19th International CODATA Conference
THE INFORMATION SOCIETY: NEW HORIZONS FOR SCIENCE
Berlin, Germany 7 - 10 November 2004

SPATIAL ELECTRICAL LOADS MODELING USING THE GEOSTATISTICAL METHODS

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1. INTRODUCTION

Spatial modeling and prediction of electrical loads are key elements in planning the development and operation of power transmission and distribution networks [9]. The effectiveness, economy and reliability of operation of the power system depend on the choice of equipment and its location in the areas where there is demand for electricity. The role of spatial modeling of electrical loads is particularly important now when a competitive energy market is being developed.

2. SUBJECT AND SCOPE OF STUDY

Estimation kriging techniques were applied to process and analyze data on electrical loads measured at high voltage network nodes 220 and 400 kV (1 variant) [2, 3] and in 110 kV network nodes (2 variant) for the area of Poland. The loads were for characteristic moments in time, i.e. 3:00 a.m. and 11:00 a.m. in the summer season and 3:00 a.m., 11:00 a.m. and 17:00 p.m. in the winter season of 2001. Two kinds of databases were created, containing the values of geographic coordinates X and Y, specifying measurement taking locations, and the power values and the successive numbers of the measurements. The results of complex geostatistical studies have been presented in the reports [2, 3].

The selected results connected with superficial modeling of electrical loads performed for the 110 kV network nodes for one moment in time, i.e. 11:00 a.m. for the both seasons were presented in this paper.

3. RESEARCH METHODS

The variogram function was used for the spatial modeling of the electrical loads and then different kriging estimators, such as ordinary kriging, simple kriging with a local mean and lognormal kriging (in their block modification) were applied to estimate the areas of average loads [1, 8].

Estimator of ordinary (block) kriging:

$$Z_{V_0}^{*} = \sum_{\alpha=1}^{n} w_\alpha Z(x_\alpha), \tag{1}$$

where:
w_α – weight coefficient of kriging,
$Z_{V_0}^{*}$ – a block value of analysed parameter from point values $Z(x_\alpha)$;

The corresponding ordinary (block) variance:

$$\sigma_{BOK}^2 = -\lambda_{BK} - \bar{\gamma}(V_0, V_0) + 2\sum_{\alpha=1}^{n} w_\alpha^{BK} \bar{\gamma}(X_\alpha, V_0) \tag{2}$$

where:
λ_{BK} – Lagrangian multiplier,
$\bar{\gamma}(V_0, V_0)$ - average value of variogram function between all possible combinations of points within the block V_0,
$\bar{\gamma}(X_\alpha, V_0)$ – average value of variogram function between sample point X_α and the block of interest V_0.

Estimator of simple (block) kriging with an estimated mean M:

$$Z_{BSK}^{*}(x_0) = \sum_{\alpha=1}^{n} w_\alpha Z(x_\alpha), \tag{3}$$

$$\overline{w} = 1 - \sum_{\alpha=1}^{n} w_\alpha^{SK}, \tag{4}$$

$$\sigma_{BOK}^2 = \sigma_{BSK}^2 + \overline{w}^2 \sigma_{KM}^2, \tag{5}$$

where:
$\overline{w}$ - weight of the mean,
w_α^{SK} - the simple kriging weights,
$\sigma_{BOK}^2 \mapsto \sigma_{KM}^2$ for $|V| \mapsto \infty$

Estimator of lognormal (block) kriging

The lognormal variable is assumed to be a log – transformed quantity

$$Y^* = \sum_{\alpha=1}^{n} w_\alpha Y_\alpha + \left(1 - \sum_{\alpha=1}^{n} w_\alpha\right) m_Y \,, \qquad (6)$$

where:
m_Y – mean of log – variable,
Y^* - the estimation of the back – transformed variable,
Y_α - information at the data points;

$$\hat{\sigma} = \frac{\sigma_Z}{M_Z + \beta} \,, \qquad (7)$$

where:
M_Z – mean of the raw punctual (original) variable,
β - shift, which makes *Z* a positive variable and *Y* is supposed to be normally distributed: $Y = \log(Z + \beta)$,
σ_Z - standard deviation of estimation for original variable,
$\hat{\sigma}$ - the corresponding relative standard deviation of estimation.

The kriging system was performed in the intrinsic case (ordinary kriging) then honoring the condition $\sum_\alpha w_\alpha = 1$ though a Lagrange parameter λ.

The average electrical loads were estimated using a grid of 10 km x 10 km elementary blocks, covering the whole area of Poland. 5775 coordinates X and Y, 5775 estimated averages Z* and 5775 standard deviations of estimation σ_k and $\hat{\sigma}$ were calculated for the block centers. As results new data bases containing the results of estimation, i.e. estimated averages Z* and values of standard deviation of estimation σ_k, together with the calculated coordinates X and Y for the grid nodes were created.

4. EVALUATION OF BASIC STATISTICS

Generally the values of means $\bar{x}$, maximum values $x_{\max}$, standard deviations S', coefficients of variation V increase, shifting from 3:00 am in the summer period to 17:00 pm in the winter period[1]. The results of kriging calculations performed for 3:00 am in the winter period are different. Values of the statistics $\bar{x}$, $x_{\max}$, S', and V are lower in comparison to the results concerning the summer 11:00 am.

[1] Basic statistics calculations and geostatistical analyses were performed using the software package ISATIS, version 5.0.2. 2004, by Geovariances – Avon Cedex and Ecole des Mines de Paris, France.

Table 1

Basic statistical parameters of loads at the network nodes 110 kV (2001 year)

Analysed period	Size n	Minimum value $X_{\min}$ [MW]	Maximum value $X_{\max}$ [MW]	Mean value $\overline{X}$ [MW]	Standard deviation S [MW]	Coefficient of variation V [%]	Skewness G	Kurtosis K
Summer 3:00 am	1025	0.08	146.51	6.81	14.43	211.86	5.86	42.02
Summer 11:00 am	1022	0.10	253.40	11.67	22.60	193.65	6.01	45.72
Winter 3:00 am	1029	0.11	243.40	10.85	19.98	184.05	5.74	44.06
Winter 11:00 am	1029	0.12	290.69	15.37	28.28	183.98	6.07	46.58
Winter 17:00 pm	1028	0.11	300.93	16.73	30.71	183.59	6.15	46.66

5. RESULTS OF STRUCTURAL ANALYSIS

Variogram function γ(h) was applied for determining isotropic empirical variograms calculated from the data on the power in the nodes of the 110 kV network for the summer and winter seasons for one moment in time i.e. 11:00 a.m. (figs. 1 – 4). Deeper analysis of variograms for other characteristic moments in time was discussed in the reports and research work [2, 3, 5].

A characteristic feature of the empirical variograms is the high percentage of random component U_L (the nugget effect) in the general load variability. U_L ranged from 81.93% (winter) to 83.99% (summer) for the considered moment in time (11 a.m.) After logarithmic transformation the U_L values were slightly lower than the results for the original data, ranging from 70.65% (winter) to 74.16% (summer). This character of the variograms could be due to the large and diverse sampling population, covering the whole area of Poland, which was used to calculate function γ(h). It seems that the power variability structure can be more accurately identified on the basis of variograms if smaller areas, characterized by lower differentiation of nodal power, are analysed.

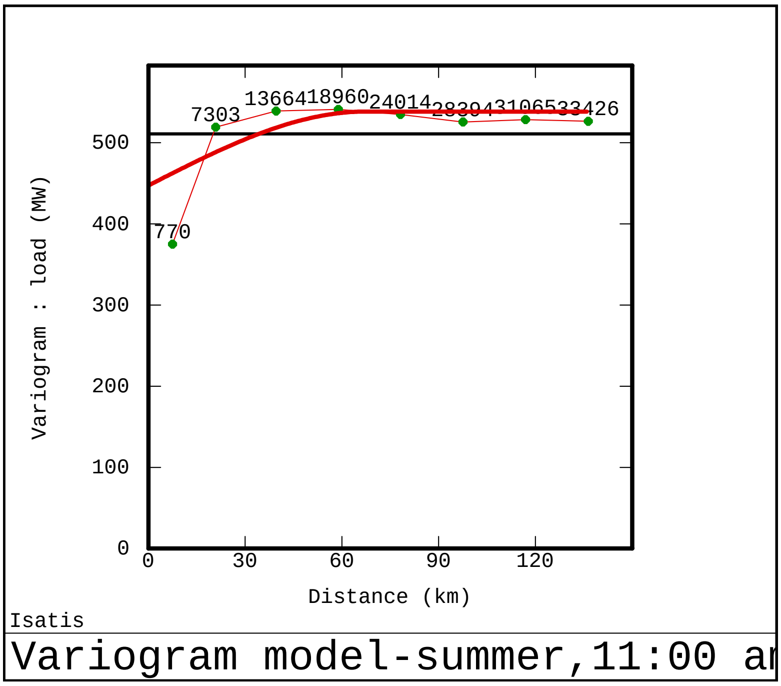

Fig. 1. Empirical variogram of the loads $[MW]^2$ at the 110 kV network nodes, fitted by theoretical model - summer, 11:00 a.m. (for the area of Poland).

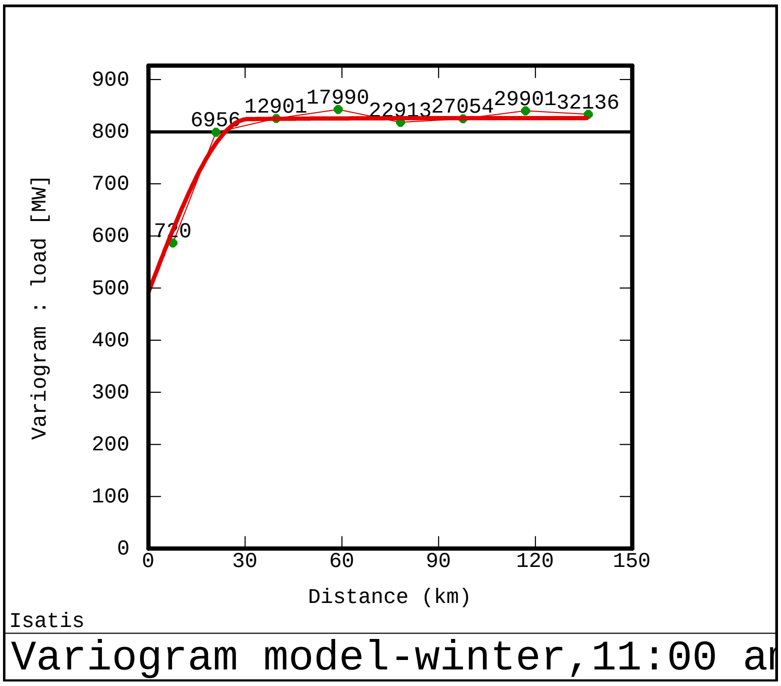

Fig. 2. Empirical variogram of the loads [MW]^2 at the 110 kV network nodes, fitted by theoretical model - winter, 11:00 a.m. (for the area of Poland);

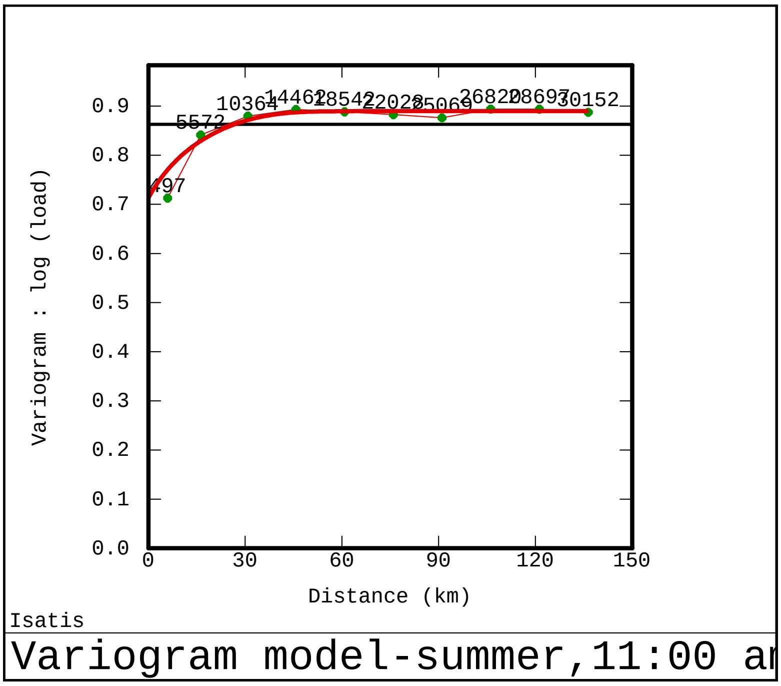

Fig. 3. Empirical variogram of the (log) loads [MW]^2 at the 110 kV network nodes, fitted by theoretical model - summer, 11:00 a.m. (for the area of Poland);

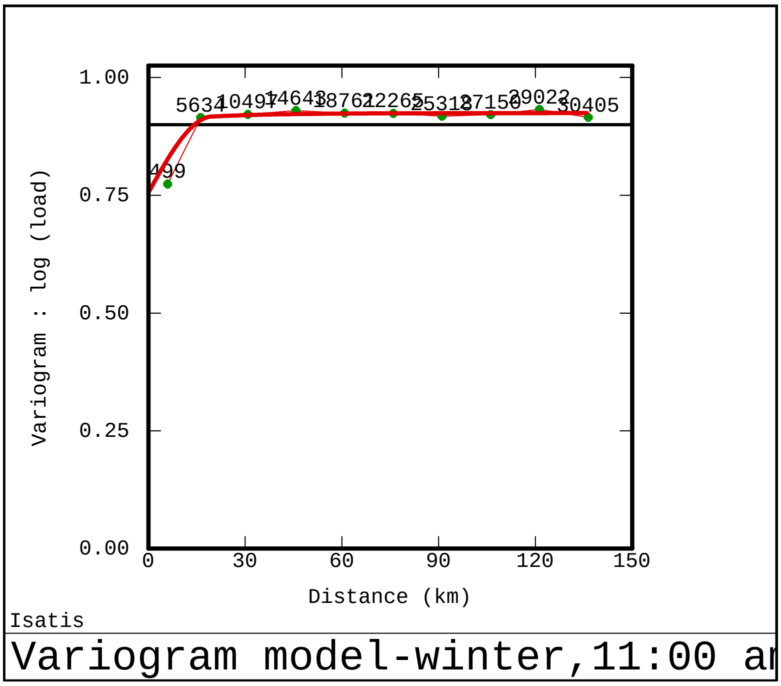

Fig.4. Empirical variogram of the (log) loads $[MW]^2$ at the 110 kV network nodes, fitted by theoretical model - winter, 11:00 a.m. (for the area of Poland);

Table 2

Values of the parameters of variograms geostatistical models for the loads at the 110 kV network *(original data)*

Analysed period	**Nugget efect C_0 $[MW]^2$**	**Variance C' $[MW]^2$**	**Total sill variance $C=C_0+C'$ $[MW]^2$**	**Range of influence a [km]**	**Applied model**
Summer 11:00 am	447.26	91.04	538.30	101	Spherical with nugget effect
Winter 11:00 am	491.76	330.51 3.62	825.89	45 115	Spherical (1), spherical (2) plus nugget effect

Table 3

Values of the parameters of variograms geostatistical models for the loads at the 110 kV network *(transformed data on log values)*

Analysed period	**Nugget efect C_0 $[MW]^2$**	**Variance C' $[MW]^2$**	**Total sill variance $C=C_0+C'$ $[MW]^2$**	**Range of influence a [km]**	**Applied model**
Summer 11:00 am	0.71	0.12 0.05	0.88	52 101	Exponential (1), cubic (2), plus nugget effect
Winter 11:00 am	0.76	0.15 0.02	0.93	33 105	Spherical (1), spherical (2) plus nugget effect

6. PICTURES OF SUPERFICIAL VARIATIONS OF AVERAGE LOADS

The results of calculations performed using different estimation kriging techniques are presented in tables 4 ÷ 5.

For the summer season the averages calculated for the whole area of Poland ($\overline{X}$) using two kriging methods: ordinary kriging and simple kriging (with a local means) are almost identical (the difference amounts to 0.10 MW) (table 4). Lognormal kriging yielded a slightly lower average. A comparison of the minimum and maximum estimated averages Z* yielded by lognormal kriging with the respective results obtained by ordinary kriging and simple kriging showed larger differences**.** Lognormal kriging yielded higher minimum averages Z* and lower maximum averages Z*. The widest range between the minimum and maximum values Z* was obtained for simple kriging with a local average, which means that this technique yielded estimation results which best reflect the superficial changes of power. Estimation standard deviation averages σ_k are very similar for ordinary kriging and simple kriging (with a local means). The same applies to minimum and maximum values σ_k. The very low relative estimation standard deviations $\hat{\sigma}$ (table 4) are conspicuous. A comparison of the results obtained by ordinary kriging and simple kriging (with a local means) for the winter season shows similar regularities in the behaviour of the geostatistical parameters as for the summer season.

To sum up, simple kriging (with a local means) yielded the most reliable evaluations reflecting the extent of differentiation of the original data, regardless of the analysed season (tables 4 ÷ 5). The arithmetic means of the original load values, for both winter and summer, were almost identical with the mean calculated on the basis of averages Z* estimated by ordinary and simple kriging. Even though a comparison of the minimum and maximum estimated values Z* with the original ones showed more considerable differences, simple kriging better reflected the actual tendency in the set of original data. The results of the estimation of average loads might have been influenced by the kind of the adopted neighbourhood, i.e. the data search subarea. Since a unique neighbourhood was adopted, simple kriging (with a local means) yielded more reliable results, bringing out the local variability. The unique neighbourhood (in contrast to the moving neighbourhood) meant that each time all the data were to be taken into account in the estimation of the elementary grid's particular nodes, i.e. the centres of the elementary blocks.

Table 4

Global statistics of geostatistical parameters values of loads at the network nodes 110 kV for the summer, 11:00 am - 2001

Applied technique	Geostatistical parameter	Number of the elementary grid nodes n	Mean value $\overline{X}$ [MW]	Minimum value X_{min} [MW]	Maximum value X_{max} [MW]	Standard deviation S [MW]
Ordinary kriging	Estimated average Z^*	5775	11.36	3.60	38.27	4.09
	Standard deviation of estimation σ_k	5775	7.30	5.15	9.26	1.18
Lognormal kriging	Estimated average Z^*	5775	10.37	5.77	22.21	1.95
	Relative standard deviation of estimation $\hat{\sigma}$	5775	0.34	0.26	0.39	0.03
Simple kriging (with local means)	Estimated average Z^*	5775	11.26	2.28	46.99	5.29
	Standard deviation of estimation σ_k	5775	7.26	5.14	9.16	1.15

Table 5

Global statistics of geostatistical parameters values of loads at the network nodes 110 kV for the winter,11:00 am - 2001

Applied technique	Geostatistical parameter	Number of the elementary grid nodes n	Mean value $\overline{X}$ [MW]	Minimum value X_{min} [MW]	Maximum value X_{max} [MW]	Standard deviation S [MW]
Ordinary kriging	Estimated average Z^*	5775	15.30	3.72	118.70	8.17
	Standard deviation of estimation σ_k	5775	13.95	8.37	16.68	2.11
Lognormal kriging	Estimated average Z^*	5775	14.22	7.85	30.34	1.84
	Relative standard deviation of estimation $\hat{\sigma}$	5775	0.35	0.27	0.37	0.02
Simple kriging (with local means)	Estimated average Z^*	5775	15.23	-0.36	154.85	11.14
	Standard deviation of estimation σ_k	5775	13.92	8.37	16.63	2.09

6.1. Raster maps of the estimated averages Z* of the loads

The databases containing original values of load measurements were used in estimation by different kriging techniques (ordinary kriging, lognormal kriging, simple kriging with local means) whereby a set of raster maps of the estimation areas for the values of the two main geostatistical parameters, i.e. estimated averages Z* (figs. 5 - 8) and standard deviations of estimation σ_k was obtained (figs. 9 -10).

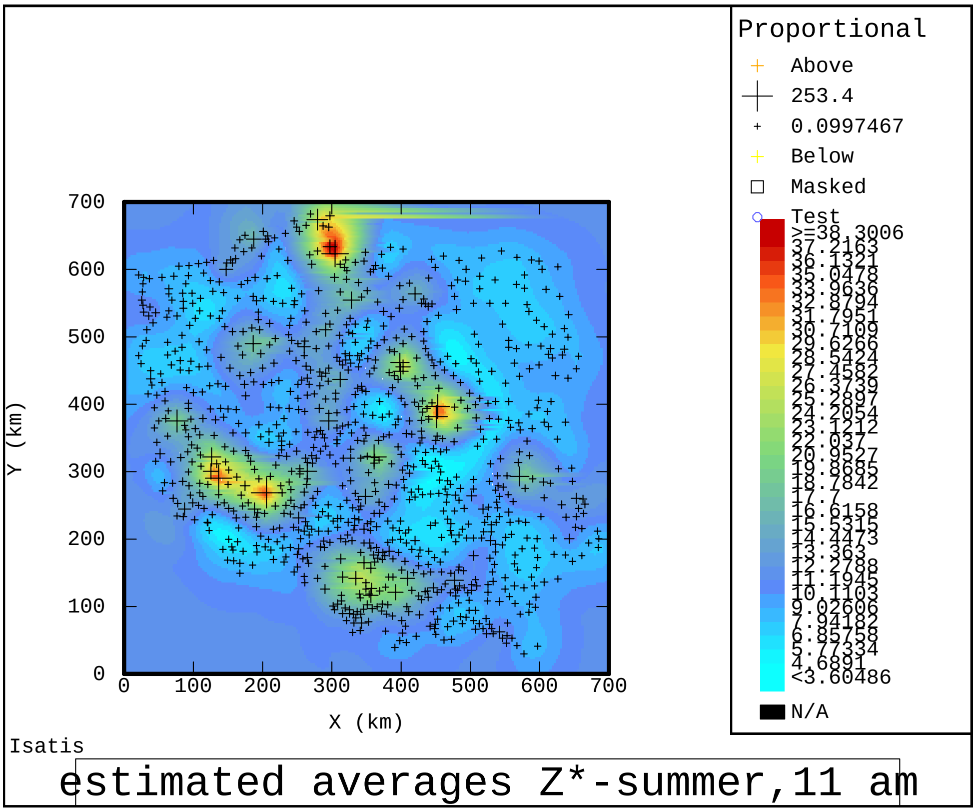

Fig.5. Raster map of estimated averages Z* of the loads [MW] at the 110 kV network nodes for the area of Poland - summer, 11.00 am; the results of the using of ordinary (block) kriging.

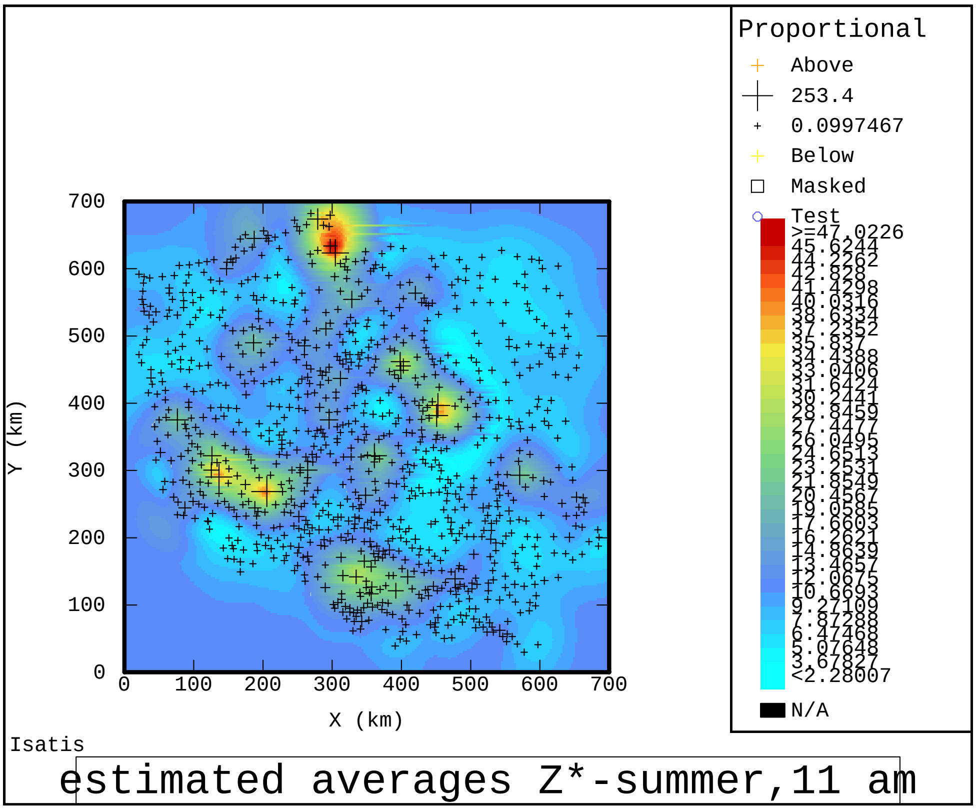

Fig.6. Raster map of estimated averages Z* of the loads [MW] at the 110 kV network nodes for the area of Poland - summer, 11.00 am; the results of the using of simple block kriging (with the local means).

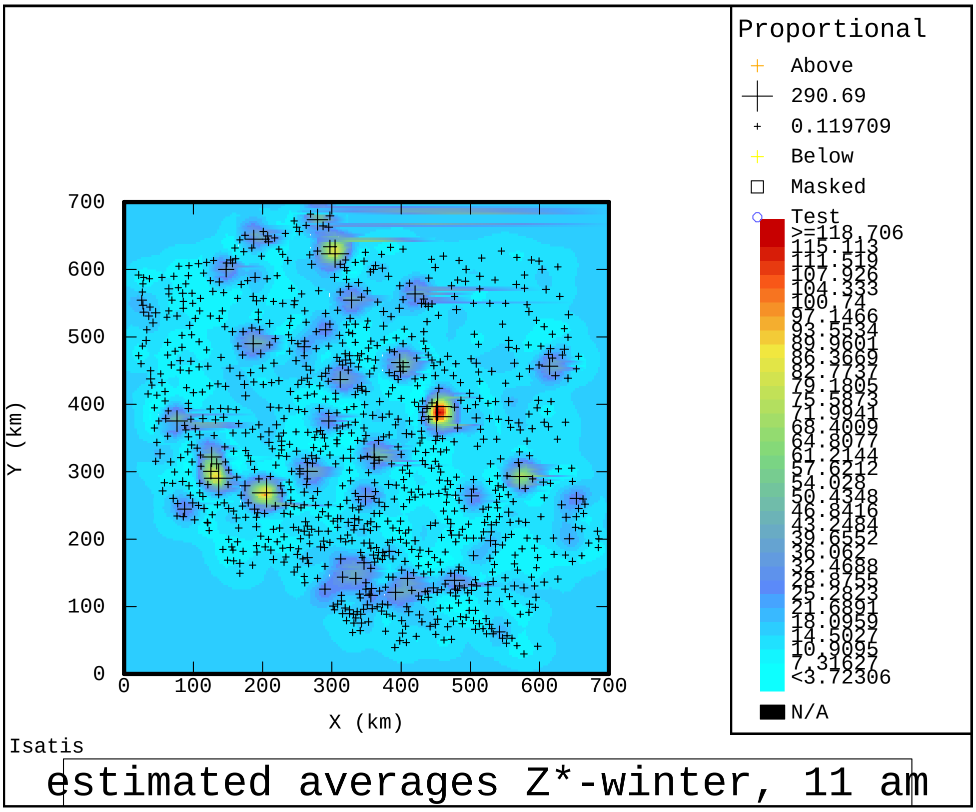

Fig. 7. Raster map of estimated averages Z* of the loads [MW] at the 110 kV network nodes for the area of Poland - winter, 11.00 am; the results of using of ordinary (block) kriging.

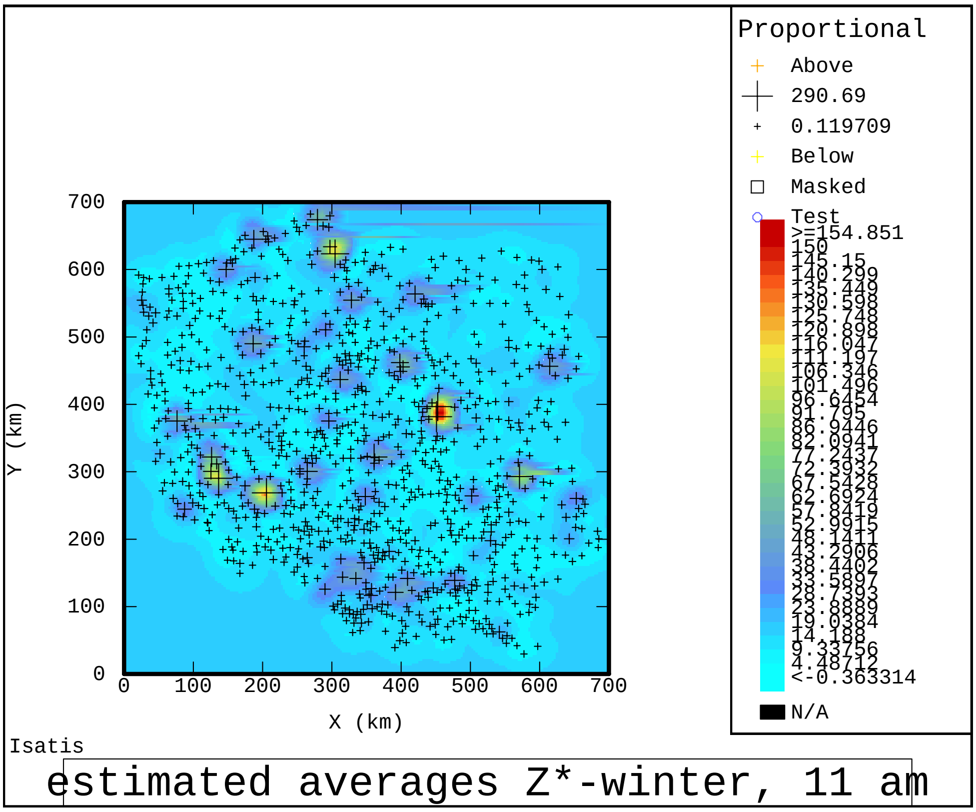

Fig. 8. Raster map of estimated averages Z* of the loads [MW] at the 110 kV network nodes for the area of Poland - winter, 11.00 am; the results of using of simple (block kriging) (with the local means).

A comparative analysis of the pictures presented in the raster maps of average loads at the 110 kV network nodes, calculated for characteristic moments in time of both seasons (the summer: 3: 00 am, 11: 00 am; winter: 3: 00 am, 11: 00 am and 17: 00 pm) applying with lognormal (block) kriging was shown in [2, 3, 6].

6.2. Raster maps of standard deviations of estimation σ_k of average loads

Raster maps of standard deviations of estimation σ_k, calculated by means of simple kriging (with local mean) were presented on figures 9 – 10 only. Spatial characteristic of values σ_k variation obtained using the ordinary kriging is similar.

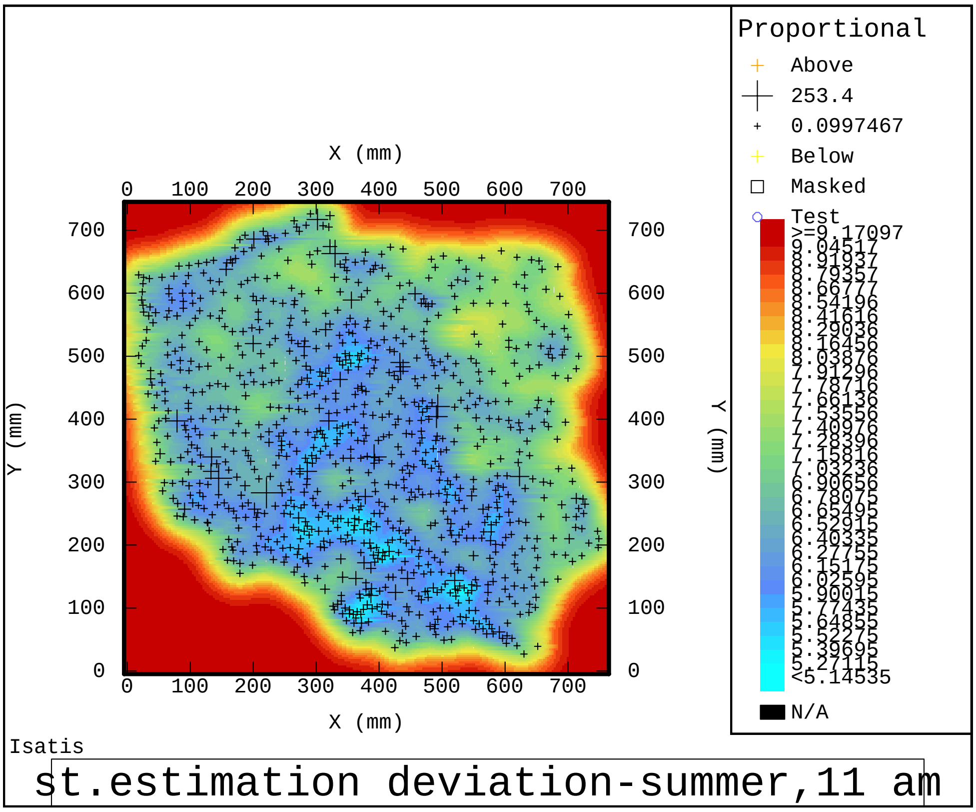

Fig. 9. Raster map of standard deviation values σ_k of average loads estimates [MW] at the 110 kV network nodes for the area of Poland - summer, 11.00. am; the results of using of simple (block) kriging.

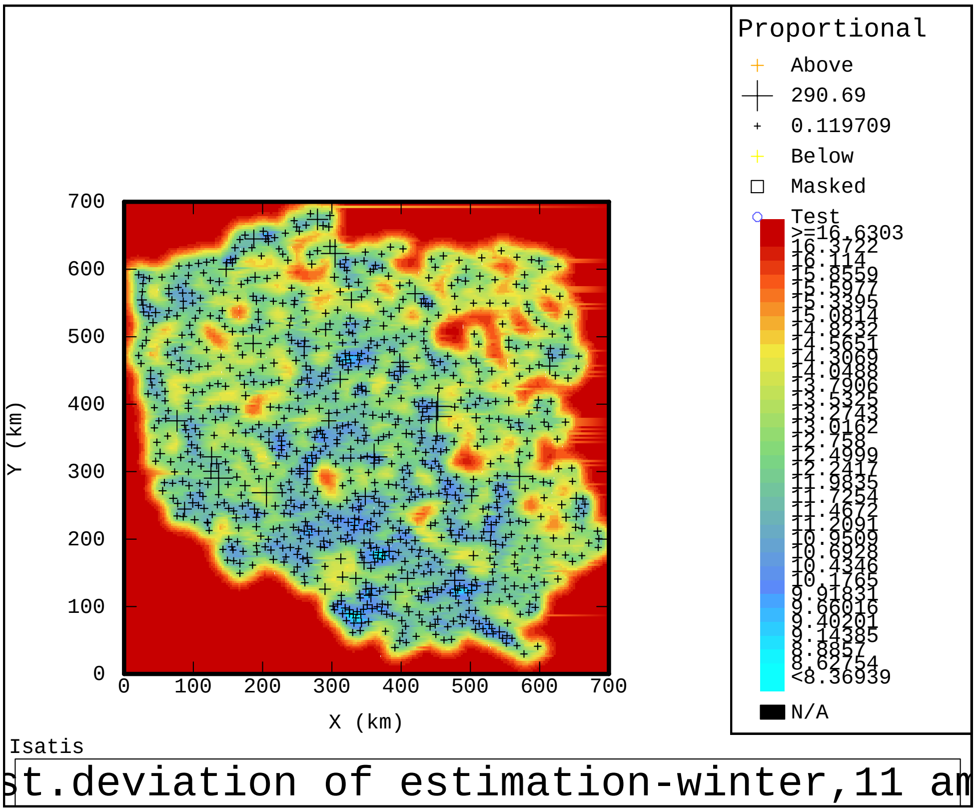

Fig. 10. Raster map of standard deviation values σ_k of average loads estimates [MW] at the 110 kV network nodes for the area of Poland - winter, 11.00 am; the results of using of simple (block) kriging.

6.3. Spatial blockdiagrams of averages Z* and standard deviation values of estimation $2\sigma_k$ and $2\hat{\sigma}$

Figures 11 ÷ 16 show spatial blockdiagrams for two different estimation areas: estimated electrical load averages Z* together with standard estimation deviation doubles $2\sigma_k$ (figs. 11, 13, 14, 16) and moreover estimated electrical load averages Z* and relative standard estimation deviation doubles $2\hat{\sigma}$ (figs. 12, 15). The diagrams were plotted using ordinary kriging, simple kriging (with a local means) and lognormal kriging for a particular moment in time (11 am). The blockdiagrams show electric power estimation results in a 3D system for the summer and winter seasons. They allow one to trace the shape of the average load areas and the location of the highest and lowest power levels. They illustrate well the transformation of the images in time and also depending on the kriging technique used. For example, lognormal kriging yields lower estimated averages Z*, their a smaller minimum-maximum interval and a much smaller lognormal kriging variance (figs. 12 and 15). The blockdiagrams made possible the visualization of the calculated estimation surfaces of Z* and $2\sigma_k$ and Z* and $2\hat{\sigma}$ for the analysed moment in time, i.e. 11:00 am, and the assessment of the reliability of the estimation on the basis of the distance between these surfaces.

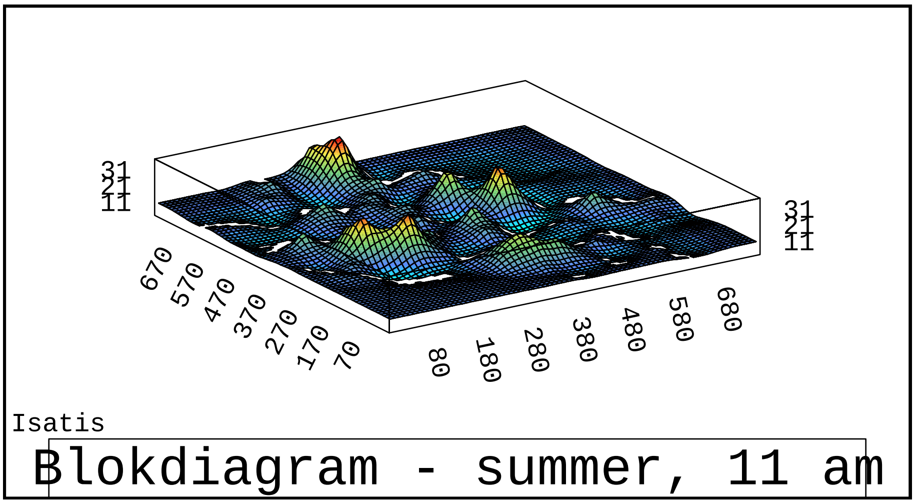

Fig. 11. Blockdiagram of the surfaces of estimated averages Z* and values of standard deviation of estimation $2\sigma_k$ for the loads [MW] at the 110 kV network nodes for the area of Poland - summer, 11.00 am; the results of ordinary kriging using.

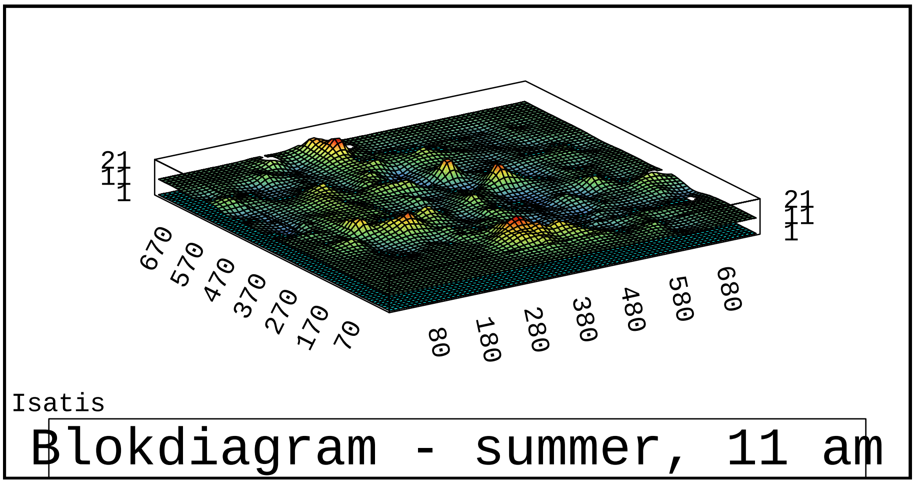

Fig. 12. Blockdiagram of the surfaces of estimated averages Z* and values of relative standard deviation of estimation $2\hat{\sigma}$ for the loads [MW] at the 110 kV network nodes for the area of Poland - summer, 11.00 am; the results of lognormal kriging using.

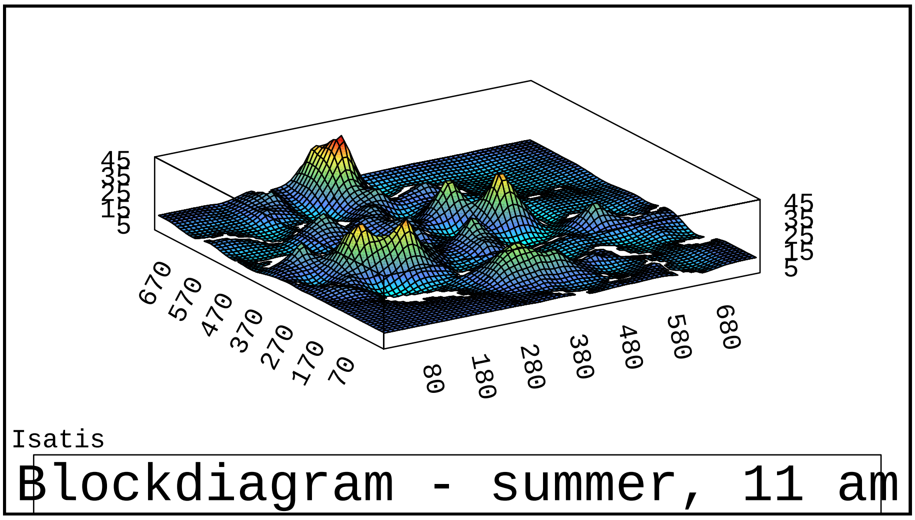

Fig. 13. Blockdiagram of the surfaces of estimated averages Z* and values of standard deviation of estimation $2\sigma_k$ for the loads [MW] at the 110 kV network nodes for the area of Poland - summer, 11.00 am; the results of simple kriging using.

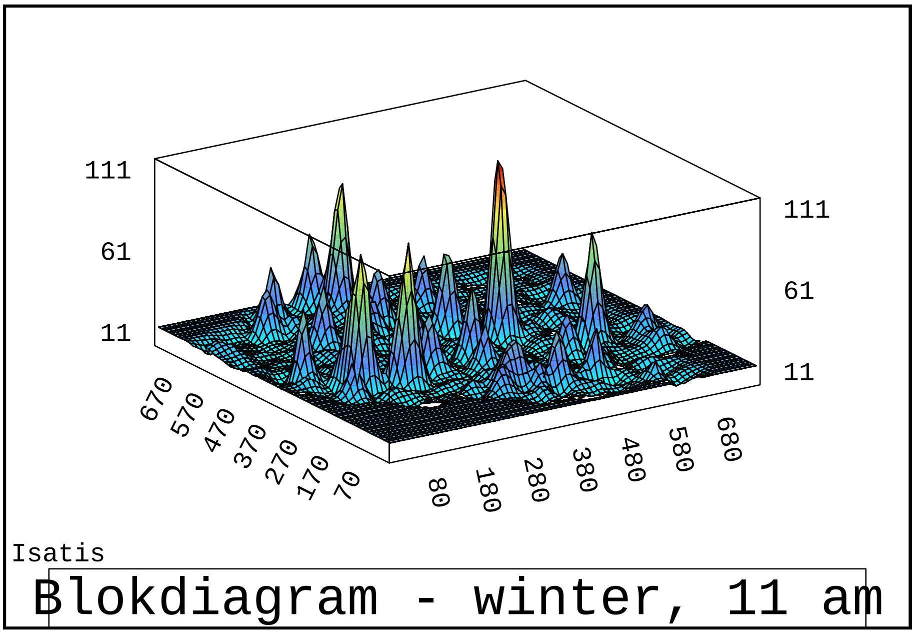

Fig. 14. Blockdiagram of the surfaces of estimated averages Z* and values of standard deviation of estimation $2\sigma_k$ for the loads [MW] at the 110 kV network nodes for the area of Poland - winter, 11.00 am; the results of ordinary kriging using.

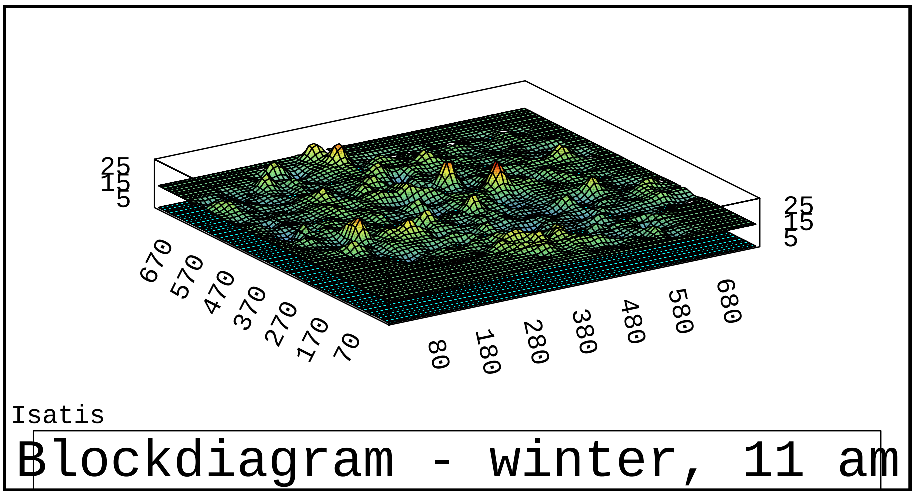

Fig.15. Blockdiagram of the surfaces of estimated averages Z* and values of relative standard deviation of estimation $2\hat{\sigma}$ for the loads [MW] at the 110 kV network nodes for the area of Poland - winter, 11.00 am; the results of lognormal kriging using.

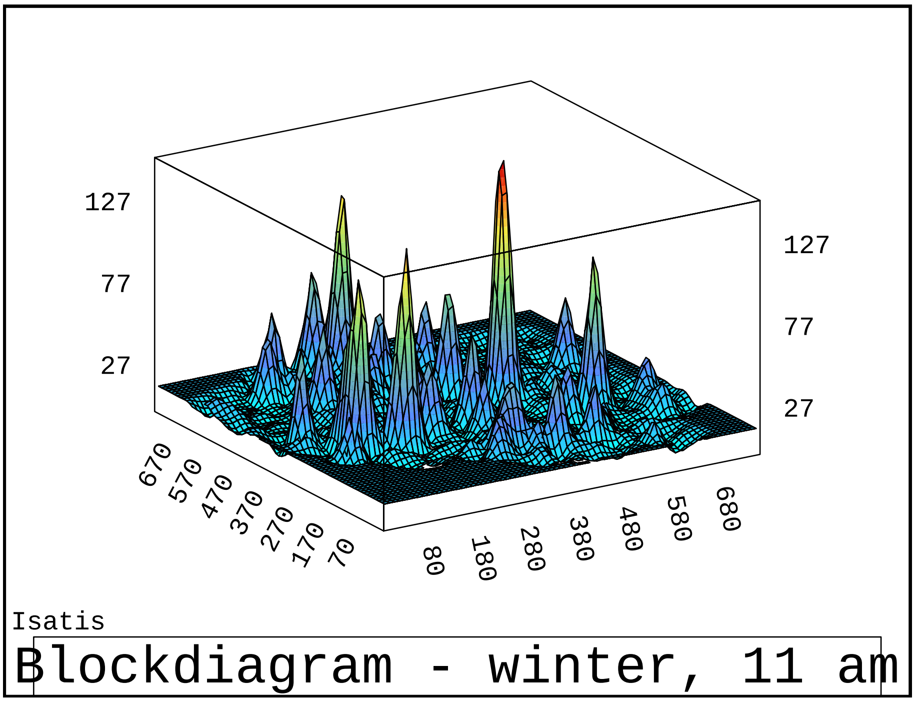

Fig. 16. Blockdiagram of the surfaces of estimated averages Z* and values of standard deviation of estimation $2\sigma_k$ for the loads [MW] at the 110 kV network nodes for the area of Poland - winter, 11.00 am; the results of simple kriging using.

7. EVALUATION OF EFFECTIVENESS AND QUALITY OF THE PERFORMED ESTIMATION

The results of calculations connected with the used kriging techniques, concerning the effectiveness and the quality of the conducted estimation are presented in tables 6 – 7 and in figures 17-22.

Table 6

Global statistics of estimated averages Z* of positive weights sum w_i and correlation r for values *Z/Z** at the network nodes 110 kV for the summer,11:00 am, 2001

Applied technique	**Number of the elementary grid nodes** *n*	**Mean value** $\overline{X}$ **[MW]**	**Maximum value** X_{max} **[MW]**	**Minimum value** X_{min} **[MW]**	**Standard deviation** *S* **[MW]**
Ordinary kriging	5775 *(positive weights sum w_i)*	1.08	1.260	1.00	0.05
	5518 *(correlation r – Z/Z*)*	0.56	0.83	0.00	0.23
Simple kriging (with local means)	5775 *(positive weights sum w_i)*	0.65	1.05	0.00	0.33
	5518 *(correlation r –Z/Z*)*	0.57	0.83	0.00	0.22

Table 7

Global statistics of estimated averages Z* of positive weights sum w_i and correlation *r* for values *Z/Z** at the network nodes 110 kV for the winter,11:00, am 2001

Applied technique	Number of the elementary grid nodes n	Mean value $\overline{X}$ [MW]	Maximum value $X_{\max}$ [MW]	Minimum value $X_{\min}$ [MW]	Standard deviation S [MW]
Ordinary kriging	5775 *(positive weights sum w_i)*	1.05	1.23	1.00	0.04
	5583 *(correlation r – Z/Z*)*	0.46	0.86	0.00	0.27
Simple kriging (with local means)	5775 *(positive weights sum w_i)*	0.49	0.98	0.00	0.32
	5583 *(correlation r - Z/Z*)*	0.47	0.86	0.00	0.27

With applying of two estimation techniques – ordinary kriging and simple kriging (with local means) similar pictures of weights w_i sum distribution were obtained. Generally solution of ordinary kriging is similar to solving of simple kriging. The weight assigned to mean value is small, but the sum of weights w_i of simple kriging is closed to 1.

In the map of distribution of positive weights sum w_i, calculated for the summer period the values ranging from 0.88 – 1.05 in the prevailing part of Poland predominate, but in northern – eastern part (NE) they are lower, mainly, 0.65 – 0.78 (fig. 17).

For the winter period the sum of positive weights w_i amounted to 0.86 – 0.98 in case of simple kriging and a little higher, if ordinary kriging has been using (1,12 – 1,17) (fig. 18).

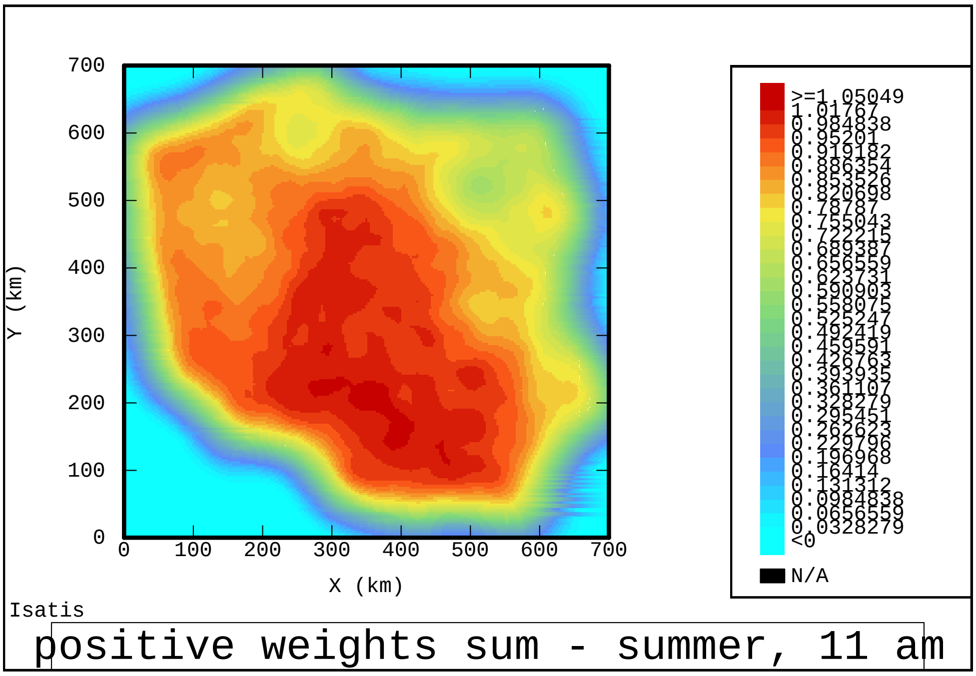

Fig. 17. Raster map of positive weights w_i sum distribution for the loads at the 110 kV network nodes for the area of Poland - summer, 11.00 am; results of simple kriging using.

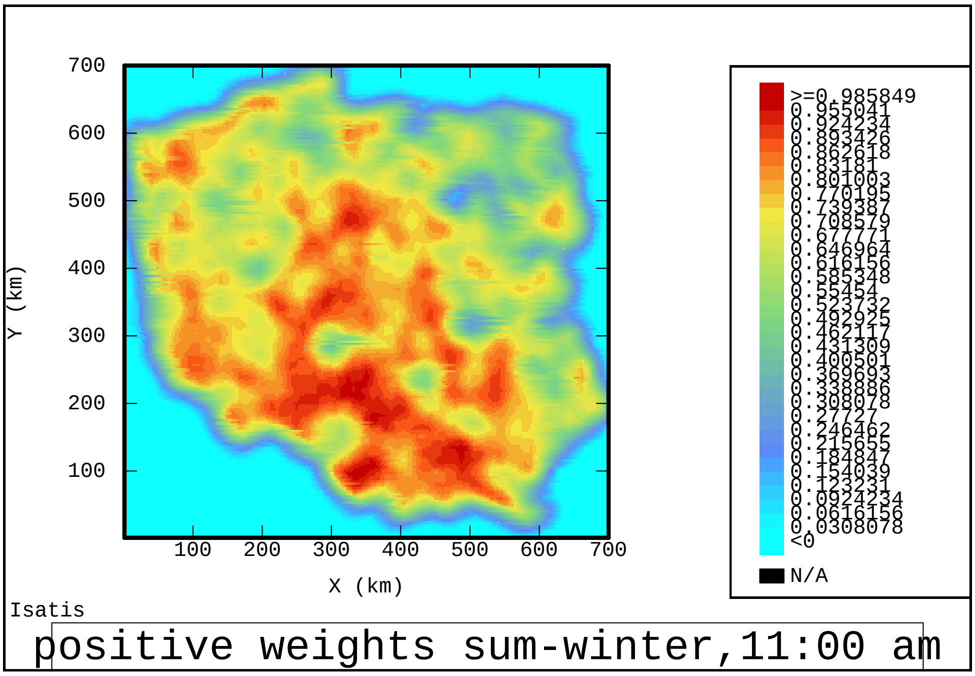

Fig. 18. Raster map of positive weights w_i sum distribution for the loads at the 110 kV network nodes for the area of Poland - winter, 11.00 am; the results of simple kriging using.

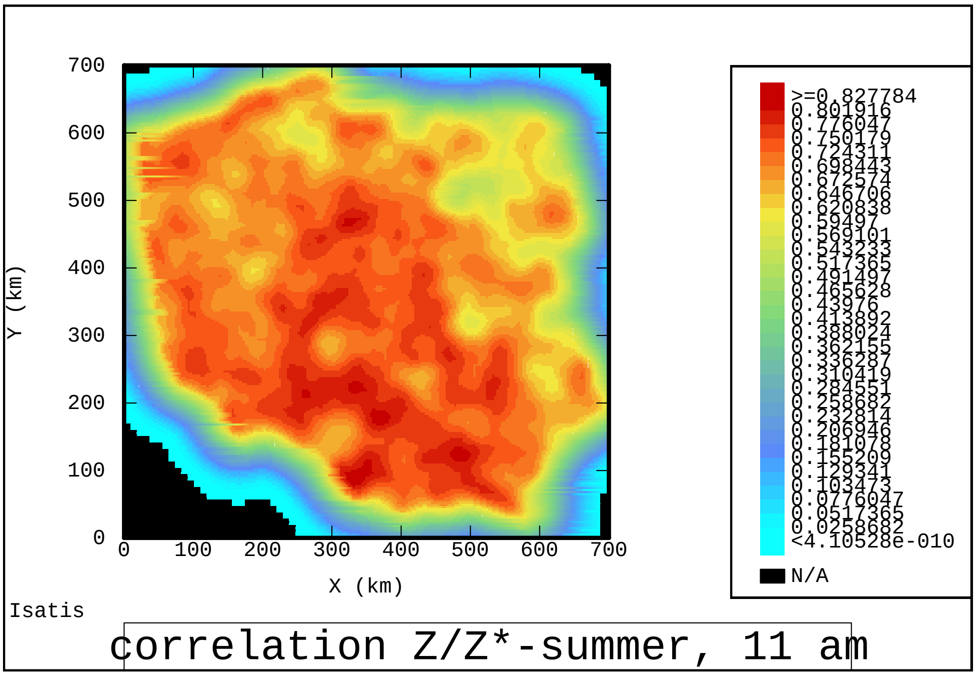

Fig. 19. Raster map of correlation *r* distribution between true values Z and estimated averages Z* (*Z/Z**) of the loads [MW] at the 110 kV network nodes for the area of Poland - summer, 11.00 am; the results of simple kriging using.

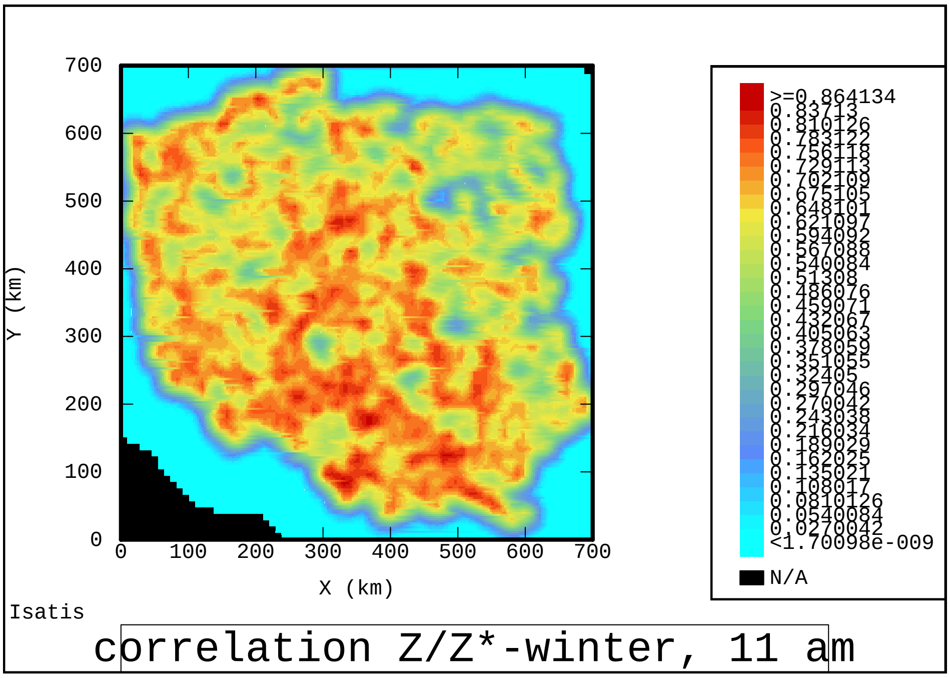

Fig. 20. Raster map of correlation *r* distribution between true values Z and estimated averages Z* *(Z/Z*)* of the loads [MW] at the 110 kV network nodes for the area of Poland - winter, 11.00 am; the results of simple kriging using.

In the summer season spatial correlation between true values Z and estimated averages Z* *(Z/Z*)* for most of Poland is characterized by high correlation coefficients *r*, assuming values in a range of 0.70 - 0.83 (fig. 19). In the smaller areas the correlation coefficients *r* are much lower – in a range of 0.54 - 0.62 (fig. 19).

The estimation results for the winter season differ from the picture of variation of average loads observed for the summer season. The largest areas of the highest correlation coefficient values *r* occur in the central and southern part of Poland (fig. 20). Their branching is observed in Lower Silesia and in the north-western (NW) part of Poland. As shown by the summer season results, no area of uniform spatial correlation *r (Z/Z*)* occurs (fig. 20). The maximum values of correlation coefficient *r* were in a range of 0.73 - 0.86 in the largest estimation areas for the winter season. Local variations in the values of the data representing the winter season (11:00 am) are much stronger than the ones observed for the summer season data (11:00 am).

Much bigger areas of maximum covariance *Z/Z** values can be noticed on raster maps elaborated for the summer, in the central and southern part of the studied territory (fig. 21). Only very small such fields are marked in case of winter (fig. 22).

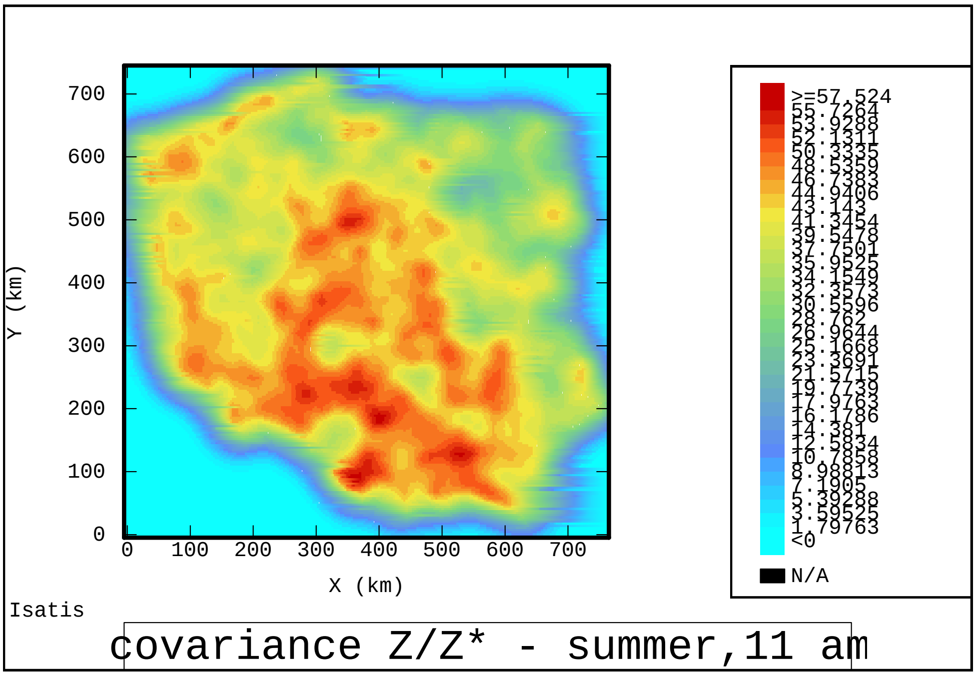

Fig. 21. Raster map of covariance *Z/Z** distribution of the loads [MW] at the 110 kV network nodes for the area of Poland - summer, 11.00 am; the results of simple kriging using.

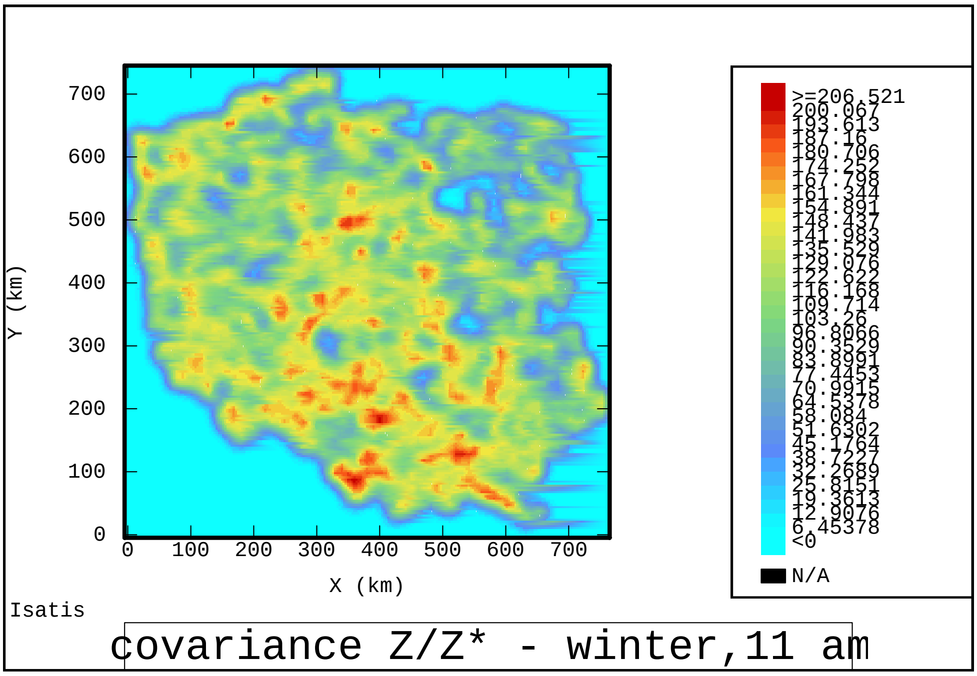

Fig. 22. Raster map of covariance *Z/Z** distribution of the loads [MW] at the 110 kV network nodes for the area of Poland - winter, 11.00 am; the results of simple kriging using.

8. CONCLUSION

The peculiarities of the electric power system whose primary function is to deliver electric energy to consumers distributed over the considered area, i.e. the entire territory of Poland, demand the planning of its operation and development in a 3D system, i.e. in the surface area dimension with the time factor taken into account.

The results of the surface area estimation of load averages Z* show that the applied kriging methods, in particular simple (block) kriging (taking into account local means), is helpful and effective in solving such problems. As a result of their application, raster maps of electrical loads showing how the surface area picture of the loads changes in time were obtained.

The presented evaluations and analyses of the estimation of loads for the nodes of a 110 kV network represent the first important stage in research aimed at developing a model for forecasting the surface area image of the loads, which may be called a 3D model since it takes the time factor into account in the estimation process.

The extensive documentation can be useful in managing the electric power system whereby the risk of blackouts can be reduced. It was found that irrespective of the analyzed power network variant (220, 400 kV) [2, 3] and 110 kV, the season (summer, winter) and the time (3:00 am, 11 am, 17:00 pm) simple kriging with a local means yielded both the highest and lowest estimated averages Z*, but with higher standard deviations S in comparison with the results obtained by the other techniques. While standard deviation S of the values of standard deviation of estimation σ_k for the 220 and 400 kV variants of the nodes grid was on the whole lower for simple kriging with a local means. As regards the other basic statistics, the differences for the values of deviation σ_k (the average, the minimum and the maximum) were statistically insignificant for all the tested techniques. As regards the nodes of the 110 kV network, the lowest standard deviation S for deviation σ_k, its maximum and minimum (zero) were obtained when ordinary (point) kriging was used. The results of calculating the statistics by simple (block) kriging with a local means did not siginificantly differ from those yielded by ordinary (block) kriging.

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