Stochastic Assessment by Monte Carlo Simulation for LCI applied to steel process chain: The ArcelorMittal Steel Poland S.A. in Krakow, Poland case study

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The article proposes an approach for the Life Cycle Assessment (LCA) study for processes production applied to the ArcelorMittal Steel Poland Power Plant (AMSPPP) in Krakow, Poland. The functional unit, which is listed as follows: "total emissions and resource consumptions' of the processes production includes all activities linked with the steel production, and system boundary, (gate-to-gate), are discussed. The emissions of SO2, CO2, NOx, dust and heavy metals (Cr, Cd, Cu, Pb, Ni and Mn), were estimated (investigated). The scope of this study covers all steel production processes in AMSPPP (including the sintering plant, blast furnace, hot rolling mill, etc.). The study is based on a reference case for the year 2005.

1 Introduction

The aim of the paper is stochastic approach for LCA/LCI probabilistic conception with uncorrelated input/output data in steel process chain with six processes (including Coke Plant, Iron Blast Furnace, Sintering Plant, BOF, Continuous Steel Casting and Hot Rolling Mill) applied to ArcelorMittal Steel Poland (AMSP) S.A. in Krakow, Poland case study. Uncertainty assessment in LCI based on a Monte Carlo simulation with the Excel spreadsheet and CrystalBall® software was used to develop scenarios for uncertainty inputs. The economic and social criteria and indicators will not further be discussed in this paper. The framework of the study was originally carried out for 2005 data because important statistics are available for this year and also because it represents the data, which are the foundation for the Environmental Impact Report of the AMSP, annually collected (2005) and evaluated [1].

A LCI analysis usually needs a large amount of data. Uncertainty of these parameters reflects directly on the outcome of LCA method. The LCI study was conducted in accordance with all requirements of the International Standards ISO 14040, 14041 and 14043 relating to Life Cycle Inventory Analysis (LCI), as well as delines (International Organization for Standardizations ISO 14040 1997) [2] and Polish standards RPrPN-EN ISO 14041 1998 [3] without the Life Cycle Impact Assessment phase).

The paper is organized as follows. Section 1 describes the introduction. In Section 2 the goal and scope of the study are presented. An overview of Uncertainty Assessment in LCI are presented in Section 3. The Benefit of Monte Carlo Simulation in to AMSP in Krakow, Poland is discussed in Section 4. The conclusions and outlook are drawn in Section 5.

Introduction to AMSP Power Plant in Krakow, Poland.

AMSP consists of four plants located in Dabrowa, Krakow, Sosnowiec and Swietochlowice. It boasts a full production system – from pig iron to final, highly processed steel products – producing around 6.5 million tons of crude steel annually. Today, AMSP is the only truly global steel maker - with operations in the USA, Canada, Mexico, Trinidad, France, Germany, Czech Republic, Poland, Romania, Bosnia, Macedonia, Kazakhstan, Algeria and South Africa [4]. The overview of the AMSP is given on the Figure 1.

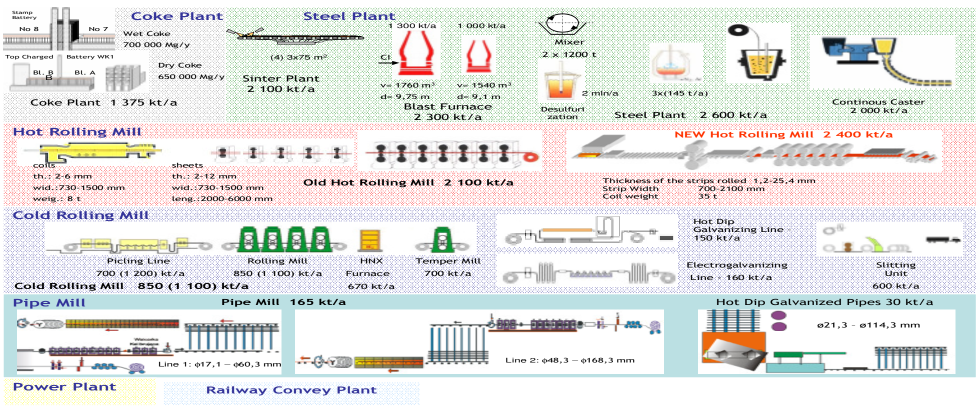

Figure 1. General view of the ArcelorMittal Steel Poland in Krakow

2 Goal, Scope, Terminology and Definitions

Goal definition and scoping is perhaps the most important component on an LCA because the study is carried out according to the statements made in this phase, which defines the purpose of the study, the expected product of the study, system boundaries, functional unit (FU) and assumptions [5]. Although many analytic models for managing inventories exist, the complexity of many practical situations often requires simulation [6, p. 152]. Monte Carlo simulation with the CristalBall® analysis tool, spreadsheet add-in software, is a practical methodology for determining the uncertainty of LCI parameters.

The goals of this study were to:

To develop a stochastic approach for Life Cycle Assessment (LCA) technique limited to a Life Cycle Inventory (LCI) study for AMSP steel process chain from Coke Plant and Sinter Plant to Hot Rolling Mill with scope to facilitate the range of emerging impact assessment methods in future studies.

Produce national et regional LCI data for energy generating industry.

Promote the development of LCI and /or LCA research and application in Poland.

The study comprises the inventory corresponding to the all process stages including the Coke Plant, Iron Blast Furnace, Sintering Plant, BOF, Continuous Steel Casting and Hot Rolling Mill. The complete inventory was integrated by main environmental loads (inputs, outputs): energy and raw materials consumed, wastes produced, and emissions to air, water and soil [7].

The functional unit in this study, central concept in LCA, is defined as "steel process chain includes all activities linked with steel production from Coke Plant and Sinter Plant to Hot Rolling Mill in 2005". System boundaries of this study was presented in Figure 2. It does not include the manufacture of downstream products, their use, end of life. For AMSP power plant, mining and transportation of raw coal, crude oil and natural gas were not included. Key characteristics for the AMSP are shown in Table 1 [1].

In this study only the following substances: hard coal, blast furnace gas, coke oven gas, natural gas, lubricant oil and the atmospheric emission of sulfur (S), cadmium (Cd), carbon monoxide (CO), carbon dioxide (CO2), nitrogen dioxide (NO2), chloridric acid (HCL), chromium (Cr) nickel (Ni), sulfur dioxide (SO2), manganese (Mn), cooper (Cu), lead (Pb) have been taken in account.

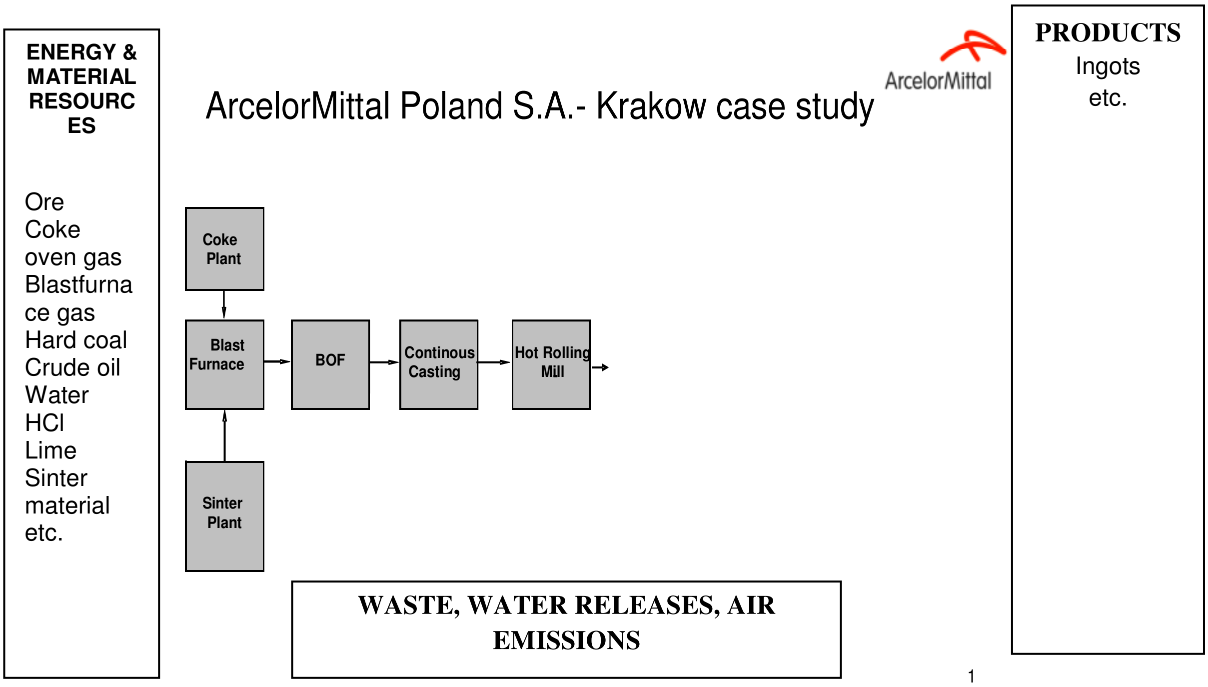

Figure 2. System boundaries of the study

Table 1: Main products of the AMSP examined

Main products of the AMSP [Mg]	2005 year
Total steel	1 677 987
Coke	1 027 905
Pig iron	1 504 088
Sinter	1 669 023
Slabs from Continuous casting	1 581 684
Sheets from Hot Rolling mill	1 494 860
Hard coal	315 680

3 Uncertainty Assessment in LCI

In the Commission Decision of 18 July 2007 establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European parliament and of the Council, uncertainty means: a parameter, associated with the result of the determination of a quantity, that characterizes the dispersion of the values that could reasonably be attributed to the particular quantity, including the effects of systematic as well as of random factors and expressed in per cent and describes a confidence interval around the mean value comprising 95 % of inferred values taking into account any asymmetry of the distribution of values" [8]. Usually the overall uncertainty of a LCI is dominated by a few major uncertainties. Likewise, the overall uncertainty of a specific process is typically dominated by one source of uncertainty and other sources of uncertainty may be ignored [9,.p. 21]. Information about uncertainty in LCI results cannot be fully captured within the LCI database, because a significant share of this uncertainty arises in practice, based on relationship between the data [10]. When the main determining parameters of an uncertainty is known, it can be eliminated or at least reduced to the uncertainty by modeling.

Three types of process modeling can be identified in LCA studies [11, p.135]: black box models of processes. This is the mostly used type in LCA because this is the easiest way of process modeling. models of processes with linear functional relations. In this concept linear relations (functions) between each input and output as well as between the different inputs are defined.models of processes with non-linear and linear functional relations. In this concept linear or non-linear relations (functions) between each input and output as well as between the different inputs are defined.In the Eco-indicator 99 [12] was presented three fundamentally different types of uncertainty: operational, or data uncertainties – the squared geometric standard deviation expressed the variation between the best estimate and the upper and lower confidence limits (97.5% and 2.5%). The uncertainties are intended for use in software tools that apply Monte Carlo analysisfundamental, or model uncertainties – many modeling choices are often rather subjectiveuncertainty due on incompleteness of the model.

The overall uncertainty of the assessment includes [13, p. 83A]:

1) uncertainty of models and parameters
2) uncertainty of the indicators interpretation.

4 The Benefit of Monte Carlo Simulation

The uncertainty stems from partial ignorance or lack of perfect knowledge. Based on the experiences regarding uncertainty in LCA/LCI studies, it seems that LCI must be performed from a probabilistic point of view, rather than by considering deterministic aspects. Among the probabilistic tools, in order to include the above aspects the use of MC analysis has been increasing in recent years, and is one of the most widespread stochastic model uncertainty analyses. This effect has been widely studied (e.g. [14,p. 272], [15,p. 174]). MC simulation uses these distributions, referred to as "assumptions", to automate the complex "what-if" process and generate realistic random values. The benefits of a simulation modeling approach are: (1) an understanding of the probability of specific outcomes (2) the ability to pinpoint and test the driving variables within a model (3) a far more flexible model; and (4) clear summary charts and reports [16]. One of the problems associated with traditional spreadsheet models is that for variables that are uncertain. Without the aid of simulation, a spreadsheet model would only reveal a single outcome. Spreadsheet uncertainty analysis uses a spreadsheet model and simulation to analyze the effect of varying inputs or outputs of the modeled system automatically. The With Crystal Ball®, commercially available software, we have the ability to replace each uncertain variable with a probability distribution, a function that represents a range of values and the likelihood of occurrence over that the range.

The MC sampling was done using an Excel® spreadsheet modified to develop scenarios for inputs given the probability distributions, means values, etc. and Crystal Ball®, a software package offered by Decisionnering, generates random numbers for a probability distribution over the entire range of possible values, based on the assumption variables. For this reason, a large number of trials are required to obtain accurate results for the true shape of the distribution. results and probabilities for those results. MC analysis-simulation is the only acceptable approach for U.S. Environmental Protection Agency (EPA) risk assessments.[17].

4.1 Data Sources Choosing input distributions

The data collection for the core of AMSP power plant generating processes has been performed rigorously, with appropriate checks on consistency and completeness. The data used in the study are obtained from the following sources:

Site-specific measured or calculated data [1]. LCA study carried out on behalf of the AGH-University of Science and Technology's Management Department by Polish Academy of Science in Krakow [7]. Value based on literature information. AMSP Environmental Impact Report [1]. Data obtained from other sources e.g. personal communication (AMSP Environmental Department director). For some variables, there may be enough empirical information to fit parametric distributions or even specify empirical histograms. For other variables, the available data may be very limited or completely absent. Sometimes it is reasonable to let experts define the shapes of the input distribution subjectively, but this is not always a workable strategy and often leads to more controversy [18]. Use of default (i.e. arbitrary) input distributions is sometimes suggested, but this approach can be criticized easily [19-20]. In this case study only the following substances: hard coal, blast furnace gas, coke oven gas, natural gas, lubricant oil, cadmium (Cd), carbon monoxide (CO), carbon dioxide (CO2), nitrogen dioxide (NO2), chloridric acid (HCL), chromium (Cr) nickel (Ni), sulfur dioxide (SO2), manganese (Mn), cooper (Cu), lead (Pb) have been taken in account. The probability distributions for the hard coal, blast furnace gas, coke oven gas and natural gas were considered to be normal with coefficient of variation (CV) of 0.20 according to the [20] and [21]. The probability distributions for the lubricant oil was considered to be normal with CV of 0.1, according to the estimations published by Weidema and Wesnaes [22]. The proper determination of the log-normal probability distributions in the case of SO2 (emissions), CO (emissions), NO2 (emissions), Cr, Cd, Ni and HCl data with a geometric standard deviation (σg) between 1.5 and 2.2 is possible according to the estimations published by Sonnemann et al. [16, p. 191] based on Rabl and Spadaro [23] and STQ [24], as well as data taken from Kulczycka, Henclik study [7]. It was possible to simulate the following parameters emitted in air (e.g. lack of an information regarding geometric standard deviation, σg): Cu, Mn, S and Pb, because according to criteria proposed by Sonnemann et al. [16, p. 29], that "heavy metals is a sum parameter in the form of Pb equivalents of following heavy metals: As, B, Cr, Cu, Hg, Mn, Mo, Ni Pb and Sb",. the log-normal probability distributions with a geometric standard deviation (σg) equal 2.5 were selected from STQ [24]. The geometric standard deviations consideration as well as normal standard deviations was done due to a lack of Polish data applied to the concentrations in emissions of the AMSP steel processes. In the study presented by Sonnemann et al. [16, p. 191], related to the uncertainty assessment by Monte Carlo simulation for LCI applied to waste incinerator in Tarragona, the data were obtained from the ETH database [21]. These data have been collected from a Swiss perspective on a European scale The probability distributions for other elements of Site-Specific Data had to be derived from CrystallBall® analysis experimental results. Confidence level is specify to 95%. Meier [20] proposed to assume classes of normal probability distributions with following CVs:

1) for data obtained by stochiometric determination, a CV of 2% needs to be considered
2) for actual emission measurements or data computable in well-known process simulation, a CV of 10% is expected
3) for well-defined substances or summed parameters, a CV of 20% can be assumed
4) for data taken from specific compounds by an elaborated analytical method, a CV of 30% is expected.

According to Hofstetter several reports in risk assessment and impact pathway analysis have shown that the log-normal distribution seems to be a more realistic approximation for the variability in fate and effect factors than the normal distribution [25]. The 50th percentile of a lognormal distribution is related to the mean of its corresponding normal distribution. The log-normal distribution is calculated assuming that logarithm of the variable has a normal distribution. The geometric mean, μg, and the geometric standard deviation, σg, of the sample is very practical and correspond to the mean and coefficient of variation for the normal distribution. Moreover, they provide multiplicative confidence intervals such as:

[μg/ σg, μg*σg] for confidence interval (level) of 68%

[μg/ σg2, μg*σg2] for confidence interval of 95% [16].

Figure 3 presents the lognormal distribution parameters related to the SO2 emissions, while Figure 4 show the results of 10 000 replications of the CrystalBall® screenshot (define assumption dialogue box for normal and log-normal distributions as well as the final provision) related to the SO2 emissions. The quantity of the SO2 emissions in 2005 was 3 138.1 Mg.

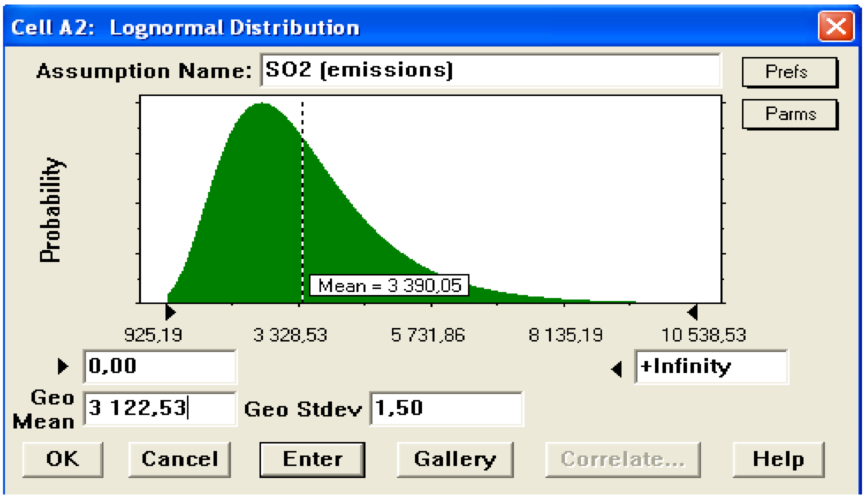

Figure 3. Lognormal distribution assigned to SO2 emissions

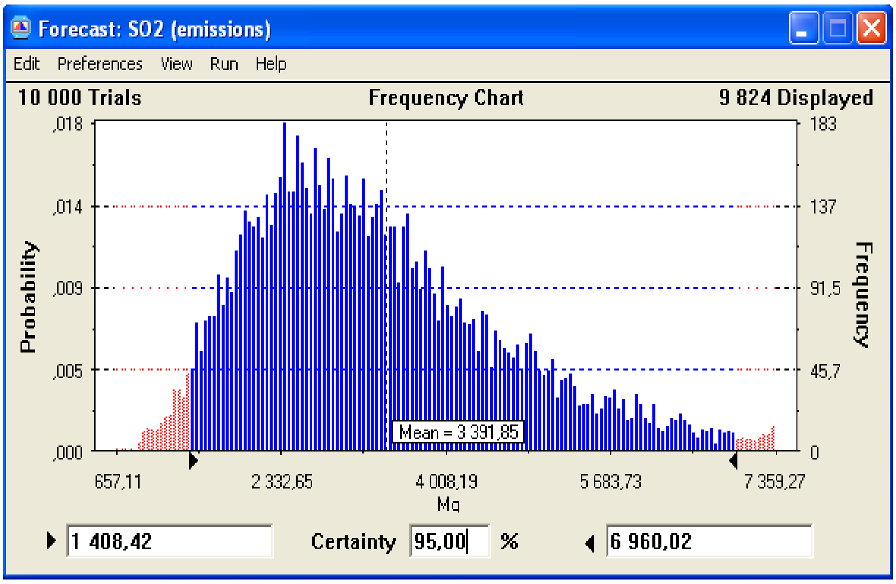

Figure 4. Frequency chart results of 10 000 replications of the CrystalBall® simulation

5 CONCLUSIONS and OUTLOOK

5.1 . Conclusions

The aim of the study is to use of a stochastic assessment by Monte Carlo Simulation for LCI applied to steel process chain: The ArcelorMittal Steel Poland S.A. in Krakow, Poland case study and to promote the use of uncertainty estimation as routine in environmental science. Uncertainty analysis in LCA methodology has received increasing attention over the last years. The functional unit in this study, central concept in LCA, is defined as "steel process chain includes all activities linked with steel production from Coke Plant and Sinter Plant to Hot Rolling Mill in 2005".

LCA/LCI data are full of uncertain numbers. The benefits of Monte Carlo simulation are saving in time and resources. CrystalBall® eliminates the need to run, test, and present multiple spreadsheets. With CrystalBall® analysis we can show the benefit of investing more on a monthly basis. Cristal Ball® can handle dozen assumptions simultaneously, and can establish correlation coefficients among variables.

Simulation models are generally easier to understand than many analytical approaches [6, p.12]. Usually the overall uncertainty of an LCI is dominated by a few major uncertainties [26]. The use of stochastic model helps to characterize the uncertainties better, rather than pure analytical mathematical approach. Monte Carlo analysis generates a mean value and upper and lower boundary value for each LCI exchange [27, p. 82]. The created inventories using the probabilistic approach facilitate the environmental damage estimations for industrial process chains with complex number of industrial processes (e.g. steel production). Consequently, Monte Carlo analysis is a power full method for quantifying parameter uncertainty in LCA studies. In this study the most likely SO2 emissions values are ranged between 1 408.42 Mg and 6 960.02 Mg. Certainty level is 95%. The quantity of the SO2 emissions used in the model calculation was 3 138.1 Mg.

5.2 Outlook

The research described in this paper can also serve as the basis for future work. The potential direction for future research is to integrated LCA and risk assessment for industrial processed based on the probabilistic and statistical modeling for decision making under risk analysis, because this technique accounts for uncertainties in the assumptions. The baselines presented in this study using deterministic input values. In a deterministic model, all data are known, or assumed to be know, with certainty. In a probabilistic model, some data are described by probabilistic distributions. Simulation models are generally easier to understand than many analytical approaches [7, p.12].

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1) The paper (doc and pdf files) and supporting documents have to be uploaded in the LCM2011 website by **15.04.2011** (https://www.conftool.com/lcm2011/index.php?page=login). Any delay will necessarily lead to the exclusion from the selection of papers for the conference book; the paper can then be published electronically only.
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8 Style for heading 1 (note: capitalize the first letter of the first word but leave the rest lower case)

8.1 Style for heading 2 (note: capitalize the first letter of the first word but leave the rest lower case)

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9 Format

9.1 Tables

Use the table layout “seetable” for creating your tables or modify the example inserted below. Ensure that all tables have a caption like the example and are cited in the text in the correct order (e.g. Table 1).
To format the table columns, use the table function. Do not use the space bar to separate columns, and do not use Excel to create tables. If a table cell has to be left empty, please type a hyphen (-) in it.

Tab.1: Example for table caption (note: capitalize the first letter of the first word but leave the rest lower case)

9.2 Figures

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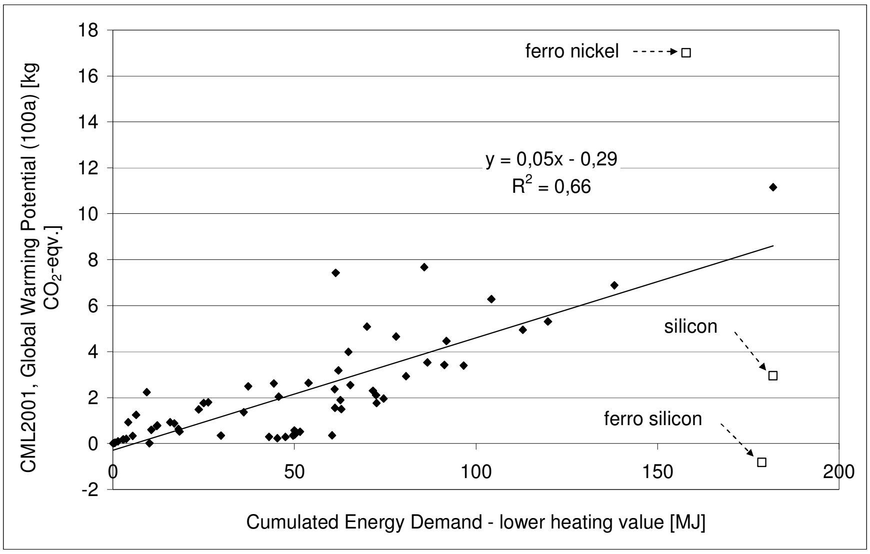

Fig.1: Example for figure caption (note: capitalize the first letter of the first word but leave the rest lower case)

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Note: please, only use the format styles mentioned in this instruction, do not insert any footnotes and do not add any page numbers.

9.3.1 Paragraph format styles

- Abstract
- Authors
- Table/Figure Heading
- Contact
- Equations
- Heading 1/2/3
- Title
- List (Symbol)

5) List (Numbering)

- References
- Standard

9.3.2 Character format styles

- **Bold**
- *Italics*
- Inferior Characters
- Special Characters (Arial Unicode MS, type size 10)
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Please use MathType or the Microsoft equation editor and the paragraph template "equations". Equations of the type 2a+4b=5c can be written as normal text.

Examples:

$$A_i = \frac{E}{(R_i)^2} \cdot \frac{(T)^2}{R_{Sb}} \qquad (1)$$

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[29] Author(s), Title of paper, International Conference, Place, YEAR, Vol. X, pp. YY-YY.
[30] Author(s), *Title of the book*, Xth Ed., Publishing house, YEAR.
[31] <http://…>, (Accessed DD.MM.YEAR).
[32] <http://…>, (Accessed DD.MM.YEAR).