the highest impact has to be done, while through the standardized comparison, future optimization can be measured.

If main processes of different companies are the focus of a benchmark, the module- and energy carrier intensities in Figure 11 to Figure 14 and the results in Table 13 can be taken to carry out the process benchmark. A melting process of a different company can be compared with the obtained results. Most interesting in this case is the comparison of material ratios, because they show optimization potential of material usage.

For a further life-cycle analysis the results on company level from the Bottom-up calculation can be used. F.e. the primary material input ratio determines how much primary resources are used to produce one unit of product output. Thus, this value is of crucial importance for all upstream life-cycle processes. The energy consumptions are calculated on company level, thus energy consumptions of up-and downstream life-cycle processes can be added.

Energy efficiency and energy optimization are measured through the Top- down indicators on one hand, and through the Bottom-up indicators on the other hand. Most important indicators are the production unit indicators of the Bottom-up approach, see Table 11 and Table 12. They clearly determine the thermal efficiency and the specific energy consumptions of every energy carrier. Those two indicators are the main indicators for energy efficiency. If another production unit is calculated through the same steps, efficiency, as defined in this thesis, can be evaluated.

For optimization purpose, theoretical heat recovery potential is calculated for all production units. Those energy streams can be taken for a Pinch-Analysis to implement heat recovery measures.

The last chapter will summarize the results draws the conclusion and presents future research potentials.

# 5 Summary and conclusion

This work shows the development and application of a framework for evaluating and optimizing energy efficiency in foundry companies. In the beginning the problems and challenges of that industry branch are outlined. It is stated that a framework for analyzing energy consumption and increasing energy efficiency is needed in order to fulfill current and future legal regulations. The objective of this thesis is therefore to develop this framework which main targets are to analyze and evaluate energy efficiency and to provide the possibility for different benchmarks.

Theoretical aspects are discussed in the beginning, where the impact of the new act on energy efficiency on the foundry branch is analyzed. The literature on evaluation indicators for different system level is screened and indicators are carefully chosen. The thermodynamic basis is briefly given.

The model development shows the content of the model. A data acquisition methodology is developed with which it is possible to derive adequate data information. Main parts are the questionnaire and the data sheets, presented in Annex A. The model is developed hierarchically with three system level, interconnected to each other. The model design shows that two approaches of evaluation are carried out. Those are the Top-down and the Bottom-up approach. The first one uses aggregated data on company and main process level in order to calculate energy consumption based on economic allocation. The second approach uses thermodynamic data of production units to calculate their characteristic balances with which it is possible to calculate the main processes through the connection of those units.

The results of those two approaches are the basis for the benchmark and evaluation purpose. They consist of different indicators on three system level. Each indicator has its own meaning and can be used for a benchmark purpose. This allocation is summarized in the end of the model development.

Finally, the application chapter shows the applicability of the model. The model is applied to a foundry company in Austria. Due to confidentially no names or representing data are shown. Both the Top-down and the Bottom-up approaches are carried out. Due to a lack of information, the Bottom-up application does not include all module of the company, However, the two which are taken into account can be found in every foundry, so the application should proof the applicability of the model.

In the end the results of both approaches show contradictory results. The reasons are explained through a mixture of issues which derive through the model development. Nevertheless it can be seen, that through the definition of different system levels interconnected through a hierarchical order, different indicators can be derived. Those can be used for different benchmarking purposes or general evaluations. Future research should therefore eliminate these issues through a further development of the model. All relevant indicators for the benchmarks are determined through the application.

Future works should apply this model to different companies to evaluate the benchmarking procedure. Pinch-analysis and exergy analysis should be included to find minimum process needs and carry out heat recovery implementation.

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# Annex A

## Questionnaire

Please fill out the questionnaire as accurate as possible and send in advance or prepare actual data for the workshops

### 1. General information on data availability

1.1 Does your company has implemented an **energy management system** or is certified by ISO 50001?

☐ Yes, both ☐ Yes, but not certified ☐ No

1.2 Is production data of energy-intensive processes measures, and are they monitored through a **common data basis**?

☐ Yes, both ☐ Yes, but not monitored ☐ No

1.3 Do you have an **energy monitoring system** or did you already energy audits or measures in **energy efficiency**?

☐ Yes, both ☐ No ☐ only energy audits

1.4 Do you have actual data on **material-and energy balances** of your main- and support processes?

☐ Yes ☐ No ☐ Yes, for main processes

1.5 Do you know **energy consumption** of your products and processes?

☐ Yes, in detail ☐ Yes, in general ☐ No

1.6 Are shift schedules and production times of your processes available and do you know their operating time?

☐ Yes, fully ☐ Yes, but no everything ☐ No

## 2. Energy carriers and energy consumption

2.1 Which **primary energy carriers** do you use and what is their **yearly consumption**?

| Energy carrier e.g. natural gas | Yearly consumption e.g. $Nm^3/a$ |
|---|---|
| | |
| | |
| | |
| | |
| | |

2.2 Which **final energy sources** do you use and what is their **yearly consumption**?

| Final energy source e.g. compressed air | Yearly consumption e.g. MWh/a |
|---|---|
| | |
| | |
| | |
| | |

2.3 Do you **measure and save** the energy consumption of your production units

☐ Yes, fully ☐ Yes, for main processes ☐ No

2.4 Is data from the **energy-costing** department available?

☐ Yes, in detail ☐ Yes, in general ☐ No

2.5 Do you operate energy conversion units, like a cogeneration device? If yes, please specify.

| Primary source (natural gas) | Final source (electricity) | Technology (cogeneration) | Yearly consumption MWh/a |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

## 3. Products and processes

3.1 Which kind of **products** to you have and what are the material inputs? Which kind of **alloying material** do you use?

| Product (AlSi7) | Metal (Fe, Al...) | Quality (metal, scrap...) | Alloys (Si, Mg ...) |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |

3.2 Please describe your **main-and supporting processes** as well as the corresponding **production units** and their **energy consumption**.

| Process (e.g. melting) | Production units (E.g. shaft furnace) | Energy carrier (natural gas; electricity) | Consumption ($m^3$/h or kW) |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

3.3 Do you use continues monitoring systems; do you have accurate time resolutions of your energy consumption

☐ Yes, in detail ☐ Yes, but not everywhere ☐ No

3.4 Do you operate **gas treatment facilities**, like thermal post-combustion units

☐ Yes, everywhere ☐ Yes, but few ☐ No

3.5 Please prepare the **following documents** of your processes for the upcoming workshops.

- *Melting*
- *Casting*
- *Heat treatment*
- *Sand preparation*
- *Thermal post-combustion*
- *Compressed air production*
- *Water treatment facility*
- *Transport*
- *Tool workshop*

Thank you in advance for carefully filling out this questionnaire. Please prepare all the data as accurate as possible for the following workshops.

| Production unit data | | Shaft furnace | | |
|---|---|---|---|---|
| | | Answer | Value | Unit |
| Refractory material | Which refractory material is used? | | | |
| | How often is that substituted? | | | |
| Isolation | Which isolation is used? | | | |
| | How often is that substituted? | | | |
| Handling | How is the tilting process, manual or automatic? | | | |
| | Which energy carrier is used for tilting? | | | |
| | How is the feeding process done, manual or automatic? | | | |
| | How is the extraction done, manual or automatic? | | | |
| | Is the unit completely empty after extraction? | | | |
| General properties | What is the capacity of the unit? | | | |
| | How high is the maximum material input? | | | |
| | How high is the maximum extraction amount? | | | |
| | Is an inert gas used, or is a vacuum necessary? | | | |
| | Is the unit only used for holding? | | | |
| Cooling system | Which cooling system is installed (open, closed)? | | | |
| | Which coolant is used (water, pressurized air...)? | | | |
| | Is the cooling heat recovered? | | | |
| Material input | Which material inputs are used? | | | |
| | Which alloys are used? | | | |
| | What is the pre-heating temperature? | | | |
| Energy input | What is the design power? | | | |
| | Is the pre-heating of combustion air implemented? | | | |
| | Is there an O2-enrichment implemented? | | | |
| | What is the design power of auxiliary units? | | | |

| | | Shaft furnace | | | |
|---|---|---|---|---|---|
| **Process data** | | Mean value | Unit | Time resolution | Available? |
| Material balance | Material input | | [kg/h] | Yes | |
| | Material input (batch operation) | | [kg] | | |
| | Material output | | [kg/h] | Yes | |
| | Material output (batch operation) | | [kg] | | |
| | Mass of the melting material in the furnace | | [kg] | Yes | |
| | Flue gas volume/mass flow | | [Nm$^3$/h] or [m$^3$/h] | Yes | |
| | Mass of dross material | | [kg/h] or [%] | | |
| Temperatures | Temperature of the input material | | [°C] | Yes | |
| | Extraction temperature | | [°C] | Yes | |
| | Temperature of the melting material | | [°C] | | |
| | Furnace wall temperature (outer wall) | | [°C] | | |
| | Combustion air temperature | | [°C] | Yes | |
| | Flue gas temperature | | [°C] | Yes | |
| Unit process data | Furnace pressure (abs.) | | [bar] | | |
| | Furnace temperature | | [°C] | | |
| | Overall operating time | | [min] | Yes | |
| | Melting time | | [min] | | |
| | Ratio of burn-off loss | | [%] | | |
| Cooling system | Mass flow of coolant | | [m$^3$] | Yes | |
| | Mass return of coolant | | [m$^3$] | Yes | |
| | Temperature of flow | | [°C] | Yes | |
| | Temperature of return | | [°C] | Yes | |
| Energy balance | LHV of used natural gas | | [kJ/kg] or [kJ/Nm$^3$] | | |
| | Volume flow of natural gas | | [Nm$^3$/h] | Yes | |
| | Inflow temperature | | [°C] | Yes | |
| | Mean melting volume consumption | | [Nm$^3$/kg] | | |
| | Power during melting | | [kW] | Yes | |