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GEOSTATISTICAL MODEL (2D) OF THE SURFACE DISTRIBUTION OF ELECTRICITY TRANSMISSION MARGINAL COSTS

Abstract: The paper presents a surface model of the accounting costs of electricity transmission over the 220 kV and 400 kV networks. In the further stages of the studies, taking into account the results of structural analysis of marginal costs variation, an estimation technique, such as the ordinary (block) kriging, was used to build the model (2D). The model describes the area and time variation of marginal costs, and has great potential in the electrical power sector, especially in the context of the development of market mechanisms in electric energy trading. The model has made it possible to observe the existing tendencies in cost (directional and time) variation, which is useful for setting electricity transmission tariffs stimulating properly the behaviour of the electric power network users – the electricity suppliers and consumers. Thus, this way of stimulating takes into account the electric power network's specificity and operating conditions, including the network losses (caused by electricity transmission), the transmission constraints and the broadly understood operational safety of the electric power system. The model of the area variation of electricity transmission marginal costs is also useful in electric power system development planning procedures.

Keywords: marginal transmission costs, variation, electric energy, estimation, surface distribution costs, ordinary kriging.

1. Introduction

By creating models representing the observed reality, one can gain a deeper insight into the different phenomena involved. This particularly applies to the power industry because of the complexity of the correlations and interactions between the electricity generation and transmission technology and the consumption of electric energy in the conditions of developing market mechanisms. A model of nodal marginal prices makes it possible not only to faithfully represent the cost pattern, but also to apply a proper methodology of investigating and analyzing cost values variation and the directionality of variation trends, using geostatistics. Spatial analyses of costs distribution were carried out to confirm the viability of using nodal electricity transmission prices instead of a transmission tariff uniform for the whole country.

2. Investigative methodology

This paper proposes the geostatistical methods and procedures which were used here to analyze spatially correlated data on marginal transmission costs. The distinguishing feature of the proposed methodology is the use of the isotropic variogram and the directional variogram functions for the quantitative representation and modelling of the spatial structure of the studied process, i.e. cost values variation [5]. Then the geostatistical studies, i.e. estimation (2D) of cost averages Z^* was carried out using ordinary (block) kriging [5]¹.

Estimation of surface distribution of estimated cost averages Z^* by means of ordinary (block) kriging technique

Kriging is a technique of interpolation performed using the weighted average. In the process of kriging, a set of weights assigned to the values of the analyzed variable (samples, cost measurements) minimizes the estimation variance (kriging variance) calculated as a function of the assumed variogram model and the position of the samples relative to each other and to the point or block being the subject of estimation [1–4]. Kriging is used for local estimation purposes only if data from the nearest neighbourhood are taken into account.

In practice, the ordinary (point or block modification) procedure is most often used. In this study, the block kriging technique was used to estimate the block average of costs values Z^* for the node of a regular elementary grid (the centre of a block), as weighted average Z^* of sample values coming from a local neighbourhood – a sample search area or the centre of an ellipse, or a circle – situated in a block. Simultaneously, with each estimated average Z^* (kriging estimate) a standard estimation deviation – kriging deviation s_k or kriging variance s_k^2 – is calculated.

Weighted (moving) cost average Z^* is estimated using the following relation:

$$Z_k^* = \sum_{i=1}^n w_{ik} z_i, \quad (1)$$

where: z_i – a cost value in point i , for $i = 1, \dots, n$;

w_{ik} – a kriging weight coefficient assigned to sample i .

By employing the so-called kriging estimation system, one determines kriging weight coefficients w_{ik} assigned to the sample data within the estimated area and in its vicinity. Then the average error, called a kriging error, can be calculated. The variance of this error is given by the formula:

$$\sigma_k^2 = \sum w_i \bar{\gamma}(S_i, A) + \lambda - \bar{\gamma}(A, A), \quad (2)$$

where: $\bar{\gamma}(A, A)$ – the variogram average between each two points of block A .

¹ The statistical and geostatistical analyses were carried out using selected computing programs included in the ISATIS software package – version 2012.4, dongle for Isatis (ISATIS Isatis Software Manual. Geovariances & Ecole Des Mines de Paris, Avon Cedex, France) (January, 2001, p. 531).

The kriging variance value depends on the position of the samples relative to the location which is to be estimated and on the parameters of the adopted variogram model.

Ordinary kriging is one of the simplest and most powerful kriging techniques capable of tolerating extreme data distribution skewness before the latter diminishes. Kriging with unknown average m is called ordinary kriging. A constraint that the sum of the weights directly assigned to samples should be equal to 1 is imposed in ordinary kriging. Ordinary kriging should be applied only to stationary processes.

Block kriging is usually ordinary kriging with linear averages used to estimate a regionalized variable when the estimate's support (n) represents a larger block than the sample's support. Ordinary kriging can be used to estimate a block value in the block's centre, instead of a point value in a point. The block value is estimated on the basis of point value

$$Z_{vo}^* = \sum_{\alpha=1}^n w_{\alpha} Z(x_{\alpha}). \quad (3)$$

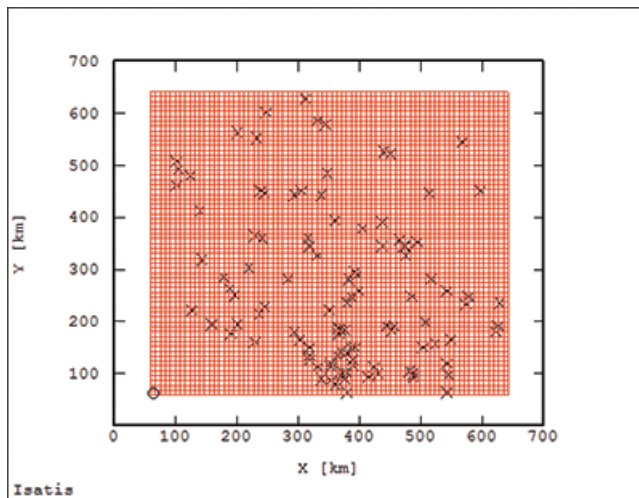


Figure 1. Elementary grid adopted for kriging computations; elementary block: 0.0025 [km] \times 0.0025 [km] and number of grid nodes = 4599: 73 along X-axis, 63 along Y-axis

Source: own calculations.

A grid of elementary square blocks with an elementary block surface area of 0.0025 km², covering the area of the whole country (Figure 1) was adopted for kriging computations.

3. Results of estimating surface distribution of marginal electricity transmission costs

Averages Z^* and estimation standard deviation σ_k of marginal costs were estimated for 4599 nodes of the elementary grid covering the whole area of the country (Figure 1) (Tables 1–4). The unique neighbourhood (a sample search sub-area) and the moving neighbourhood were taken into account in the kriging computations (Figures 2, 3, 5, 6, 8, 9, 11, 12).

A comparison of the global statistics results for the summer season shows slightly lower Z^*_{\min} and Z^*_{\max} values (for the night off-peak period and the morning peak) and slightly higher standard deviations for estimated averages Z^* and variation coefficients V (for the summer night off-peak period) when the moving neighbourhood was used (Table 1). In the case of the summer morning peak, lower Z^*_{\min} , Z^*_{\max} values and average $\overline{\overline{Z^*}}$ were obtained when the moving neighbourhood was used (Table 1). Averages $\overline{\overline{Z^*}}$ are almost identical for the same time moments of the analysed seasons.

Table 1. Global statistics of estimated averages Z^* of marginal costs in nodes of 220 kV and 400 kV networks for the summer season of 2000

Analyzed parameter	Z^*_{\min} [PLN/MWh]	Z^*_{\max} [PLN/MWh]	Average $\overline{\overline{Z^*}}$ [PLN/MWh]	Standard deviation S [PLN/MWh]	Variation coefficient V [%]	Skewness g_1	Kurtosis g_2
Summer night off-peak period*	35.17	39.14	37.55	0.92	2.00	-0.23	2.06
Summer night off-peak period**	35.16	39.11	37.55	0.94	3.00	-0.22	1.97
Summer morning peak*	49.87	54.87	52.96	1.44	3.00	-0.57	2.12
Summer morning peak**	49.68	55.34	52.93	1.44	3.00	-0.50	2.13

* – unique neighbourhood, ** – moving neighbourhood.

Source: own calculations.

Higher minimal Z^*_{\min} , maximal Z^*_{\max} values of estimated averages Z^* , average $\overline{\overline{Z^*}}$ and the standard deviation are characteristic of the summer morning peak (Table 1). The very low negative values of skewness coefficient g_1 for the distributions of averages Z^* indicate that the latter are slightly underestimated (Table 1). The distributions of averages Z^* are flattened, which is confirmed by the very low values of kurtosis coefficient g_2 .

Similar conclusions as for the summer season emerge from an analysis of the kriging computation results for the winter season (Table 2). When the moving neighbourhood is taken into account in the computations, lower values of Z^*_{\min} , Z^*_{\max} , of the average \bar{Z}^* and the slightly lower values of the standard deviation and the identical value of variation coefficient V are obtained. Higher values of Z^*_{\min} , Z^*_{\max} and of the average of averages \bar{Z}^* and lower values of the standard deviation and of cost variation coefficient V are a characteristic of the winter morning peak, whereas the higher values of the standard deviation and coefficient V were obtained for the winter night off-peak period.

The low positive skewness coefficients g_1 of the distributions of averages Z^* (except for the winter morning peak) indicate that the latter were slightly overestimated and, in the case of the winter morning peak, quite accurately estimated (Table 2). Similarly as in the case of the summer season, the very low values of kurtosis coefficient g_2 indicate that the histograms are flattened.

A comparison of the computed global statistics of estimated cost averages Z^* (Tables 1, 2) and the basic statistical parameters of original costs Z (Part I., Tables 1, 2) shows good agreement between the values, regardless of the neighbourhood used. To sum up, the results of the computations carried out using the moving neighbourhood are more accurate (close to the real costs), especially for the winter season.

Table 2. Global statistics of estimated averages Z^* of marginal costs in nodes of 220 kV and 400 kV networks for the winter season of 2000

Analyzed parameter	Z^*_{\min} [PLN/MWh]	Z^*_{\max} [PLN/MWh]	Average \bar{Z}^* [PLN/MWh]	Standard deviation S [PLN/MWh]	Variation coefficient V [%]	Skewness g_1	Kurtosis g_2
Winter night off-peak period*	53.34	64.09	57.14	2.96	5.00	0.53	2.06
Winter night off-peak period**	51.77	62.93	56.99	2.87	5.00	0.37	1.75
Winter morning peak*	56.66	64.30	60.42	2.08	3.00	-0.09	1.78
Winter morning peak**	56.18	66.16	60.39	2.16	4.00	4.00	1.90

* – unique neighbourhood, ** – moving neighbourhood.

Source: own calculations.

Two very extensive sub-areas of respectively the highest and lowest averages Z^* (38.13÷39.11 PLN/MWh; 35.18÷36.65 PLN/MWh), and a band of intermediate values of Z^* (38.13÷36.65 PLN/MWh) are visible on the raster map of the surface distribution of estimated cost averages Z^* for the summer night off-peak period (Figures 2, 3). The boundaries of the ranges of averages Z^* are very similar for the

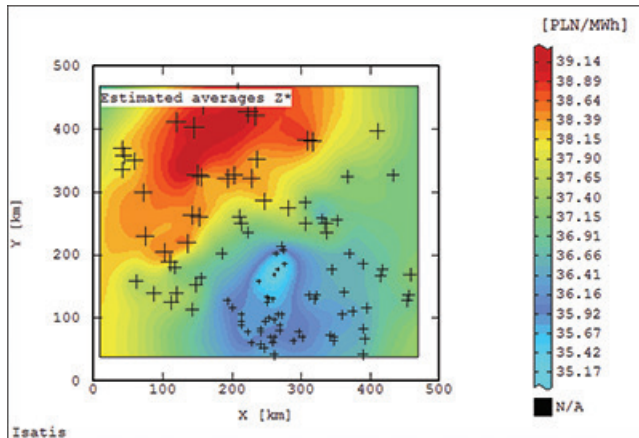


Figure 2. Raster map of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for summer night off-peak period (*unique neighbourhood – sample search sub-area*)

Source: own calculations.

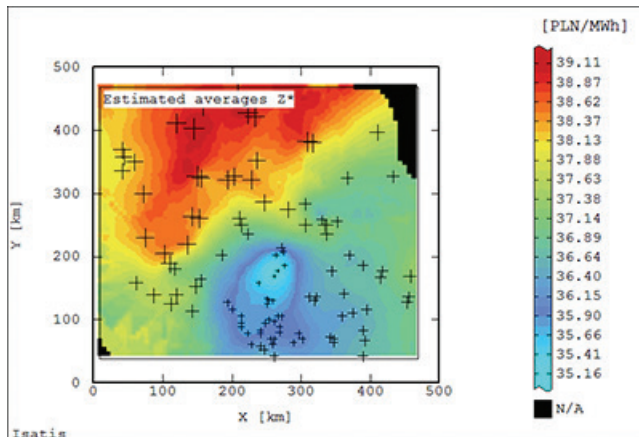


Figure 3. Raster map of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for summer night off-peak period (*moving neighbourhood – sample search sub-area*)

Source: own calculations.

two neighbourhoods used in kriging, becoming less smooth and more irregular in the case of the moving neighbourhood (Figures 2, 3).

When the moving neighbourhood (Figure 3) was used, a sub-area with the highest averages Z^* and with the smaller surface area and a different shape than the one obtained in the case of the unique neighbourhood appeared (Figure 2), whereas the sub-area with the lowest averages Z^* was more pronounced and had a larger surface area.

The above ranges of cost averages Z^* for the summer night off-peak period, visible on the raster maps (Figures 2, 3), are clearly reflected by the histogram of the distribution of estimated averages Z^* (Figure 4) computed using the moving neighbourhood. The classes ranges comprising the maximum averages Z^* (38.35÷38.61 [PLN/MWh]) and lower averages Z^* (36.74÷37.00 [PLN/MWh]) have very large shares.

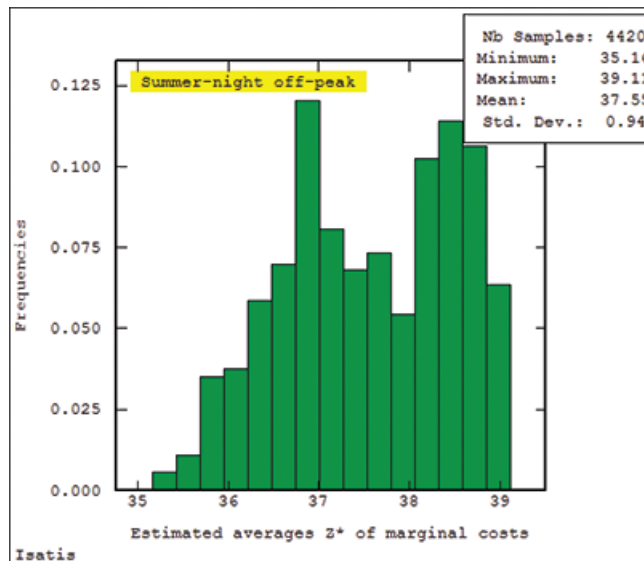


Figure 4. Histogram showing distribution of estimated averages Z^* of marginal costs [PLN/MWh] nodes of 220 kV and 400 kV networks for summer night off-peak period (moving neighbourhood)

Source: own calculations.

On the raster maps of the distribution of cost averages Z^* for the summer morning peak, calculated using the unique neighbourhood (Figure 5), one can discern two very distinct centres, being sub-areas with the highest and lowest averages Z^* (53.62÷54.87 PLN/MWh; 49.87÷51.43 PLN/MWh), and a band of intermediate values Z^* (51.43÷53.62 PLN/MWh). The boundaries of the ranges of averages Z^* do not show similarity for the two neighbourhoods used (Figures 5, 6), as was observed on the map for the night off-peak period (Figures 2, 3).

The raster map computed using the moving neighbourhood shows a slightly smaller, more irregular sub-area with maximum averages Z^* (Figure 6). The shape of the sub-area with lowest averages Z^* is even more irregular. The calculated ranges of estimated costs averages Z^* are: 53.93÷55.34 PLN/MWh (maximum Z^* values), 49.68÷51.80 PLN/MWh (minimum Z^* values) and 51.80÷53.93 PLN/MWh (intermediate Z^* values). The boundaries separating the sub-areas of Z^* values are irregular (Figure 6) and not as smooth as the ones on the map computed using the unique neighbourhood (Figure 5).

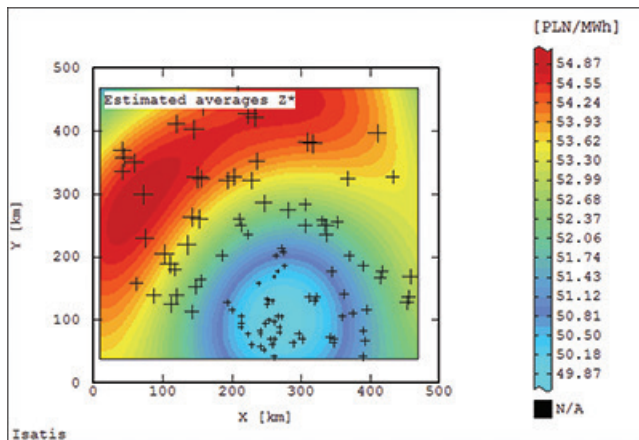


Figure 5. Raster map showing distribution of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for the summer morning peak (*unique neighbourhood – sample search area*)

Source: own calculations.

In the case of the summer night off-peak period, the distribution of cost values is similar, but the sub-area of the highest averages Z^* covers the Pomeranian Province, the West-Pomeranian Province, the west part of the Warmian-Masurian Province and the northern parts of: the Kuyavian-Pomeranian Province, the Greater Poland Province and the Lubusz Province (Figures 2, 3). The sub-area where minimum costs Z^* occur is much narrower than in the morning peak and it is situated in the Silesian Province and the S part of the Łódź Province.

The maximum cost level (estimated averages Z^*) in the summer morning peak occurs in the northern belt of Poland, which also includes the Greater Poland Province and Lubusz Province (Figures 5, 6). The minimum level of costs Z^* in this period occurs in the Silesian Province and partly in the Lesser Poland Province.

The above cost sample subpopulations are very distinct in the histogram of averages Z^* computed using the moving neighbourhood (Figure 7). One can discern the primary modal class, comprising the maximum Z^* values (54.20÷54.60 [PLN/MWh]), with the largest share in the histogram, a secondary classes comprising intermediate Z^* values (52.33÷52.66 [PLN/MWh]), with a much smaller share, and a class range comprising the lowest Z^* values (50.40÷50.80 [PLN/MWh]), with a twice smaller share in comparison with the previous class.

In another map, computed using the moving neighbourhood (Figure 9), the sub-area with maximum Z^* values (60.63÷62.59 [PLN/MWh]) is more extensive, has a larger surface area and extends along the same line (W-E) as above. The area with minimum Z^* values (52.18÷55.40 [PLN/MWh]) extends along the NE-SW line. The sub-area with intermediate Z^* values represents a Z^* values range of 55.40÷60.63

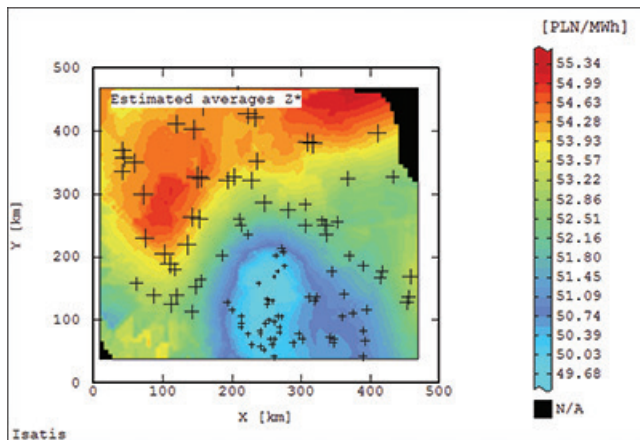


Figure 6. Raster map showing distribution of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for the summer morning peak (*moving neighbourhood – sample search area*)

Source: own calculations.

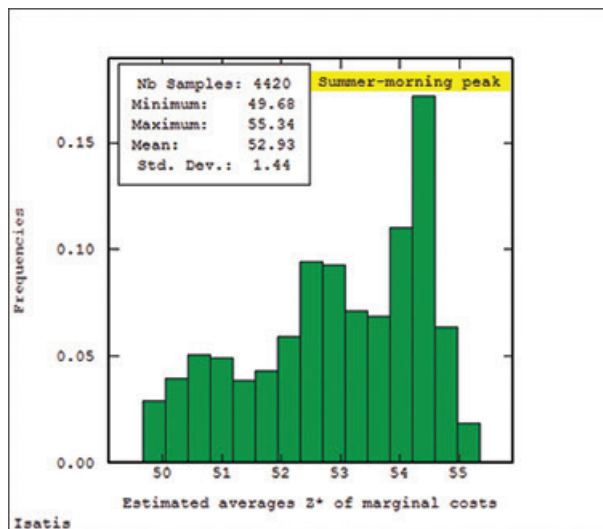


Figure 7. Histogram showing distribution of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for the summer morning peak (*moving neighbourhood*)

Source: own calculations.

[PLN/MWh]. Generally, averages Z^* are slightly lower than the ones obtained when the unique neighbourhood was used (Figure 8).

On the raster map showing the distribution of estimated cost averages Z^* for the winter night off-peak period, computed using the unique neighbourhood (Figure 8),

one can see two sub-areas: a sub-area with maximum Z^* values (61.40÷64.09 [PLN/MWh]), located along the W-E line and a sub-area with minimum Z^* values (53.34÷56.70 [PLN/MWh]), extending in the ENE-WSW direction (Figure 9). A sub-area containing intermediate Z^* values (56.70÷61.40 [PLN/MWh]) is situated between the two above mentioned sub-areas.

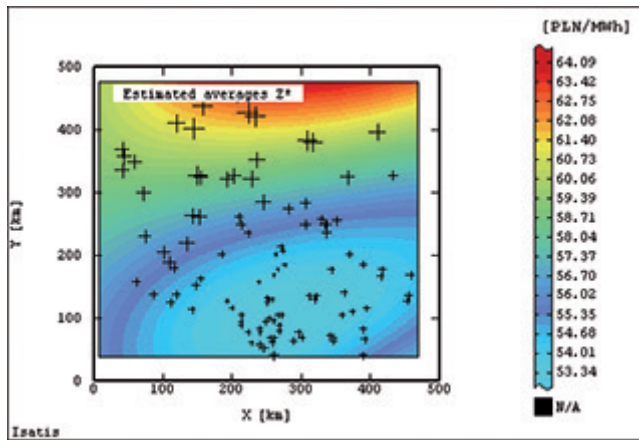


Figure 8. Raster map showing distribution of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for the winter night off-peak period (*unique neighbourhood – sample search area*)

Source: own calculations.

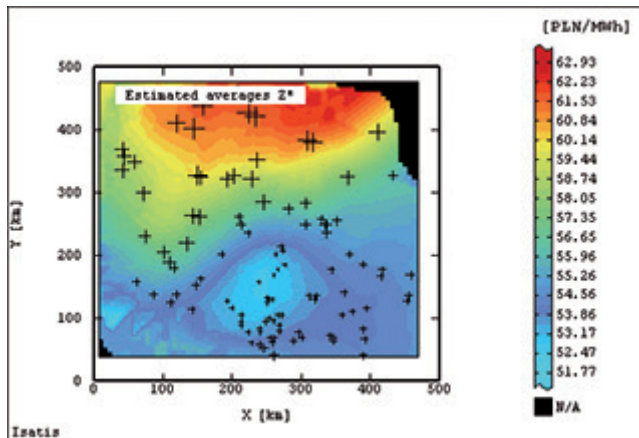


Figure 9. Raster map showing distribution of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for the winter night off-peak period (*moving neighbourhood – sample search area*)

Source: own calculations.

In the histogram showing the distribution of estimated averages Z^* , computed using the moving neighbourhood (Figure 10), there is one modal class having the largest share – a range comprising the lower values of Z^* (53.88÷54.63 [PLN/MWh]), and other secondary classes containing higher values of Z^* , having equal shares.

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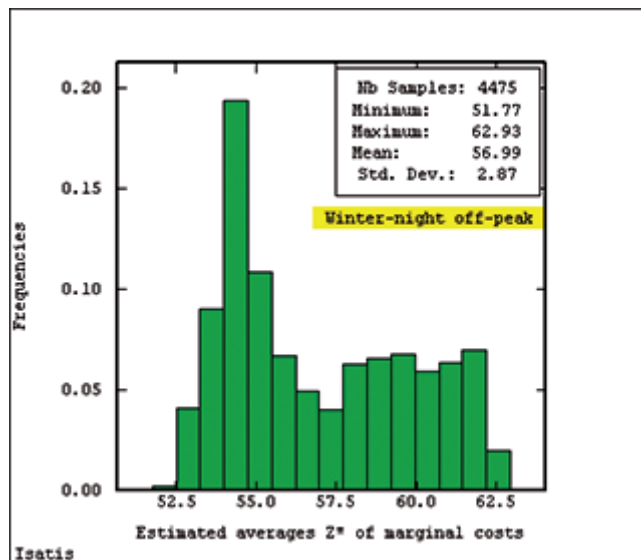


Figure 10. Histogram showing of distribution of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for the winter night off-peak period (*moving neighbourhood*)

Source: own calculations.

The raster maps of the distribution of estimated cost averages Z^* , computed for the winter morning peak, show images differing in the surface area, shape and situation of the sub-areas, comprising respectively maximum and minimum averages Z^* , for the two types of neighbourhood (Figures 11, 12). The large sub-area with the highest cost averages Z^* (62.39÷64.30 PLN/MWh), visible on the map computed using the unique neighbourhood (Figure 11), extends along the ENE-WSW direction. The sub-area comprising the lowest Z^* values, being within a range of 56.66÷59.05 PLN/MWh, extends along the NE-SW line. Intermediate cost values Z^* , ranging from 59.05 to 62.39 PLN/MWh, occur between the two sub-areas.

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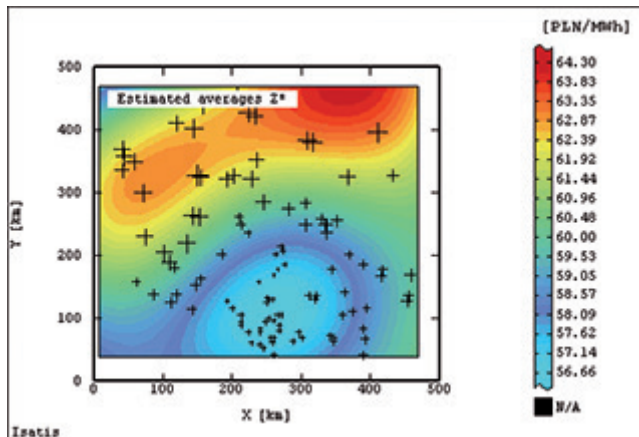


Figure 11. Raster map showing distribution of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for the winter morning peak (*unique neighbourhood – sample search area*)

Source: own calculations.

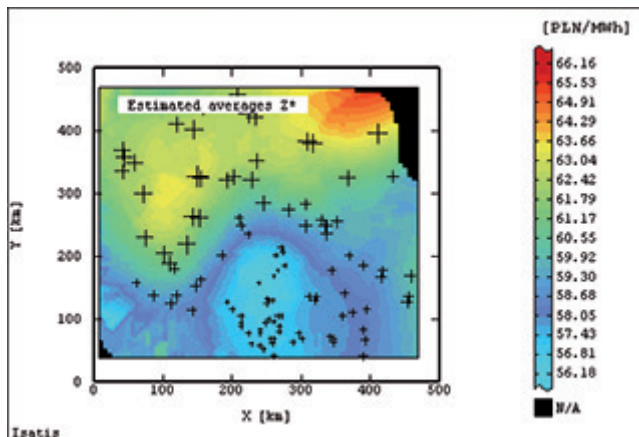


Figure 12. Raster map showing distribution of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for the winter morning peak (*moving neighbourhood – sample search area*)

Source: own calculations.

a range of 56.66÷59.05 PLN/MWh, extends along the NE-SW line. Intermediate cost values Z^* , ranging from 59.05 to 62.39 PLN/MWh, occur between the two sub-areas.

On the raster map computed using the moving neighbourhood (Figure 12) one can discern a small sub-area comprising maximum average costs Z^* (64.29÷66.16 [PLN/MWh]), which occurs in the NE part of the country and extends along the W-E line, deviating towards ENE-WSW. The sub-area is situated within a large extensive area containing intermediate cost values Z^* (ranging from 61.79 to 63.66 [PLN/MWh]), extending along the NE-SW direction. Another sub-area, extending along the N-S line, comprises the lowest cost values Z^* ranging from 56.18 to 59.30. Slightly higher (maximum and intermediate) Z^* values, in comparison with the case when unique neighbourhood was used (Figure 11), were obtained using the moving neighbourhood (Figure 12).

As already mentioned, the boundaries between the sub-areas on the map computed using the moving neighbourhood are more distinct and show the variation in the costs in more detail (Figure 12). Whereas on the map computed using the unique neighbourhood such boundaries are smoother (Figure 11).

In the histogram of the distribution of estimated cost averages Z^* computed using the moving neighbourhood (Figure 13) modal class with the highest Z^* values (62.16÷62.84 [PLN/MWh]) and intermediate cost values Z^* (58.86÷59.43 [PLN/MWh]) clearly stand out.

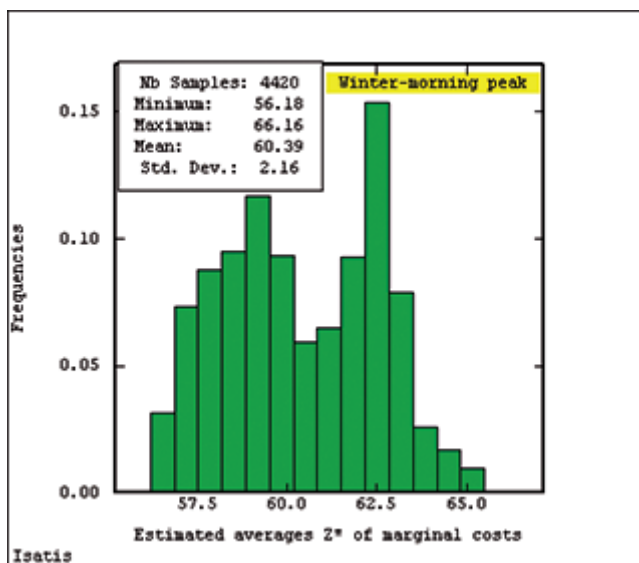


Figure 13. Histogram showing distribution of estimated averages Z^* of marginal costs [PLN/MWh] in nodes of 220 kV and 400 kV networks for the winter morning peak

Source: own calculations.

The raster images of the distribution of electricity transmission costs indicate a distinct shift in the maximum and minimum cost levels in the winter season (Figures 8, 9, 11, 12). In the winter morning peak the maximum level of costs Z^* occurred in the NE part of the country – in the Warmian-Masurian Province (Figures 11, 12). Whereas the minimum level of costs Z^* was found to occur within the area of the Silesian Province and the Lesser Poland Province. In the winter night off-peak period the sub-area with the highest averages Z^* covers the northern part of the country (the Warmian-Masurian Province, the Pomeranian Province and the eastern part of the West Pomeranian Province) (Figures 8, 9). The sub-area of minimum Z^* values is limited to the area of the Silesian Province, the southern part of the Łódź Province and the western part of the Lesser Poland Province (Figures 11, 12).

To sum up, one should emphasize that in the case of the moving neighbourhood the boundaries of the sub-areas comprising respectively the highest and lowest cost values Z^* are more accurate, reflecting the variation in the costs in more detail. Moreover, the surface areas of such sub-areas are markedly smaller.

4. Conclusions

A model of the distribution of electricity marginal costs for the area of Poland has been created. The 2D geostatistical model of cost variation made it possible to obtain accurate characteristics of the parameter values for the whole area of Poland for two time instants in the summer and winter seasons in the year 2000. The isotropic variogram function, the directional variogram function and the ordinary kriging procedure were used to build the model. This model made it possible to determine estimated averages Z^* (together with the corresponding value of estimation standard deviation σ_k) in the particular nodes of the two-dimensional grid covering the area of the country and in selected points within this area at a given time.

The proposed methodology constitutes a new approach to the characterization and analysis of network operating conditions for the purposes of network development and designing tariffs. It enables one to indicate locations for new generating and consuming nodes and electric power network connections.

The surface estimation of the costs gives an objective picture of their variation in the particular places of the electric power network, and as the results of the computations show, the costs vary considerably across the country. At the same time, it becomes apparent that the electricity transmission tariff with equal rates for the whole area is a faulty approach to transmission service billing. A much better solution is the nodal tariff, which reflects the actual costs occurring in the particular nodes of the transmission network, or the so-called layered tariff proposed by the authors in [6; 7]. Such transmission tariffs stimulate properly the behaviour of the network users (electricity consumers and producers), contributing to, among other things, the elimination of network constraints and the reduction of transmission losses.

In the dynamically changing electricity market conditions, the use of the surface methods of estimating marginal costs is one of the factors minimizing the system costs of electricity supply. The proposed methods can be useful for the planning of investments in the electric power network infrastructure.

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MODEL GEOSTATYSTYCZNY (2D) POWIERZCHNIOWEGO ROZKŁADU KOSZTÓW MARGINALNYCH PRZESYŁU ENERGII ELEKTRYCZNEJ

Streszczenie: W artykule przedstawiono sposób budowy powierzchniowego modelu kosztów krańcowych przesyłu energii elektrycznej siecią 220 kV i 400 kV. Wykorzystując rezultaty analizy strukturalnej zmienności kosztów, zastosowano estymacyjną technikę krigingu zwyczajnego (blokowego). Opracowany model opisujący zmienność obszarową i czasową kosztów marginalnych ma duże walory aplikacyjne w sektorze elektroenergetycznym, szczególnie w sytuacji rozwijania mechanizmów rynkowych w obrocie energią elektryczną. Model ten umożliwił zaobserwowanie istniejących tendencji zróżnicowania kosztów – czasowej i kierunkowej, co jest przydatne w tworzeniu taryf przesyłowych energii elektrycznej, właściwie stymulujących postępowanie użytkowników sieci elektroenergetycznej – dostawców oraz konsumentów energii elektrycznej. Taki sposób stymulowania uwzględnia wówczas specyfikę i warunki pracy sieci elektroenergetycznej, w tym straty sieciowe, spowodowane przesyłem energii, ograniczenia przesyłowe i szeroko rozumiane bezpieczeństwo pracy systemu elektroenergetycznego. Model obszarowej zmienności kosztów marginalnych przesyłu energii elektrycznej jest również przydatny w planowaniu rozwoju systemu elektroenergetycznego.

Słowa kluczowe: koszty krańcowe przesyłu, zmienność kosztów, energia elektryczna, estymacja powierzchniowego rozkładu kosztów, kriging zwyczajny (blokowy).