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# Application of the Mathematical Statistics for the Evaluation of the Waste Incineration Process

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## 1. Introduction

The sharp increase in the amounts and in the variety of available products on the market causes also an increase in the amounts of different packaging's and other elements that come with any given product. The large amounts of communal waste stem from different anthropomorphic activities and from different aspects of human consumption cause an increased demand for effective waste disposal, either by incineration, separation, recycling or by organic processing.

The technology of the incineration systems developed over years and currently reached state, when this form of waste disposal can be environmentally friendly, with the added value of produced thermal energy (Parobek & Paluš 2016, Pavlas et al. 2011). The acquired thermal energy can be then used for heating purposes, or be transformed into electrical energy. An efficient incinerator is not only assessed by the amount of thermal energy utilization but also by the levels of emissions and quality of the ash it produces (Goh et al. 2000). The thermal energy has some significant advantages, such as the greatly reduced volume of waste, the disposal of fungi, bacteria and germs, and the production of thermal power. There are however also some disadvantages in terms of environmental impacts such as the production of various toxic gases. As it is highly unlikely that there should be occur any significant decrease in the amount of available products on the market, also the rate of consumption will not cease, thus one can safely forecast that there will be an increased demand for efficient waste disposal by incineration. Therefore, it is important to pay to environmental protection aspects of waste disposal in incineration facilities. As the future development in this area can only be estimated based on the statistics and conditions from the previous years, it is appropriate to apply mathematical and statistical analysis.

This appears to indicate a problem that is related to the effective use of means of mathematical statistics for the needs solutions for reducing the environmental impacts of waste incineration process in the concrete region and thus ensure sustainable environmental development in the region.

Under the process of waste incineration one can understand a production system with its components, facilities with its flows (Fontanili et al. 2000, Gottinger 1986, Sangmin et al. 1994). Due to large variations of waste types and difficulties in feed characterization (physical, chemical and thermal properties), the incineration process meets great challenges in a smooth operation, with substantial fluctuations of gas temperatures within the system (Belevi & Langmeier 2000, Lombardi et al. 2013, Noguchi et al. 2000, Yang et al. 2002). The aim within this case study is to set up the system of waste incineration in a way, where the negative effects of its activities and the associated environmental impacts are minimal. In ideal case there would be no negative impacts whosoever. The aim of this case study is to discuss the use of principles of mathematical statistics for the management of waste incineration processes in the context of environmental protection. Not less important is the combination of these three approaches within one cohesive methodological framework to achieve the most efficient waste incineration process within the region of interest and thus, to ensure in practice a long-term sustainable development of the environment.

## 2. Theoretical base

### 2.1. Logistics and mathematical statistics in environment

To achieve the highest production performance by maximizing the efficiency, the logistics at the strategic, tactical and operational level defines and proposes actions that lead to the desired results using all available means of science and technology, economics and computer science. The aim of logistics is to create a single, integrated, optimized material flow that can be created by connecting the various parts of the system so that a continuous exchange of goods and services can be provided. Logistics is gradually evolving and at the same time the views on its scope and level of influence is evolving (Straka 2013). The process of waste management is important for the health of the public and aesthetic and environmental reasons (Rushton 2003, Sahlin et al. 2004, Šomplák et al. 2014). The waste processing and disposal and the streamlined processing flows performance can be provided by the means of reverse logistics (Abdessalem et al. 2012, Pokharel & Mutha 2009, Sheu 2008).

When planning waste management, it is important to know that the choice of waste treatment method affects processes outside the waste management system (Eriksson et al. 2005). In waste treatment processes different materials and products are usually mixed (Finnveden 1999).

With these options available, different systems investigators are able to better understand the details of the operation within the system and to address them in terms of effective utilization of business resources.

The possibility for impacts of waste incineration solution is application of mathematical modelling (Hellweg et al. 2011, Luo et al. 2008, Yang et al. 2004). Gaussian least squares method is one of the basic methods for data processing. So called theoretical regression, that is the relation of one value to another, or the dependence of one variable (dependent), to another variable (independent), can be obtained from the currently measured, observed data, values pairs $x_i$, $y_i$, arranged for V $\{x_i, y_i\}_n$. Regression analysis is a very popular, effective and applicable tool for identifying dependencies between the examined variables. In this article this method will be applied to determine the dependence between the amount of waste incinerated and quantity of steam and the amount of heat produced. The advantage of this method is its versatility, considering it makes it possible to calculate the most appropriate parameter values (Aczel 1989, Ryu et al. 2004, Yeomans et al. 2003).

## 2.2. Data for mathematical statistics waste incineration analysis

For realization of a statistics analysis of the waste incineration process within a concrete region is necessary to prepare and carry out a thorough analysis of the given system. The waste incineration plant in question can be classified as an industry in the area of the chemical processing. The input into the system is formed by hauling thousands of tons of communal waste from the city of Kosice Region and from Kosice – surroundings. The main activity of the company is the disposal of imported waste, by separation, sorting and the actual incineration.

Based on the results of the system analysis, in this case represented by the waste processing company one can derive the following findings:

- Every year, 83,000 tons of waste get imported into the company, that first goes through a several levels of separation.
- The first separation is intended to separate the plastics, electrical components and wood from imported waste. The total volume of imported waste is composed of 19% of the plastic and electrical components; of up to 10.00% wood in a variety of forms. The rest is represented by more than 71% of miscellaneous municipal waste.
- The second phase of separation occurs during the waste incineration phase, right after the actual burning. The resulting product of the incineration process and the subsequent separation consists of about 3% of ash, 90% of incinerated waste and about 7% are gases that arise in the process of waste incineration. The gases then pass through the filtration process, where the total volume of the flue gases consists of 65% steam and 35% of other emissions.
- The third phase of separation relates to the separation of the resulting burned material and is focused on separating metals from the remaining solid burned material. There is about 2% of metal in the charred mass, and the remaining 98% is a clean clinker.

In terms of the overall process of waste incineration some additional stations must be mentioned:

- One of such stations is the detection and measurement of waste humidity level. If the waste is too wet, it is necessary to reduce the overall waste moisture by mixing it with dry wood material. For this purpose, separated wood waste is used acquired from the imported communal waste. If necessary, this dry wood is added into the wet waste mixture. The amount of wood material that needs to be added into the waste mixture depends on the overall level of the annual rainfall. If there is a wet year with heavy rainfall, then more wood must be added. If there is a dry year, the wooden material needs to be added only occasionally. Overall, it can be stated that from the total volume of imported waste, 70% consists of dry waste without the need to add wood material and 30% consists of moist or wet waste, where there is a need to add dry wood into mixture, due to the high humidity levels.

- The second stations that must mentioned, follows the process of burning and magnetic separation. The incinerated waste is a hot material, called bottom ash or clinker. This clinker must be cooled by adding waster. For this activity about 10,000 $m^3$ of water are used per year. The cooled clinker is then stored in a landfill within the company premises.

# 3. Case study

## 3.1. Application of mathematical statistics for analyse of waste incineration

For long-term materials and energy recovery from waste it is necessary to monitor the amount of imported waste, for example by using time series analysis. The aim of the time series analysis is mostly to design a model. The model analysis primarily enables to understand the mechanics of data, where it is possible to determine for example the seasonal trends in the volumes of imported waste. Seasonal effects are caused either by direct or indirect causes. The seasonal component in this particular case has its origin in the alternation of four seasons throughout the year. The understanding of time series model enables to predict the future development of the system. The Figure 1 shows the cause of a long-term seasonal effect on the amounts of imported waste for a period of nine years (KOSIT 2015, Malindžáková 2015).

Referring to the seasonal fluctuation in the quantity of imported waste it is important to also discuss the incineration process. In terms of incineration performance of the plant, it is important to notice disposal / theoretical capacity of the boiler (DCB / TCB), hourly amount of waste incinerated (HWI) in relation to the total quality of waste incinerated (TQWI) (Fig. 2-10). The facility capacity reached in 2007 in the months of April 77.22%, in May 86.56%, in June to 98.19% in July 66.53% of available capacity. These capacities were significantly above the long term average calorific values. The actual facility capacity in August 2007 reached 45.97%, while the calorific value reached 12.21 $GJ.Mg^{-1}$ which approaches the maximum technical limit for this facility (12.25 $GJ.Mg^{-1}$).

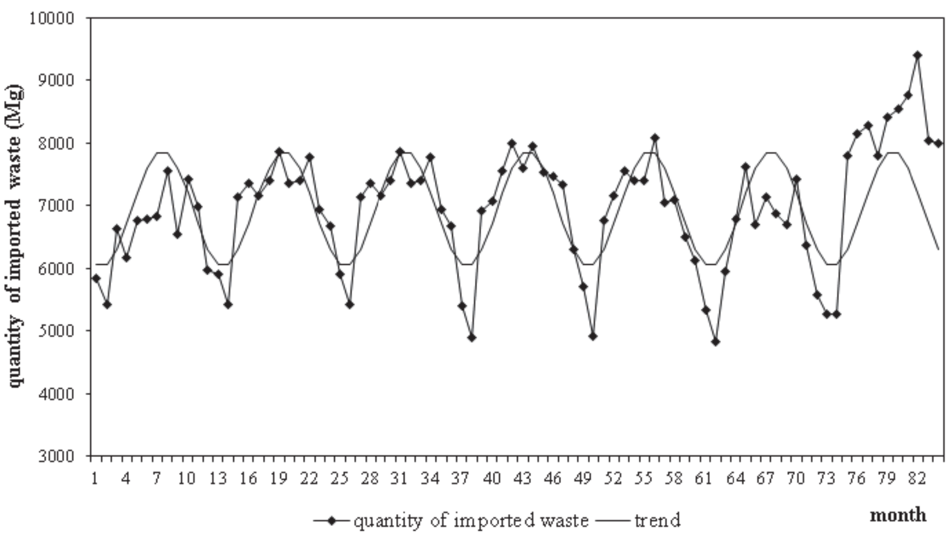


**Fig. 1.** Analysis of the seasonal component within the time series of the amounts of imported waste for the time period between the years 2007-2015
**Rys. 1.** Analiza komponentu sezonowego w ramach szeregów czasowych ilości importowanych odpadów w latach 2007-2015

In September 2007, the operational capacity dropped to 32.50%, whilst at the same time the waste calorific value was slightly reduced. The operational capacity reduction was actually caused by the boiler shutdown during major planned maintenance downtime (Fig. 2). The maximum calorific value (10.94 $GJ.Mg^{-1}$) in September 2008 indicates that dried waste, such as dry wood chips and leaves were burned. In September 2008, operational capacity was utilized to 79.72%, whilst the amount of incinerated waste was at 8.4 $Mg.h^{-1}$, but at the same time the calorific value of the waste was considerably above the average value (Fig. 3).

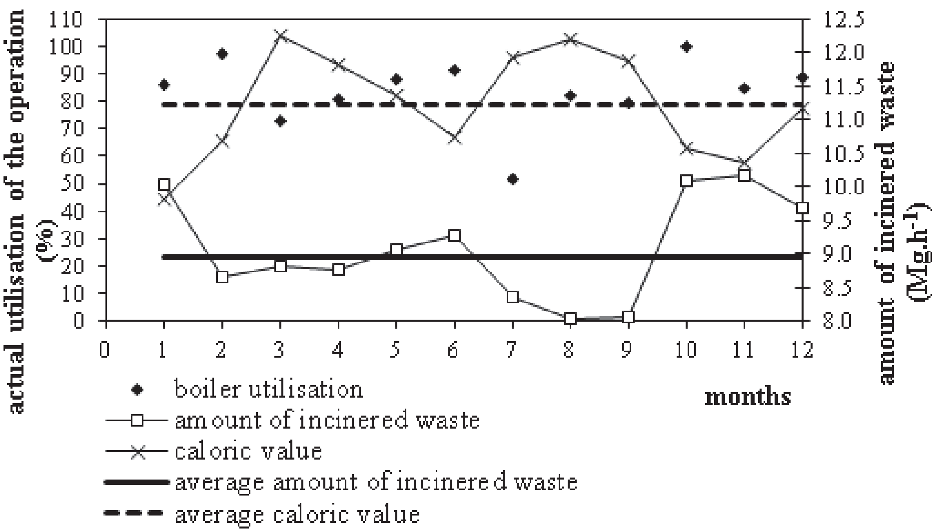


**Fig. 2.** The relationship between the operation use of TQWI in 2007
**Rys. 2.** Zależność między operacyjnym wykorzystaniem a całkowitą jakością spalanych odpadów w roku 2007

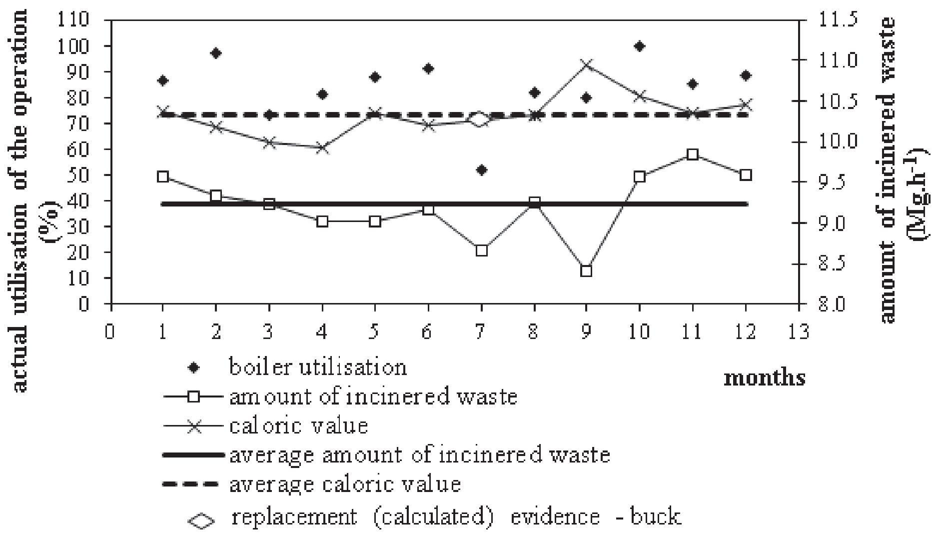


**Fig. 3.** The relationship between the operation use of TQWI in 2008
**Rys. 3.** Zależność między operacyjnym wykorzystaniem a całkowitą jakością spalanych odpadów w roku 2008

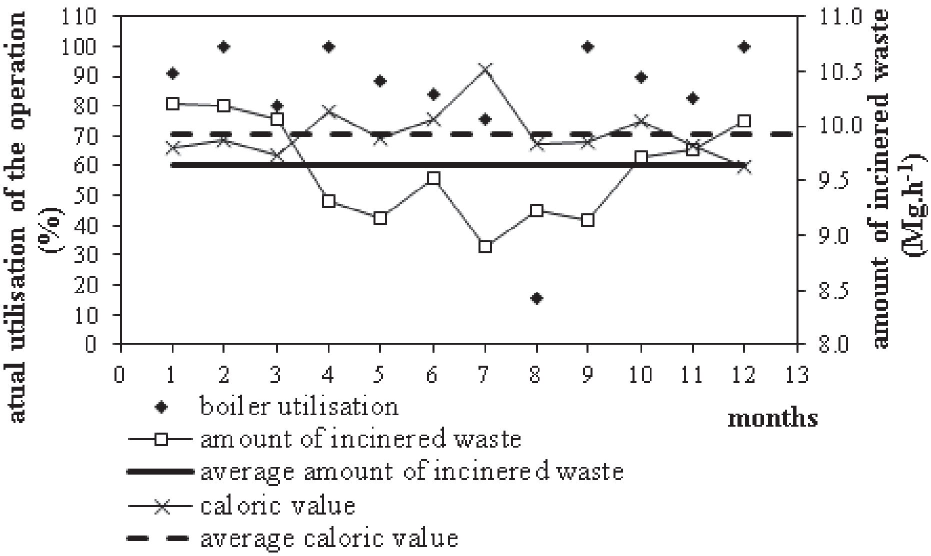


**Fig. 4.** The relationship between the operation use of TQWI in 2009
**Rys. 4.** Zależność między operacyjnym wykorzystaniem a całkowitą jakością spalanych odpadów w roku 2009

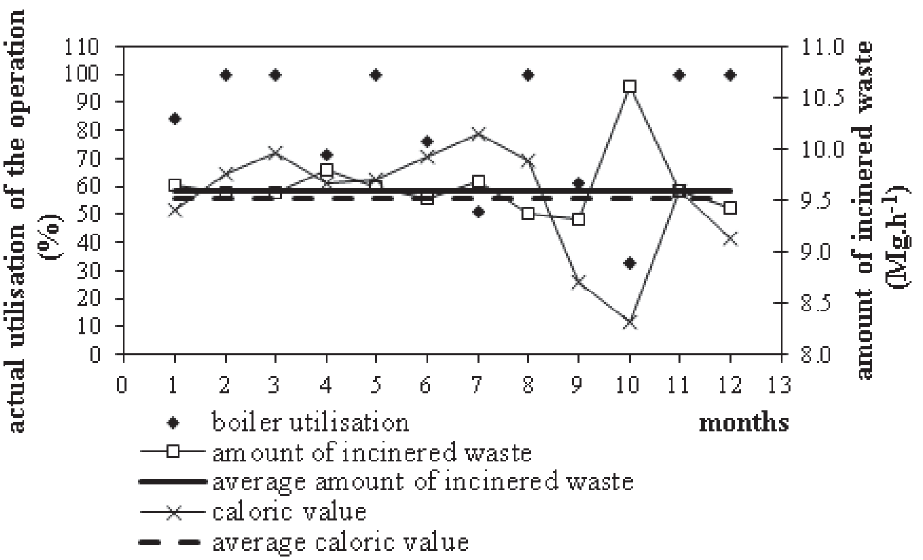


**Fig. 5.** The relationship between the operation use of TQWI in 2010
**Rys. 5.** Zależność między operacyjnym wykorzystaniem a całkowitą jakością spalanych odpadów w roku 2010

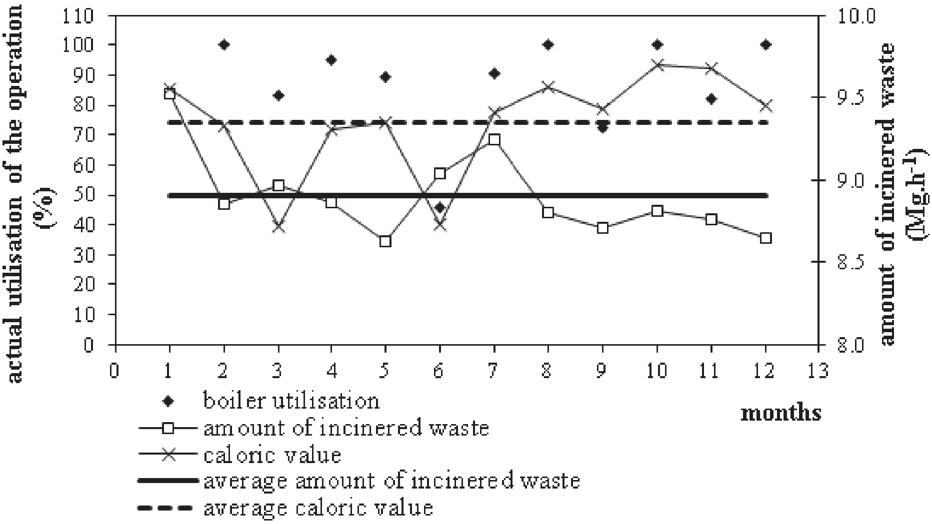


**Fig. 6.** The relationship between the operation use of TQWI in 2011
**Rys. 6.** Zależność między operacyjnym wykorzystaniem a całkowitą jakością spalanych odpadów w roku 2011

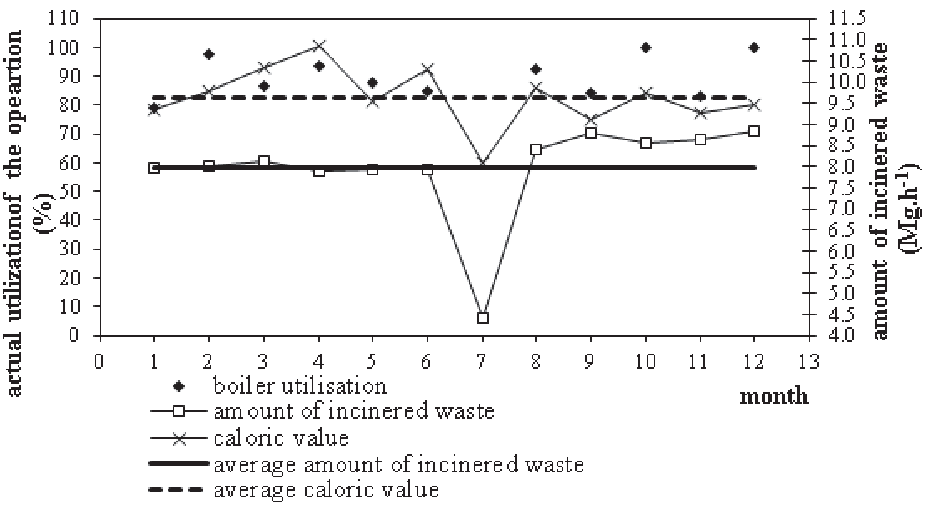


**Fig. 7.** The relationship between the operation use of TQWI in 2012
**Rys. 7.** Zależność między operacyjnym wykorzystaniem a całkowitą jakością spalanych odpadów w roku 2012

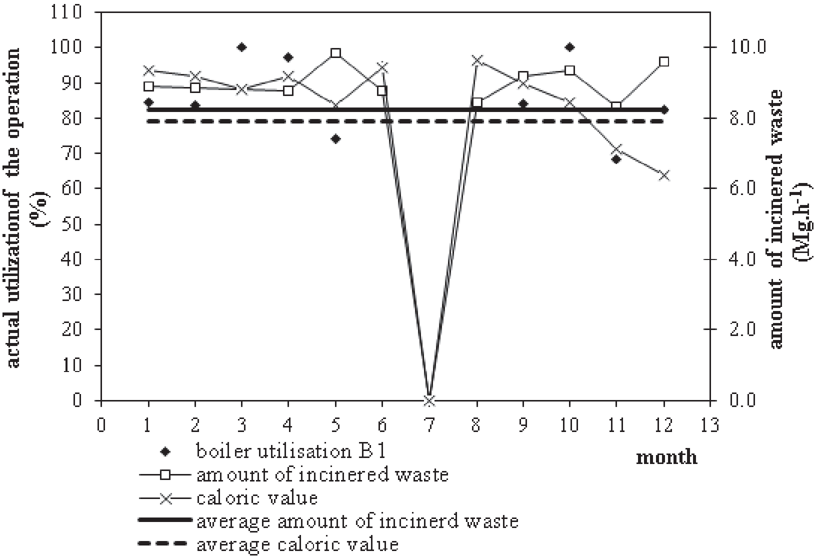


**Fig. 8.** The relationship between the operation use of TQWI in 2013
**Rys. 8.** Zależność między operacyjnym wykorzystaniem a całkowitą jakością spalanych odpadów w roku 2013

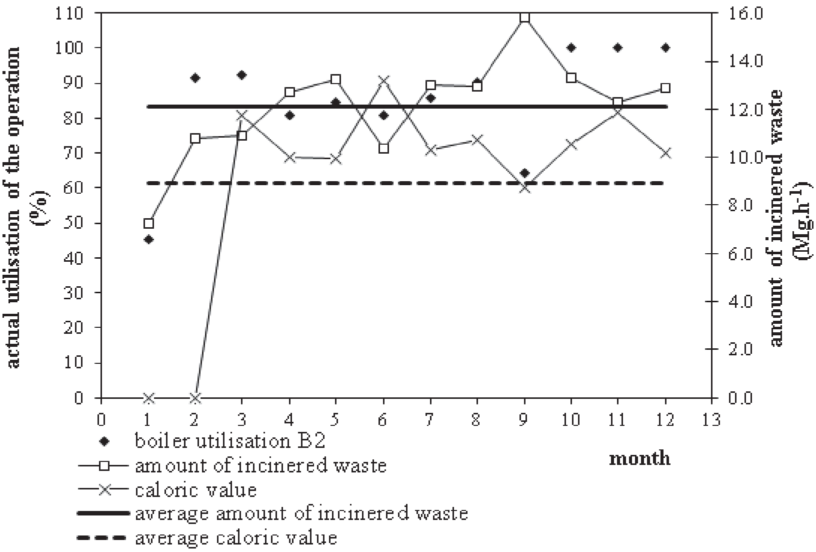


**Fig. 9.** The relationship between the operation use of TQWI in 2014
**Rys. 9.** Zależność między operacyjnym wykorzystaniem a całkowitą jakością spalanych odpadów w roku 2014

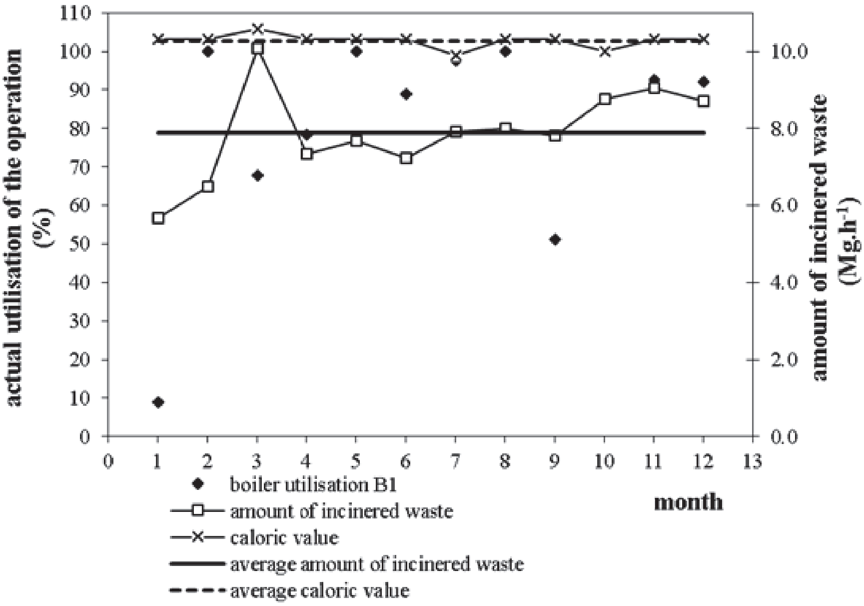


**Fig. 10.** The relationship between the operation use of TQWI in 2015
**Rys. 10.** Zależność między operacyjnym wykorzystaniem a całkowitą jakością spalanych odpadów w roku 2015

During 2009 the operational capacity was utilised in the months of April to 100% in May to 88.17%, in June to 83.75% and in July to 75.81%, but the calorific value during these months was significantly above the average calorific values. Due to the fact that in August 2009, the incinerator boiler maintenance took place, the operational capacity dropped significantly at the time, down to 15.32%, while the calorific value of the waste was slightly below average calorific values. Paradoxically, in September 2009, the operational capacity has been utilized to 100%, but the calorific value of the waste was only little different from the calorific value of the previous month, when operational capacity was limited to merely 15.32% of full production capacity (Fig. 4).

In Figure 5 it can be seen that in October 2010 the operation worked at 32.80% of available capacity, while the amount of waste incinerated in the month was 10.61 $Mg.h^{-1}$ and the calorific value was significantly below the average calorific value. This observation can be explained by the fact that the incinerator underwent maintenance at the time. It can be observed that the operational capacity in 2011 (Fig. 6) was utilised to 100%

during February, August, October and December, while the calorific value in these months was also above average calorific value. Operating capacity has decreased significantly in June, down to 45.83%, when the calorific value was slightly below the average calorific value.

In August 2011 the operational capacity has been utilized to 100%, but the calorific value was slightly above average.

The 2012 results (Fig. 7) show significantly below average amounts of incinerated waste. In July the boiler reached only 5.91% of available capacity, which was due to the boiler maintenance. Given the fact that the operation reached 86.83% in March, 93.61% in April, and 84.72% in June, the average calorific value has reached above average calorific value. In 2012 the operation was utilised to 100% only during 2 months, namely during October and in December.

The operation utilisation in July 2013 (Fig. 8) was at 0.00%, as in that month a complete shutdown was ordered for the boiler K1, due to the maintenance reasons. Only during the last months of 2013 the K1 boiler ran at 100%. K1 boiler was then shut down and subjected to reconstruction.

In the January 2014 (Fig. 9) a new boiler was put into operation (boiler K2) designated for the incineration of municipal waste. The efficiency of the K2 boiler during the initial period (January) was 45.43%. In the coming months the utilisation of the K2 boiler was at about 90%. The new boiler K2 reached the 100% capacity in the months of October, November and December 2014. As paradox one can mention the month of September 2014, when the amount of waste incinerated was 15.84 $Mg_w.h^{-1}$, but the calorific value of waste reached only 8.72 $GJ.Mg^{-1}$.

The beginning of 2015 (Fig 10) was for the incineration of municipal waste particularly difficult because there was a serious malfunction of the turbine in the boiler K2. Due to a major breakdown, the boiler K2 was shut down and it was necessary to carry out the general maintenance. The company responded immediately by launching the original reconstructed boiler K1. The values for the quantity of the incinerated waste were within the range from 5.68 $Mg_w.h^{-1}$ to 10.08 $Mg_w.h^{-1}$. On the other hand, the calorific value of the waste in the corresponding month of 2015 was stable, fluctuating around the average number of 10.27 $GJ.Mg^{-1}$.

Given the importance of the relation between the quantity of heat and of the generated steam to the heating value, a graph was created showing the long term relationship of these three essential characteristics

(Fig. 11). Since the company does not have data for the generated heat and steam for the year 2007, in Figure 11 this part of the trend shows no values. The downward trend of the calorific value was probably the result of wear and tear in the sheath inside the boiler. This has resulted in a downward trend in production of heat and steam produced from 2009.

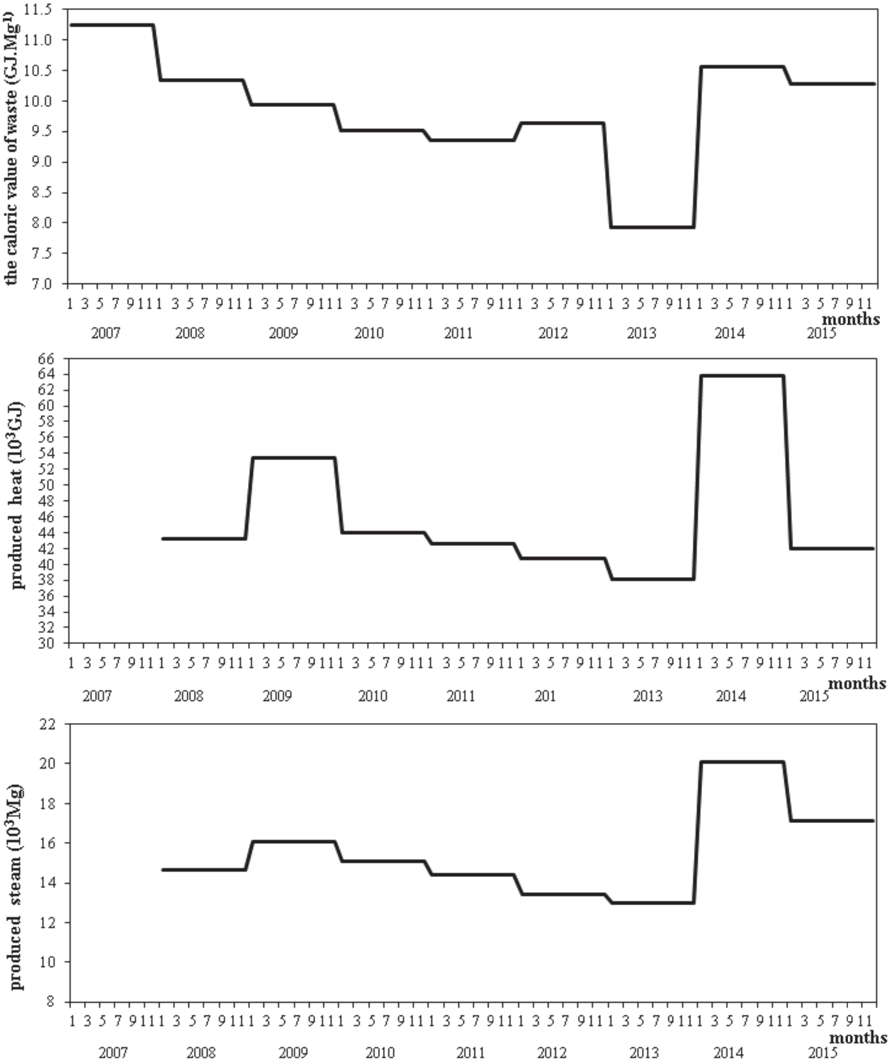


**Fig. 11.** The production of heat and of steam in relation to the net caloric values
**Rys. 11.** Produkcja ciepła i pary w stosunku do wartości kalorycznych netto

### 3.2. Statistics data for Gaussian least squares method

The steam resulting from the incineration of municipal waste can be used to produce heat and electricity in steam and gas turbines. For the model calculation of the relation between the incinerated waste amount and the steam quantity produced, the Gaussian least squares method was applied.

This method is considered to be the basic working method for data processing. The basic methods of Gaussian least squares principle (Chatfield 2003, Fischer 1995, MATH 2013) can be expressed a follows (1)(2)(3):

$$ZY = \sum_{i=1}^{n} dy_i^2 = \sum_{i=1}^{n} \left(Y_i - y_i\right)^2 = \sum_{i=1}^{n} \left(a_0 + a_1 \cdot x_i - y_i\right)^2 \quad (1)$$

$$\frac{\partial Z}{\partial a_0} = 2\sum_i \left(a_0 + a_1 \cdot x_i - y_i\right) = 0 \quad (2)$$

$$\frac{\partial Z}{\partial a_1} = 2\sum_i \left(a_0 + a_1 \cdot x_i - y_i\right) \cdot x_i = 0 \quad (3)$$

$$\begin{bmatrix} n & \sum x_i \\ \sum x_i & \sum x_i^2 \end{bmatrix} \cdot \begin{bmatrix} a_0 \\ a_1 \end{bmatrix} = \begin{bmatrix} \sum y_i \\ \sum x_i \cdot y_i \end{bmatrix}$$

$(\boldsymbol{X^T} \cdot \boldsymbol{X}) \cdot a = (\boldsymbol{X^T} \cdot \boldsymbol{y})$ => normal system of equations $\left[\hat{a}_0 \, \hat{a}_1\right] = \hat{a} = (\boldsymbol{X^T} \cdot \boldsymbol{X})^{-1} \cdot (\boldsymbol{X^T} \cdot \boldsymbol{y})$

The calculation of the Pearson correlation coefficient (4):

$$r_{xy} = r_{yx} = r = \frac{cov_{xy}}{s_x \cdot s_y} \quad (4)$$

where:
$cov_{xy}$ – the mixed dispersion of *x* and *y*
$s_x$ – standard deviation for the variable *x*,
$s_y$ – standard deviation for the variable *y*.

The relationship between the amount of incinerated waste $\{x_i\}$ and quantity of steam $\{y_i\}$ is expressed by the theoretical mode (5):

$$Y = 1434.3 + 2.3661 \cdot x \tag{5}$$

Its strength is also reflected by the Pearson correlation coefficient. The resulting correlation coefficient $r_{xy}$ = 0.82 confirms that among the variables being monitored is a very strong linear relationship – with the growing values of the incinerated waste quantity, in proportion also the values for a quantity of generated steam grow which can be demonstrated by the "correlation scissors" that are almost closed (Fig. 12).

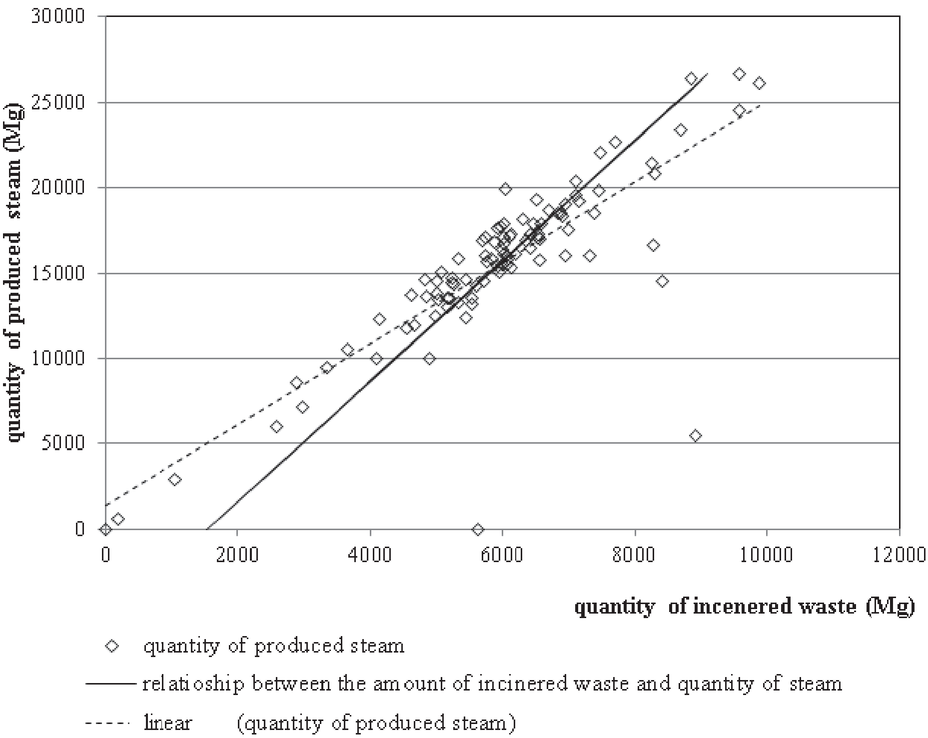


**Fig. 12.** The relationship between the amount of incinerated waste and the quantity of steam
**Rys. 12.** Zależność między ilością spalanych odpadów a ilością pary

It is also possible to calculate the model depending on the amount of waste incinerated and the amount of heat produced. This model can be expressed by the formula (6):

$$Y = 17.437 + 0.0048 \cdot x \tag{6}$$

The Pearson correlation coefficient $r_{xy}$ = 0.54 indicates that there is a moderate linear relationship, presented by a direct proportion between the values of incinerated waste quantity and the quantity values of produced heat (Fig. 13).

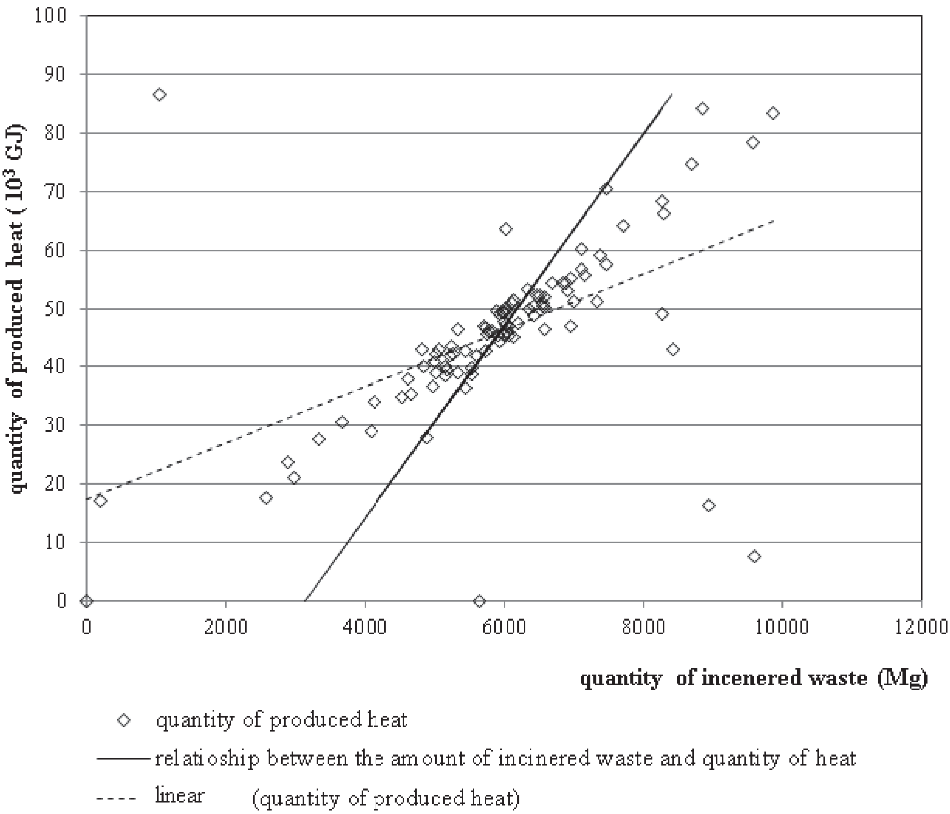


**Fig. 13.** The relation between the amount of waste incinerated and the amount of produced heat
**Rys. 13.** Zależność między ilością spalanych odpadów a ilością produkowanego ciepła

## 4. Conclusions

Many research studies show that the adverse environmental impacts can be minimized by reducing the amount of waste production (whether within industrial or municipal sector), and in this way reduce also the related emissions release. An essential step in waste reduction is the use of green materials as well as its secondary recovery, starting with the separation of waste.

Currently within the case study company, the operating costs are mainly affected by the composition of the input material for incineration, the amount of waste, the amount of used fuel and the amount of natural gas needed to support the burning process. This indicates that a cost reduction is possible by ensuring a thorough separation of input materials. This was achieved by raising awareness among the population towards the sorting and secondary recovery of municipal waste, which indirectly affected also the total cost of fuel (less waste means fewer trips for waste transport vehicles) and also the costs of the actual incineration process due to a smaller amount of natural gas used. Therefore, throughout the entire product life cycle from raw material acquisition through production, use, disposal at the end of product life, including the recycling and the final disposal (from cradle to grave) it is important to perform efficient sorting of related waste such as the product packaging.

The results of this years of research for this case study show that the correct operation setting of the waste processing, utilising the principle of logistics and modern technologies, whilst adhering to current legislation for the field of waste can lead to achieving a sustainable development of the environment within the given region.

The results of mathematical statistics show that there is a direct relationship between the amount of incinerated waste (negative aspect) and the production of electricity (positive), but also the amount of heat produced (positive) and the amount of produced flue gas and ash (negative aspect).

The environmental assessment is an important step in building and implementing Environmental Management System (EMS), which consists of the development and evaluation of the analysis followed by the adoption of measures to remedy the deficiencies. The aim of the analysis of the environmental situation within the region of the case study company is a fact-finding in the field of protection of environment that affects the production and non-production operations, and should be monitored:

– the manufacturing practice compliance of the company with the current legislation,
– the status of operational documentation,
– the status of internal and external communications in the area of the environmental protection,
– the responsibilities and liabilities between departments and employees.

Despite the amount of obtained results, there are still open question and topics for further research such as:

– What influence can have the combination of a climate change and the continuous waste incineration process on the population in the region?
– Will make the technological developments in the future possible to recover up to 100% of waste without the need of incineration?

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# Zastosowanie statystyk matematycznych do oceny procesu spalania odpadów

## Streszczenie

W artykule omówiono wpływ procesów spalania odpadów na środowisko w danym regionie za pomocą statystyk matematycznych. Obszar zainteresowania niniejszego studium przypadku uwzględnia aspekty praktycznego za-

stosowania powyższych metod i zasad w celu zmniejszenia wpływu na środowisko procesu spalania odpadów w konkretnym regionie. Współczynnik korelacji Pearsona $r_{xy}$ = 0,54 wskazuje, że istnieje umiarkowana liniowa zależność, wprost proporcjonalna, między ilością spalonych odpadów a ilością wytworzonego ciepła. Wyniki analizy statystycznej pokazują, że spalarnia w ciągu jednego roku generuje około 15 266 ton odzyskanych elementów plastikowych i elektrycznych, około 590 000 GJ energii, około 199 000 ton pary, 287 ton innych emisji przy zaledwie 3 miligramach dioksyn. Statystyka matematyczna służy do analizy, a następnie dostosowania i udoskonalenia procesu spalania odpadów w celu osiągnięcia pożądanych wartości parametrów, w szczególności wartości opałowej, ilości wytwarzanego ciepła i pary oraz zanieczyszczeń powietrza.

Wyniki statystyki matematycznej pokazują, że istnieje bezpośredni związek między ilością spalanych odpadów (aspekt negatywny) a produkcją energii elektrycznej (aspekt pozytywny), ale także ilością wytworzonego ciepła (aspekt pozytywny) i ilością wytworzonych gazów spalinowych i popiołów (aspekt negatywny).

Oceny środowiskowe są ważnym krokiem w budowaniu i wdrażaniu Systemu Zarządzania Środowiskiem, który polega na opracowaniu i ocenie analizy, a następnie przyjęciu środków mających zaradzić niedociągnięciom. Celem analizy sytuacji środowiskowej w regionie firmy ze studium przypadku jest ustalenie stanu faktycznego w zakresie ochrony środowiska, które ma wpływ na działalność produkcyjną i nieprodukcyjną. To powinno być monitorowane zgodnie z praktyką produkcyjną firmy oraz obowiązującym ustawodawstwem, stanem dokumentacji operacyjnej, stanem komunikacji wewnętrznej i zewnętrznej w zakresie ochrony środowiska, odpowiedzialności między działami i pracownikami.

## Abstract

The article deals with the research on the impacts of waste incineration processes on the environment within a particular region by the means of mathematical statistics. The area of interest for this case study considers the aspects of practical application of using the above methods and principles in order to reduce the environmental impacts of waste incineration process in the concrete region. The Pearson correlation coefficient $r_{xy}$ = 0.54 indicates that there is a moderate linear relationship, presented by a direct proportion between the values of incinerated waste quantity and the quantity values of produced heat. The statistics results show that the incineration during a one-year period produces about 15,266 tons of plastic and electrical components, and will release about 590,000 GJ of energy and about 199,000 tons of steam and 287 tons of other emissions with only 3 milligrams of dioxins. The mathematical statistics

is used to analyse, and subsequently adjust and improve the waste incineration process in order to achieve the desired parameter values, specifically the calorific values, the amount of heat produced, and the amount of generated steam and air pollutants.

The results of mathematical statistics show that there is a direct relationship between the amount of incinerated waste (negative aspect) and the production of electricity (positive), but also the amount of heat produced (positive) and the amount of produced flue gas and ash (negative aspect).

The environmental assessments are an important step in building and implementing Environmental Management System (EMS), which consists of the development and evaluation of the analysis followed by the adoption of measures to remedy the deficiencies. The aim of the analysis of the environmental situation within the region of the case study company is a fact-finding in the field of protection of environment that affects the production and non-production operations, and should be monitored the manufacturing practice compliance of the company with the current legislation, the status of operational documentation, the status of internal and external communications in the area of the environmental protection, the responsibilities and liabilities between departments and employees.

**Słowa kluczowe:**
spalanie odpadów, ocean wpływu na środowisko, statystyki matematyczne, analiza, dane

**Keywords:**
waste incineration, environmental impacts evaluation, mathematical statistics, analysis, data