Application of exergoeconomic, exergoenvironmental and advanced exergy analyses on Carbon Black production

Pieter Mergenthaler\textsuperscript{a}, Arndt-Peter Schinkel\textsuperscript{b}, George Tsatsaronis\textsuperscript{c}

\textsuperscript{a} Institute for Energy Engineering, Technische Universität Berlin, Berlin, Germany
pieter.mergenthaler@tu-berlin.de, CA
\textsuperscript{b} Process Development Carbon Black, Orion Engineered Carbons GmbH, Köln, Germany
arndt-peter.schinkel@orioncarbons.com
\textsuperscript{c} Institute for Energy Engineering, Technische Universität Berlin, Berlin, Germany
tsatsaronis@iet.tu-berlin.de

Abstract:
Carbon Black is an industrial produced material of fine carbon particles. These particles are aggregates of primary particles having a mean diameter usually below $1 \, \mu m$. Carbon Black is mainly used in printing and coating applications as a pigment, in plastic applications as a UV protector, and in rubber applications as filler material to improve mainly the mechanical properties of the rubber like stiffness and abrasion resistance. Volume wise the most important production technique is the furnace black production. The pertinent industrial plants are highly energy intensive and in the case of the investigated system a lot of effort has been carried out to improve the existing plant by individual projects. To improve the efficiency even further a more detailed analysis is necessary. It has been approved that inefficiencies of such complex systems can be discovered lucidly by exergy based methods. For this work, a Carbon Black Plant is modeled using a free available tool called COFE. The behavior of the components was verified by measurements. The effect of components’ exergy destruction on the system's exergoeconomic and exergoenvironmental behavior is analyzed. Furthermore, the interdependencies between components are studied. The burners have the highest exergy destruction among all components of the total plant. These burners however, neither have the highest impact on cost generation caused by exergy destruction, nor the highest impact on the exergoenvironmental values. Nonetheless, they contribute significantly to the exogenous exergy destruction within other components. The largest cost generation takes place within the boilers’ heat exchangers. The most important components considering the exergoenvironmental analysis are the reactors.

Keywords:
Carbon Black, furnace process, advanced exergy analysis, exergoeconomic analysis, exergoenvironmental analysis.

1 Introduction
This work is based on a project which is conducted in cooperation between the Institute for Energy Engineering at TU Berlin and the manufacturer Orion Engineered Carbons GmbH and deals with the application of exergy-based methods on chemical plants. The objective is to quantify the real inefficiencies with the help of exergy based methods and to enhance the performance of real plants. Some major tasks of the project are to build a software environment which matches the following characteristics:

\begin{itemize}
\item To enable engineers to quickly simulate carbon black plants with a free available tool,
\item to analyze simulated plants preferably and largely automated with the help of exergy-based methods,
\item to derive improvement opportunities, and
\item to be easy transferable.
\end{itemize}

The application of exergy-based methods on a carbon black (CB) plant was chosen, because CB is such an important and energy intensive product. Experts forecast a dynamic growth of global demand for CB. Its yearly production could increase up to more than 15 million tonnes per year by 2022 [1].
Whereby, the theoretical recoverable energy potential\(^1\) can be estimated to approximately \(13.7 \text{TWh}^2 \text{ year}^{-1}\) in the U.S. alone. Most part of the used residual oil is utilized as feedstock by the furnace process\(^3\). Hence, a high amount of gases such as \(\text{CO}_2\) are produced that are harmful to the climate. Ca. 90 % of the produced CB is used to reinforce rubber [3].

Up to now, it has not been practicable to analyze the thermodynamic inefficiencies on a component level in detail for individual CB plants to derive improvement ideas. Furthermore, real mechanisms of cost generation and environmental pollution in combination with the thermodynamic inefficiencies have not been analyzed so far. Instead, best practice technologies are usually adopted from other plants to increase the component efficiency [4] in the chemical and petrochemical sector.

This paper is divided into three parts. First, a presentation of the applied methods is given. The investigated plant is introduced in the following section. In the third part, the results are shown and briefly discussed. Here, the most important outcome of the analyses are the effects of exergy destruction on the systems exergetic, economic and environmental behavior.

2 Methodology

2.1 Exergy Analysis

It has been shown that component inefficiencies in complex systems can be discovered lucidly by exergy-based methods [5–10]. Compared to an energetic analysis this method also takes the quality of each energy stream into account. For the calculation of chemical exergies Szargut’s standard chemical exergies are used. The ambient conditions \(T_0\) and \(p_0\) are set to 25 °C and 1.01325 bar, accordingly.

The exergy destruction rate \(\dot{E}_{D,k}\) within the \(k\)-th component is calculated as the difference between the exergy rate of fuel \(\dot{E}_{F,k}\) and the exergy rate of product \(\dot{E}_{P,k}\) [11].

\[
\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k}
\]

The SPECO approach [12] is used, to define the exergy rates of fuel \(\dot{E}_{F,k}\) and product \(\dot{E}_{P,k}\). Thereby, the exergy destruction \(\dot{E}_{D,k}\) quantifies the thermodynamic irreversibilities occurring within the considered component. The exergetic efficiency \(\varepsilon_k\) of the \(k\)-th component, is

\[
\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}
\]

The exergetic efficiency is the only objective measure to determine the true thermodynamic performance of a component [13]. Additionally, the exergy destruction ratio \(y_{D,k}^*\) is used to identify the contribution of each component to the reduction of the overall system’s exergetic efficiency.

\[
y_{D,k}^* = \frac{\dot{E}_{D,k}}{\dot{E}_{D,tot}}
\]

Usually, the indicator \(y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}\) is widely used to analyze the outcome of an exergy analysis. However, to compare the results lucidly between the different types of analyses, the component wise effects of the exergy destruction will be divided by the sum of all components. By this, a comparison between the importance of components on different methods can be made, without considering the effect of different values of total fuel.

\(^1\)The given number does not adress the economic feasibility of recovery. [2]

\(^2\)The referenced value is 46.6 \(\text{TWh}^2\), whereby \(\text{TWh}\) stands for trillion british thermal units which is approx. \(10^{12} \cdot 1055.06 \text{ J}\).

\(^3\)Only carbon black made in furnace processes is investigated in this work. Other processes such as lamp black and gas black etc. are not considered.
2.2 Exergoeconomic Analysis

An exergoeconomic analysis combines the exergy analysis with economic principles [11]. Compared to exergetic and economic analyses separately, this combination provides additional information. The main objective is to minimize the overall product cost. It can also help to understand how cost rates are distributed throughout complex energy conversion systems. In addition, the product generation costs of each product in a cogeneration plant can be quantified separately. The cost rate $\dot{C}_i$ of each stream $i$ is obtained by multiplying the stream’s exergy rate $\dot{E}_i$ with its specific cost $c_i$:

$$\dot{C}_i = \dot{E}_i \cdot c_i$$  \hspace{1cm} (4)

The specific costs of each stream entering the overall system are known. All the other streams are then calculated by a cost balance for each component and auxiliary equations. For a $k$-th component with $n$ input and $m$ output streams the cost balance can be written as:

$$\sum_{i=1}^{n} \dot{C}_{i,k} - \sum_{j=1}^{m} \dot{C}_{j,k} + \dot{Z}_k = 0$$  \hspace{1cm} (5)

Here, $\dot{Z}$ is the component specific levelized cost stream caused by investment and operating and maintenance expenses. If the number of outlet streams is higher than one, auxiliary equations have to be used to determine how the costs are split among the outlet streams. This can be done by using the P-principle or the F-principle. The P-principle states that the cost per unit of exergy which is supplied to all streams that belong to the definition of the component’s product is constant\(^4\). On the other side, the F-principle states that a stream leaving a component has the same specific cost as this stream entering the component\(^5\).

An important outcome of the exergoeconomic analysis is the component-level-related information about the cost of exergy destruction $\dot{C}_{D,k}$. For each component its cost of exergy destruction can be calculated as:

$$\dot{C}_{D,k} = c_{F,k} \cdot \dot{E}_{D,k}$$  \hspace{1cm} (6)

2.3 Exergoenvironmental Analysis

In analogy to the exergoeconomic analysis, an exergoenvironmental analysis is applied to combine the exergy analysis with a Life Cycle Assessment (LCA). In this paper the environmental impact is measured\(^6\) according to the damage oriented ECO-indicator 99 from the default hierarchist perspective [15]. This indicator helps to appraise different damage categories like human health, ecosystem quality and resources. As described in [16], LCA is not capable to allocate the environmental impact on the component level. To obtain the rate of environmental impact of each stream leaving a component, the following equation is used:

$$\sum_{i=1}^{n} B_{i,k} - \sum_{j=1}^{m} B_{j,k} + \dot{Y} + \dot{B}_{PF} = 0$$  \hspace{1cm} (7)

Here, $\dot{B}$ is the rate of environmental impact measured in $\text{Pts} \cdot \text{h}$. Analogously to the value $\dot{Z}$ in the exergoeconomic analysis, the value $\dot{Y}$ is the component specific impact stream for the exergoenvironmental analysis. It is obtained by an LCA and consists of the sum of the environmental impacts that result

\(^4\)E.g. boiler, that produces steam on different pressure levels.
\(^5\)E.g. hot streams in heat exchangers, which are operating above ambient temperature.
\(^6\)Definition of one ECO99-point according to [14]: "The scale is chosen in such a way that the value of 1 Pt is representative for one thousandth of the yearly environmental load of one average European inhabitant." Thus, it’s the total environmental load in Europe divided by the number of inhabitants and multiplying it with 1000.
from construction, operation, maintenance and disposal of a component. The term $\dot{B}_{PF}$ stands for the pollution formation within a component. Pollution can be formed and destroyed by chemical reactions. Whether it is formed or destroyed depends on the difference between the toxicity of the reactants and the reaction products.

An important outcome of the exergoenvironmental analysis is the information about the environmental impacts which are caused by the exergy destruction within a component $\dot{B}_D$. It is calculated by:

$$\dot{B}_{D,k} = b_{F,k} \cdot \dot{E}_{D,k}$$  (8)

### 2.4 Advanced Exergy Analysis

An advanced exergy analysis helps to identify the system’s inefficiencies due to component interactions. This can be done by splitting the exergy destruction of a component into its endogenous and exogenous parts.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{\text{Endo}} + \dot{E}_{D,k}^{\text{Exo}}$$  (9)

The endogenous exergy destruction $\dot{E}_{D,k}^{\text{Endo}}$ describes the irreversibilities within the $k$-th component when it operates with the same exergetic efficiency $\varepsilon_k$ as under real conditions and all the remaining components operate in an ideal way [13].

The exogenous exergy destruction itself is split into the sum of exogenous exergy destruction induced by component couples $j$ and $k$ (exogenous in couples) and the exogenous exergy destruction caused by higher-dimensional component interactions (mexogenous).

$$\dot{E}_{D,k}^{\text{Exo}} = \sum_{j=1}^{n} \dot{E}_{D,k}^{\text{Exo},j} + \dot{E}_{D,k}^{\text{Mexo}}$$, with $j \neq k$  (10)

For the calculation of the endogenous exergy destruction several approaches [17–19] have been suggested. However, the different methods are still time-consuming to use, if applied to complex systems. They can face theoretical shortcomings [17, 18] and computational problems for chemical reactions [19] as described by [20]. To analyze the CB-plant and enable the software tools to compare different cases quickly with each other, a mathematically automated way was developed. Thereby, the approach suggested in [20] was used after some modifications. An essential assumption is that all types of exergy can be transferred into each other and that ideal components are thermodynamically ideal ($\varepsilon_{\text{ideal}} = 1$). Another assumption needed for automation is that all states (and consequently the specific exergies) upstream and downstream of an ideal component are the same as under real conditions.

$$e_{k,\text{ideal}} = e_{k,\text{real}}$$  (11)

The exogenous part of exergy destruction induced by component couples can be determined by equation (12). Here, $j$ is the current variable of an interacting component operating under real conditions.

$$\dot{E}_{D,k}^{\text{Exo},j} = \frac{\dot{E}_{D,k,\text{real}}^{\text{Exo}}}{\dot{E}_{E,\text{tot,real}} - \dot{E}_{L,\text{tot,real}} - \sum_{j=1}^{m} \dot{E}_{D,k,\text{real}}}$$  (12)

Information about the components’ real improvement potentials can be derived by splitting the exergy destruction into its avoidable (AV) and unavoidable (UN) parts. However, this splitting was not conducted in this work.
3 System Description

A base case scenario for a total carbon black plant has been developed and simulated by using the flow-sheeting program COFE\(^7\). Within this software, mass and energy balances are solved. The property data are used as largely as possible from the software’s database. Thermodynamic data of feedstock oil and carbon black are manually implemented based on measured data. Set conditions within components are derived from data measured in September 2015. The flowsheet of the investigated plant is rather very complex. That’s why the three most important plant units
- Carbon Black production
- Drying process
- Power plant

are presented separately first, before schematically united in subsection 3.4.

3.1 Carbon Black generation

![Carbon Black furnace process](image)

**Fig. 1. Carbon Black furnace process**

The flowsheet of a typical furnace process is shown in Fig. 1. The process itself can be characterized by decomposition of oil at high temperature to carbon, hydrogen and volatile hydrocarbons. To investigate the inefficiencies in detail, the furnace is split into four separate components (precombustor, main reaction zone, pre quench and main quench). Some of the here shown components are optional. E.g., instead of an air preheater 2 (APH2), other plants might use a waste heat boiler (WHB).

\(^7\)www.cocosimulator.org
Air is taken from the environment by a fan and pushed through an air preheater 1 (APH1). This preheated air is then mixed with hydrocarbons and this mixture is combusted in a precombustor. Highly aromatic oils are used as feedstock in the reactor. Before entering the reactors nozzles, this feedstock gets preheated by hot air\(^8\). Downstream of the reaction zone some reactors use a pre-quench to achieve certain specifications\(^9\) for the desired product. The quench achieves three main objectives:

- it stops the reaction process,
- it can be used to vary the product specifications and
- it cools down the offgas to a temperature below the APH1’s maximum temperature.

Thus, in the exergetic analysis a differentiation between pre- and main-quench can help to identify the avoidable inefficiencies associated with the three objectives separately. Typically, the APH1’s off gas comes with a temperature above 500 °C. To recover some energy before it is cooled down for the filters, a second air pre-heater is installed. It supplies consumers like oil heaters, combustion chambers of dryers and boilers with hot air. Downstream the APH2 there’s a filter which splits up the oven’s offgas into pure carbon black and low caloric tailgas\(^10\). Its maximum inlet temperature depends on the filters material, which commonly allow a temperature of around 200-250 °C.

### 3.2 Carbon Black processing

![Fig. 2. Carbon Black drying process](image)

Carbon Black is usually sold as pellets or as powder. There are dry and wet pelletizers. Processes using wet pelletization are the most interesting ones from the energetic and exergetic points of view. Fig. 2 shows such a process with a wet pelletizer.

Carbon Black is transported by pneumatic transportation systems to the pelletizer. Here, the powder gets blended with water. Afterwards, the pellets are mixed with hot air and dried in very large\(^11\) drums before sent to a storage.

---

\(^8\)Alternatively steam is used as heat source in other plants.

\(^9\)Required specifications are e.g. surface areas and the product’s conductivity [3]

\(^10\)The tailgas’ higher heating value (HHV) is strongly depended on the produced grades. Under base case conditions the average HHV is approx. 4.1 \(\text{MJ/kg}\).

\(^11\)Approximately 3 m in diameter
3.3 Cogeneration plant

The flowsheet shown in Fig. 3 provides an idea of the complexity of the affiliated power plant. Here, tailgas\textsuperscript{12} and hot air are used to generate shaft work\textsuperscript{13}, electricity and heat on different pressure and temperature levels. The investigated plant has evolved over the past decades. Several boiler produce steam on two different pressure levels. Boiler 6 supplies turbine 2 with 90 bar steam to produce electricity. Boilers 3, 4, 5, 7 and a waste heat boiler from a non-furnace processes feed the 40 bar steam net. This net in turn delivers steam to feedwater turbines, an air pre-heater turbine and turbine 1 which produces electricity. Furthermore, heat consumers are also supplied by this 40 bar net.

\textsuperscript{12}Remaining gas after the filtration of CB [3]
\textsuperscript{13}Shaft work is used next to electricity production to drive feedwater pumps and air fans.
3.4 Total plant

In Fig. 4 the three production units CB generation, CB processing and power plant are used to illustrate how they are connected together. At base case conditions, several reactors are producing carbon black. Thereby, different grades of CB are produced at the same time. One grade which is produced on two different reactors is sold in both forms, as powder and dry pelletized. In total, three grades are wet pelletized under base case conditions. The affiliated power plant is almost operating under full load conditions. The total output of carbon black is nearly $1.4 \ t_{\text{CB}} h$. Within the power plant $26 \ MW_{\text{ex}}$ electricity is produced. The output of heat amounts ca. $5 \ MW_{\text{ex}}$.

4 Results

The flowsheet of the total plant is highly aggregated\(^\text{14}\). For this paper ca. 500 material streams and 211 components were studied. To condense the obtained results, only the most interesting numbers will be presented. The 211 individual components of the total plant are therefore summarized in 26 typical main component groups. First, the results of the exergy analysis of these groups are presented. Subsequently, the results of an exergoeconomic, an exergoenvironmental and the advanced analysis are discussed.

4.1 Exergy Analysis

One of the main objectives that comes along with an exergy analysis is a statement about the quantifiable exergy destruction on a component level. The total exergy destruction of the carbon black plant is approx. $134 \ MW$. Applied to the plants main product Carbon Black, it means that the exergetic "fuel" (ca. $34.3 \ \frac{\text{MJ}_{\text{ex}}}{\text{kg}}$) to produce the main product is nearly as high as its higher heating value (ca. $34.7 \ \frac{\text{MJ}_{\text{en}}}{\text{kg}}$).

In Fig. 5 the ratio of exergy destruction $y_D^*$ within each component group is shown. The exergy destruction of each component group is generally induced by endogenous, and exogenous causes. Exogenous in couples means the sum of the exogenous exergy destruction obtained when components are considered to operate in couples with their real efficiencies whereas all other components are ideal. Mexogenous refers to the part of the exogenous exergy destruction obtained through the component’s interactions in groups of more than two. The mexogenous part of exergy destruction is significant which indicates the strong interactions among the components.

The unit in which with ca. 50% most of the exergy is destructed is the power plant. The boilers’ burners have the largest share (more than 20%) of the overall exergy destruction. Almost 45% of the total exergy destruction takes place in the CB production unit of the plant. The reactors are thereby responsible for the highest value of exergy destruction within this unit. A former study \cite{2} states that the furnace and quenching operations within a typical U.S. CB plant account for about 70% of the exergy destruction\(^\text{15}\) within the CB production unit. The investigated plant shows a number up to 81% for the same group. However, this number strongly depends on the produced grades. Nonetheless, it shows in both cases the necessity of improvements within these components.

\(^{\text{14}}\)The flowsheet simulation itself consists of up to several thousand streams and components.

\(^{\text{15}}\)The study uses the term "internal exergy losses", instead.
The leftover part of the exergy destruction (5 %) is attributable to the unit of CB processing. An issue to be emphasized at this point, is the comparison between the dryers and their combustion chambers. Only three of the eight produced CB grades are processed by wet pelletizers. The other grades are either sold as powder or dry pelletized and do not need to be dried. Usually, in an exergy analysis, those parts of components which are responsible for combustion destroy the highest amount of exergy. However in this case, the dryers show a higher value than their upstream combustors. The reason can be understood by taking Fig. 2 into consideration. Hot air from the hot air net flows around the wet pelletized material to carry out the flash steam. Furthermore, these combustors operate only with preheated air\(^{16}\) which does not need to be heated up as much as if ambient air were used. Thus, the combustion chamber is not responsible to deliver all the heat that is necessary to dry the wet pellets.

### 4.2 Exergoeconomic Analysis

Some expedient assumptions are made to simplify the analysis. The investigated plant grew over the past decades. Thus, most of the components can be considered as depreciated. Furthermore, the real market prices of the main product carbon black is directly dependent from the cost of fuels. So, to keep the analysis clear by obtaining as much information as possible at the same time, the specific levelized cost streams caused by investment, operating and maintenance \(\dot{Z}\) are neglected in this paper. To run the exergoeconomic analysis, the following values\(^{17}\) were assumed:

- \(c_{\text{feedstock}} = 8.4 \frac{\text{€}_{2015}}{\text{GJ}_{\text{ex}}}\)
- \(c_{\text{electricity}} = 10.2 \frac{\text{€}_{2015}}{\text{GJ}_{\text{ex}}}\)
- \(c_{\text{natural gas}} = 10.4 \frac{\text{€}_{2015}}{\text{GJ}_{\text{ex}}}\)

Approx. 58 % of the total fuel cost rate is caused by exergy destruction. If all variable costs have to be payed by selling CB only, the average variable share of CB price must be higher than 0.7 \(\frac{\text{€}_{2015}}{k_{\text{SCB}}}\).

---

\(^{16}\)In contrast to the boilers’ combustors that also use ambient air as secondary air.

\(^{17}\)The given values are derived from stock exchange data.
In Fig. 6 the ratio of costs of exergy destruction ($\dot{C}_{D,k}$) within each component group is shown. Furthermore, a differentiation between endogenous, exogenous in pairs and mexogenous causes is displayed.

Three component groups\(^{18}\) stand out from the others. The reactors and burners cause both higher exergy destructions than the heat exchangers within the boilers. However, the specific costs of fuel is generally lower in upstream components compared to downstream components. Especially, the irreversibilities caused by the boilers’ burners cause a noticeably increase of specific costs. That’s why the heat exchangers (HX) cause the highest costs of exergy destruction among all component groups.

### 4.3 Exergoenvironmental Analysis

In analogy to the above discussed exergoeconomic analysis, the environmental impacts which would result from construction, operation and maintenance and disposal of the components ($\dot{Y}$) are neglected. To run the exergoenvironmental analysis, the following values\(^ {19}\) were assumed.

- $b_{\text{feedstock}} = 3.4 \text{ mPts} \frac{M_J}{kg}$
- $b_{\text{electricity}} = 7.2 \text{ mPts} \frac{M_J}{kg}$
- $b_{\text{natural gas}} = 3.6 \text{ mPts} \frac{M_J}{kg}$

The average environmental impact\(^ {20}\) across all produced grades of CB is ca. 53 \text{ mPts} kg\(^{-1}\)CB. Here, the assumption is made that all environmentally toxic substances are balanced, even if they are not released to the environment\(^ {21}\) to better understand the dependencies among the components. However, if only CO\(_2\) is considered, this number changes to ca. 188 \text{ mPts} kg\(^{-1}\)CB. In that case the destruction of potential polluting substances like feedstock oil in the reactors are not considered.

\(^ {18}\)Reactors, burners and heat exchangers within boilers

\(^ {19}\)The here shown values are derived from [14] and [15]. The substances’ ECO99-indicator values are obtained from [15].

\(^ {20}\)According to literature [14] a value up to 180 \text{ mPts} kg\(^{-1}\)CB can be expected.

\(^ {21}\)Such as feedstock, acetylene, hydrogen, carbon monoxide etc.
In Fig. 7 the ratio of environmental impact of exergy destruction \( \frac{\dot{B}_{B,k}}{\dot{B}_{D,tot}} \) on a component level is shown. Furthermore, a differentiation between endogenous, exogenous in pairs and exogenous causes is displayed. The reactors convert potentially harmful substances such as feedstock-oil and exhaust gas from pre-combustors into other toxic substances like acetylene, hydrogen, carbon monoxide and environmentally harmless CB. The reactor’s toxic tailgas mixture is then combusted downstream in the dryers’ burners and the power plant. Thereby, the named substances are converted into less harmful substances like water and carbon dioxide. With the applied assumptions the reactors are the components with the highest environmental impact among all the component groups.

### 4.4 Advanced Analyses

The conducted advanced analyses are based on the differentiation between endogenous, exogenous in pairs and exogenous causes of exergy destruction. A key information that comes along with Fig. 5, is the cause of exergy destruction. The regarded system is highly integrated. Therefore, the exogenous part of exergy destruction of each component group is at least 18% of every component group’s total exergy destruction. The exogenous part in all groups is higher than 24%. The endogenous part is at least 55%.

The results of the exergetic, exergoeconomic and exergoenvironmental analysis point out three very important component groups in the investigated plant. In Table 1, some detailed information about the origin of the exogenous exergy destruction in these three components (reactors, burners and HX within boilers) are listed. The numbers are calculated as shown in eq. (13). It is the share of each interacting component group of the sum of the total exogenous exergy destruction caused by these couples:

\[
\frac{E_{Exo,j}}{E_{D,k}} \text{ with } j \neq k
\]  

\[(13)\]
Table 1. *Origin of the exogenous exergy destruction within the three most important component groups*

<table>
<thead>
<tr>
<th>interacting component group</th>
<th>reactors</th>
<th>burners</th>
<th>boiler HX</th>
</tr>
</thead>
<tbody>
<tr>
<td>burners</td>
<td>22.7%</td>
<td>16.0%</td>
<td>22.9%</td>
</tr>
<tr>
<td>reactors</td>
<td>15.1%</td>
<td>18.7%</td>
<td>18.5%</td>
</tr>
<tr>
<td>boiler HX</td>
<td>17.3%</td>
<td>17.7%</td>
<td>12.1%</td>
</tr>
<tr>
<td>precombustors</td>
<td>7.2%</td>
<td>7.3%</td>
<td>7.3%</td>
</tr>
<tr>
<td>Quenches</td>
<td>6.2%</td>
<td>6.3%</td>
<td>6.2%</td>
</tr>
<tr>
<td>pre Quenches</td>
<td>5.4%</td>
<td>5.5%</td>
<td>5.4%</td>
</tr>
<tr>
<td>turbine 2</td>
<td>4.4%</td>
<td>4.5%</td>
<td>4.4%</td>
</tr>
<tr>
<td>dryers</td>
<td>4.2%</td>
<td>4.3%</td>
<td>4.3%</td>
</tr>
<tr>
<td>condensors</td>
<td>3.1%</td>
<td>3.2%</td>
<td>3.1%</td>
</tr>
<tr>
<td>APH2</td>
<td>2.8%</td>
<td>2.9%</td>
<td>2.9%</td>
</tr>
<tr>
<td>APH1</td>
<td>2.2%</td>
<td>2.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>dryer’s combustors</td>
<td>2.0%</td>
<td>2.1%</td>
<td>2.1%</td>
</tr>
<tr>
<td>hot air distribution</td>
<td>1.8%</td>
<td>1.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>turbine 1</td>
<td>1.4%</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>deareator</td>
<td>0.8%</td>
<td>0.8%</td>
<td>0.8%</td>
</tr>
<tr>
<td>HX</td>
<td>0.7%</td>
<td>0.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>air fans APH1</td>
<td>0.6%</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>steam injections APH2</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>pneumatic transportations</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>pumps</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>filter’s injection coolers</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>terry turbine</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>oil heaters</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>air fans APH2</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>condensate receiver tank</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>others</td>
<td>0.4%</td>
<td>2.1%</td>
<td>1.4%</td>
</tr>
</tbody>
</table>
It is apparent, that the burners which have the largest share of exergy destruction in the total plant are also responsible for a high value of exogenous exergy destruction in other components. 22.7% of a reactor’s exogenous exergy destruction is induced by irreversibilities that occur within the burners. Summed up, the total power plant causes even more than 50% of the exogenous exergy destruction within an average reactor.

In turn, the boiler burners strongly depend on the furnaces’ reaction zones. 18.7% of the exogenous exergy destruction within an average burner is caused by the reactor. The total CB production unit is responsible for ca. 45% of an average burner’s exergy destruction.

The average HX within a boiler strongly depends on the burner. 22.9% of the HX’s exogenous exergy destruction is caused by burners. The average boiler HX faces an exogenous exergy destruction of other all boilers HXs with a share of ca. 12%.

5 Conclusions

In conclusion it can be stated, that the developed software tool enables the application of exergy based-methods to a complex system. Therefore, this paper presents highly aggregated results of these methods applied on a real carbon black plant. Purposeful simplifications are made to concentrate on the major influencing factors regarding the exergoeconomic and exergoenvironmental analyses. Nonetheless, the shown numbers and figures are clearly enough to derive major knowledge about the system’s inefficiencies and the interdependencies among components and plant units. The three most exergy destructive and therefore most important component groups are the furnace’s reaction zone, boiler burners and heat exchangers within boilers. The burners within the affiliated power plant’s boilers are the most exergy destructive type of component regarding the total plant. However, these burners neither have the highest impact on cost generation caused by exergy destruction, nor the highest impact on the exergoenvironmental values. Nonetheless, they affect significantly the exogenous exergy destruction within other components. The largest cost generation takes place within the boilers’ heat exchangers. The most important group considering the exergoenvironmental analysis are the reactors.

A differentiation between avoidable (AV) and unavoidable (UN) parts of exergy destructions was not considered here. Even though, it becomes clear with the help of the information provided, that the base case plant has some space for improvements. The water pre- and main-quenches affiliated to reactors for instance, are responsible for more than 11% of the exogenously caused exergy destruction within each of the three most important components. If considered AV and UN at the installed water quench technology, barely any improvements could be identified. Nonetheless, by switching the technology e.g., to a quench boiler, a considerable amount of exergy could be used instead of being destructed. The hereby emerging savings are not only arising at the former quench’s position. But also in every other part of its interacting downstream components.

However, there are some shortcomings in the applied advanced analysis regarding the assumption about the objective of the plant. To automate the advanced analysis, the assumed objective is to generate in every case the same sum of exergy product as in the base case. Additionally, the hypothesis that every kind of exergy can be changed into another kind of exergy neglects that in reality things are more complicated. The objective of a real plant is to produce a certain amount of each carbon black grade. Each reactor is individual. So is the received product. Since there is a very large range of different carbon blacks, such CB produced in one reactor might not be easily substitutable by another reactor. The byproducts such as electricity and heat are considered to be waste products which are nice to have in the operating system. However, they are not part of a production target. This might be different for other plants, of course.

---

22 as introduced on page 5
Nomenclature

Abbreviations
APH1  Air Pre-Heater 1
APH2  Air Pre-Heater 2
AV  Avoidable
CB  Carbon Black
HHV  Higher Heating Value
HX  Heat Exchanger
LCA  Life Cycle Assessment
UN  Unavoidable
U.S.  United States (of America)
WHB  Waste Heat Boiler

Mathematical symbols
\[ b \ [\text{Pts/kg}] \]  Specific environmental impact
\[ \dot{B} \ [\text{Pts/h}] \]  Environmental impact rate
\[ c \ [\text{€/kg}] \]  Specific costs
\[ \dot{C} \ [\text{€/h}] \]  Cost rate
\[ e \ [\text{MJ/kg}] \]  Specific Exergy
\[ \dot{E} \ [\text{MW}] \]  Exergy rate
\[ y \ [%] \]  Exergy destruction fraction
\[ \dot{Z} \ [\text{€/h}] \]  Cost rate of components investment, operating and maintenance

Greek symbols
\[ \varepsilon \ [%] \]  Exergetic efficiency

Subscripts and superscripts
AV  Avoidable
D  Destruction
en  Energetic or energy
Endo  Endogenous
ex  Exergetic or exergy
Exo  Exogenous
F  Fuel
k  Component
L  Loss
mexo  Mexogenous
P  Product
PF  Pollution formation
tot  Total
UN  Unavoidable

References


Penkuhn M, Tsatsaronis G. Evaluation of component interactions in energy conversion systems for application to advanced exergy-based analyses:. Manuscript in Prepartion; DOI is not yet available.