IDENTIFICATION OF MORPHOLOGICAL TENDENCIES AND VELOCITIES IN COASTAL ZONES

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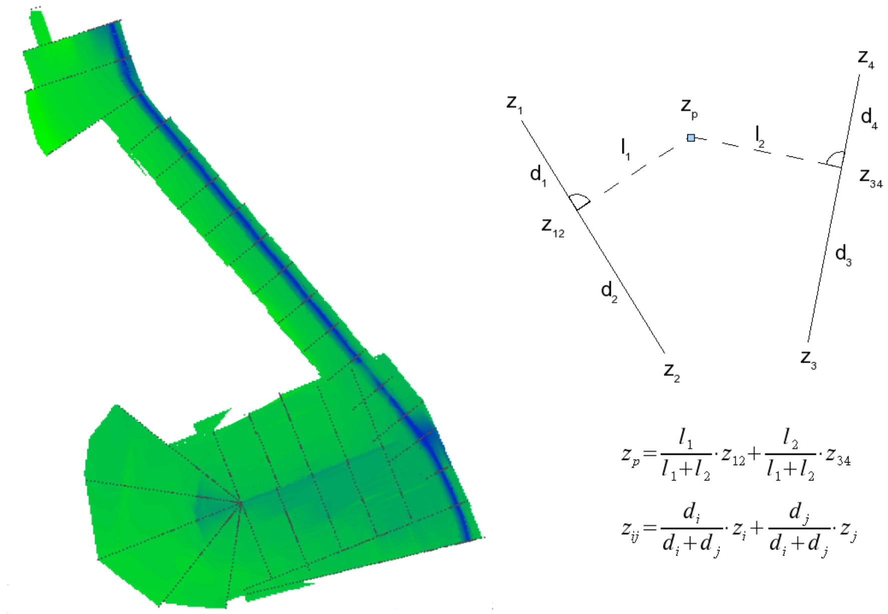
The redefinition of the concept of a digital bathymetric model as sets of basic data and corresponding interpretation rules in space and time provides new evaluation methods, e.g. to obtain new expertise of large scale morphodynamic processes from measurement data.
This paper presents the basic concept of a database-supported digital bathymetric model, time-space interpolation methods and procedures for adequate morphodynamic analysis. One important aspect of these kinds of models is the optimization of interpolation algorithms, which essentially must be able to handle inhomogeneously distributed spatial and temporal measurements. The identification of morphodynamic tendencies can be realized by tracking the shifting structures, e.g. tidal channels or dunes, and by evaluating mathematical derivations in the four-dimensional space. Through this concept, past and future variations of the seabed can be analyzed and estimated. Deficiencies in measuring campaigns can be revealed and may be optimized by identifying ranges of different morphological characters. This leads to an important improvement of significance of measurement data as well as the understanding of the morphodynamics on tidal and non-tidal coasts.
To manage the surveying data collected from several sources with the associated interpolation methods an object-oriented database (db4o) is used. Neural network algorithms extend the bathymetric interpolation and can be used for the development of data driven morphological models in coastal zones in combination with the database-supported temporal and spatial, digital bathymetric model.

INTRODUCTION

Bathymetric and topographical surveys carried out on a regular basis by several institutions and with various measurement methods and objectives form the basis for the evaluation of morphological changes in the near shore zone and coastal areas. Even though measurement techniques are being improved continuously, the synoptic bathymetric survey of large areas of the seabed will not be possible in the near future. The generalized concept of a digital terrain model in time and space is developed and can be used for the evaluation of temporal and spatial changes of the bathymetry [1]. Thus, the digital bathymetric model consists multitude of sets of basic data and their associated interpretation rule. A single set of basic data contains all survey data recorded under equal conditions. They can be utilized to describe a partial area of the bathymetry. In order to guarantee the temporal allocation, all measurements recorded by one and the same device during one day are assigned to one basic data set. The interpretation rule includes all additional information concerning the evaluation of the depth at any point in space. This initially includes the applied interpolation and approximation method in space as well as the associated confidence area. The confidence area describes all locations for which terrain elevations can be derived from the survey points by applying the interpretation rule. This definition enables the application of the suitable approximation or interpolation method for each basis data set, thereby accounting for data sets of different character obtained similarly by various methods (e.g. line and area surveys, fan-type soundings as well as laser scanning).



$$z_p = \frac{l_1}{l_1+l_2} \cdot z_{12} + \frac{l_2}{l_1+l_2} \cdot z_{34}$$

$$z_{ij} = \frac{d_i}{d_i+d_j} \cdot z_i + \frac{d_j}{d_i+d_j} \cdot z_j$$

Figure 1. Interpolation on profiles within the non-convex confidence area of a data set

If no explicit assumptions concerning the interpolation and approximation method can be made, it may be possible to use the survey data to train artificial neural networks (ANN) for the representation of the bathymetry [2]. Particularly for the transition to a temporally variable terrain model, artificial neural networks can be trained to yield to unknown interrelationships.

DIGITAL BATHYMETRIC MODEL IN SPACE AND TIME

To describe the evolution of the bathymetry we consider the digital terrain model as a continuous function in space and time *z(x,y,t)*. This digital bathymetric model in space and time is represented by discrete survey points and associated interpretation methods.

For the determination of a quasi-synoptic bathymetry at arbitrary time, temporal interpretation methods have to be additionally introduced, and temporal ranges of confidence have to be defined. Thus, a quasi-synoptic digital bathymetric model at a point of time can be considered as a horizontal section in the spatial and temporal range of confidence (see figure 2).

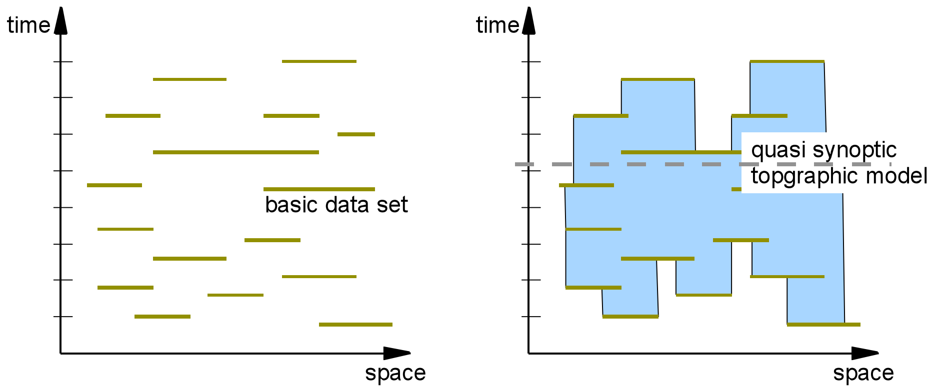


Figure 2. Schematic temporary confidence region

In the schematic figure 2 the horizontal axis describes different places within the area under investigation. The vertical axis describes the time axis. A horizontal line in this space-time coordinate system marks the spatial confidence area as well as the time stamp of a basic data set. The figure on the right side shows the resulting time-space confidence area, in addition to the geographic neighborhood of the basic data sets also their temporal neighborhood are considered. In this graphic all combinations of spatial and temporal coordinates, for which data sets are available in the past as well as in the relative future are colored light blue. It is possible in exactly these ranges to determine a depth using appropriate interpolations. The dashed horizontal line marks a quasi-consistent digital bathymetry at a specific date.

TIME-SPACE INTERPOLATION

In analogy to the interpolation in space a variety of methods can be used for the space-time interpolation. Three examples of time interpolations can be seen in figure 3.

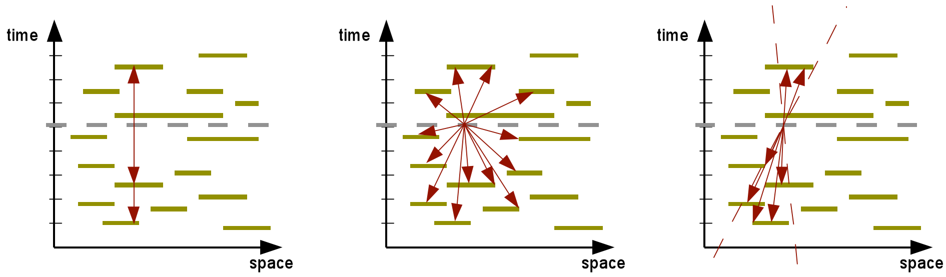


Figure 3. Interpolation methods in time and space

Temporal linear interpolation between two spatially interpolated depths from directly predecessing and following data sets is presented on the left side. Should there be extra data sets other than these direct temporally adjacent data sets, the determination of the depth can be conducted using polynomial or meshless interpolation in time. In the middle of figure 3 a meshless interpolation in space and time is used to determine the depth. It is easy to imagine that the application of this global interpolation procedures smoothen the surfaces. To optimize this interpolation the use of an appropriate circum sphere in time and space is recommended. In the left picture the interpolation uses only data points inside an inclined double cone. The opening of the cone increases with increasing distance and time. This describes the increasing fuzziness of the influence of the measured depth in the interpolation algorithms. With the inclination of the cones we can consider the effects resulting from the relocation of structures in the interpolation.

DATABASE-SUPPORTED DIGITAL BATHYMETRIC MODEL

To manage the surveying data collected from several sources, e.g. laser scanning, digitized geographical maps, sonar measurements and beach profiles, with the associated interpolation methods an object-oriented design and the object-oriented database db4o [5] are used. The basic classes include those for topographical points, digital surveying, meta data and digital terrain models. The access to the survey data is usually based on the meta data. The class `Kuefo90MetaData` is extended from a general class `MetaData` (based on ISO19115 standard). The class `DigitalSurveying` contains the actual measurement points in form of a set of topographical points, a reference to the meta data and an interpretation in form of a class implemented the interface ScalarFunction2d. The area represented by a survey measurement is described by a region in the plane (`Region2d`).

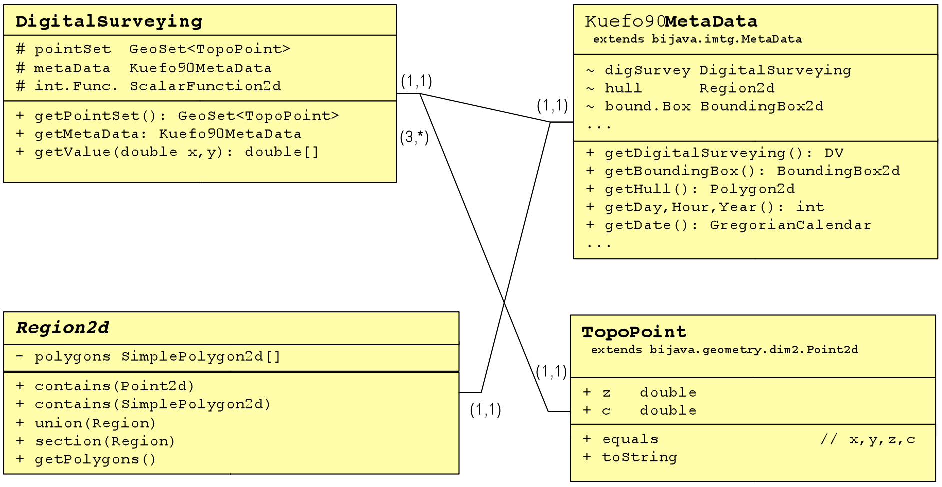


Figure 4. Class diagrams for the management of digital surveyings

The interface `TopographicModel` allows the determination of a depth and a reliable value between the measured points. The determination of a depth value will be depending on the implemented interpolation methods, for example a linear triangular-, a Sibson- [4] or different variants of the Shepard-interpolation [3]. For time associated digital bathymetric models, the abstract class `TimeAssociatedTopographicModel` is used. The determination of the depth at a location and a specific date based on the space interpolation is included in the `TopographicModel` and the specified interpolation method in time.

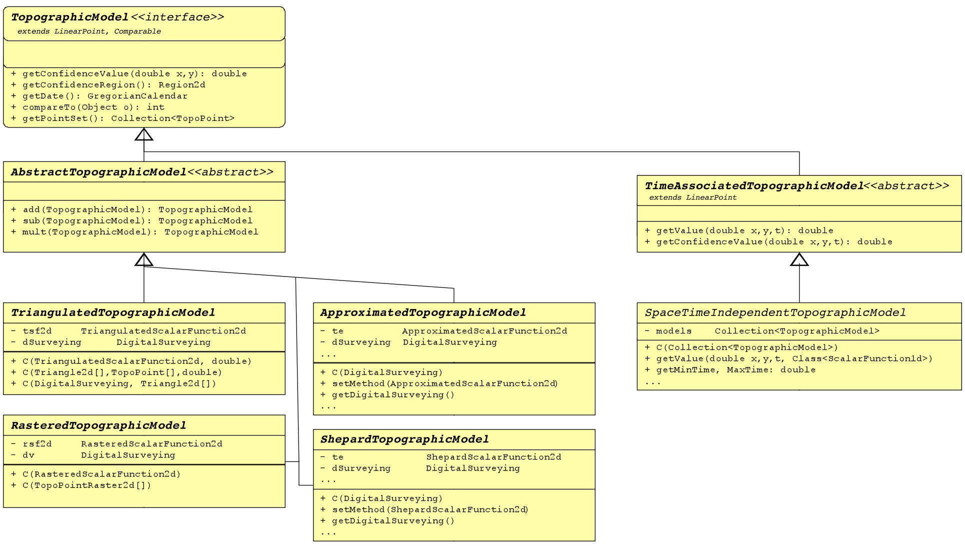


Figure 5. Class diagrams for topographic models

The efficient access to the survey data during the interpolation is implemented via a multi-level indexing based on the meta data.

MORPHOLOGICAL VELOCITIES

If digital bathymetric models are understood as three-dimensional continuous interpolated functions *z(x,y,t)* in space and time, it is easy to determine the gradients (*dz/dx* and *dz/dy*) within a measurement data set. The changing rates of the depth (*dz/dt*) can be determined by using finite differences on rays parallel to the time axis and thus areas of erosion and sedimentation can be identified.

To describe the transformation of local structures, such as the move of tidal channels or the fall of coastal line, morphological velocities $\partial \vec{x} / \partial t$. are introduced. The velocities with which characteristics of an area move are understood as morphological velocities. Such terrain characteristics are shorelines, tidal channels, transport bodies etc. that can be generally characterized by isolines or breaklines.

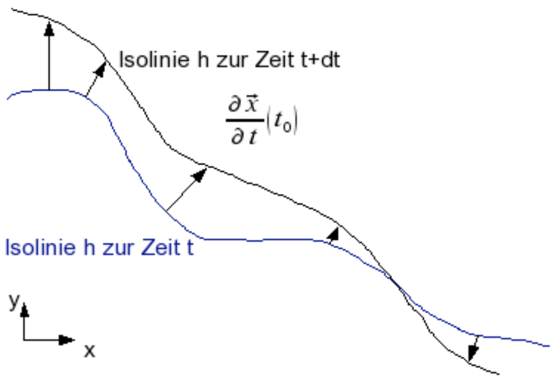


Figure 6. Determination of morphological velocities based on the tracing of isolines

Based on digitized isolines at particular times morphological velocities can be determined by computing the distances between isolines at different particular times (see figure 6).

Alternatively, if the digital bathymetry is represented by a three dimensional continuous function *z(x,y,t)*, the determination of morphological velocities can be based on the theorem of implicit functions. The isoline to the value k can be described implicitly by the function *R((x,y),t)=z((x,y),t)-k=0*. The theorem of implicit functions states that if the equation *R((x,y), t) = 0* (an implicit function) satisfies some mild conditions on its partial derivatives, then one can in principle solve this equation for *x(t)* and *y(t)*, at least over some small time interval. Moreover, the theorem delivers the morphological velocities where the local space gradients are not zero:

$$\frac{\partial x(t)}{\partial t} = -\left(\frac{\partial z}{\partial x}\right)^{-1} \cdot \frac{\partial z}{\partial t} \text{ and } \frac{\partial y(t)}{\partial t} = -\left(\frac{\partial z}{\partial y}\right)^{-1} \cdot \frac{\partial z}{\partial t}$$

In figure 7 the computed morphological velocities are presented for a near shore area of the island of Langeoog, which is off the German coast of the North Sea. On the left side of the figure a tidal channel, which deviates to the east (right) can be seen. Also the drift of the sand banks to east and the erosion of the coastline can be identified.

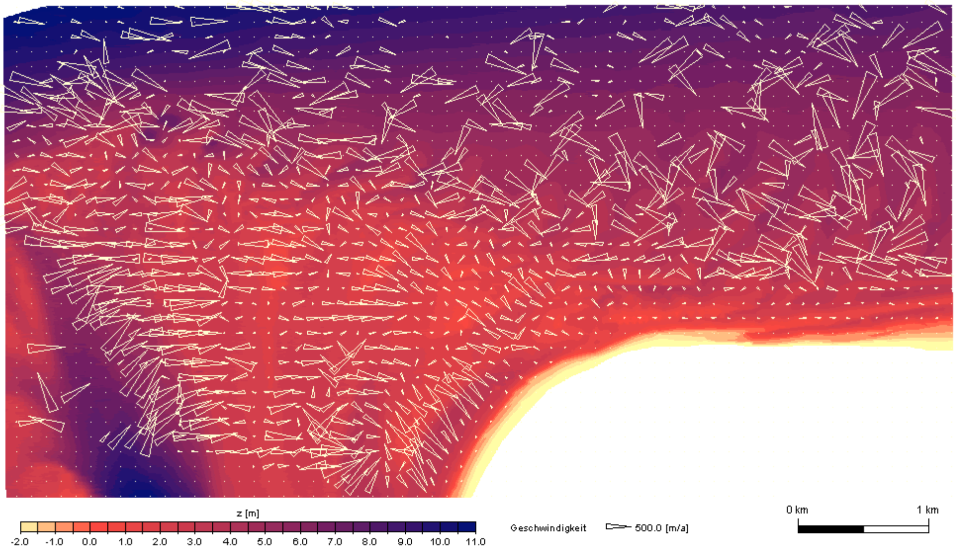


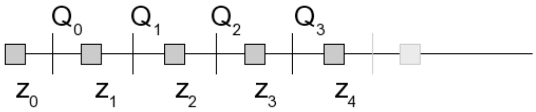
Figure 7. Determination of morphological velocities based on the tracing of isolines

DATABASED DETERMINATION OF RESULTING SEDIMENT TRANSPORT RATES

The knowledge of the resulting sediment transport rates, which produce the observed morphological changes, have immense significance for the maintenance and for protecting coastal lines as well as for validating morphodynamic process-based numerical simulation models.

The evolution of the bathymetry fulfills for each control volume a continuity condition and can be described by the bottom evolution equation. Process-based numerical simulation models solve this bottom evolution equation with finite elements, finite volumes or finite differences. Hereby the sediment transport rates can be computed on the base of the current velocities and the sediment parameters.

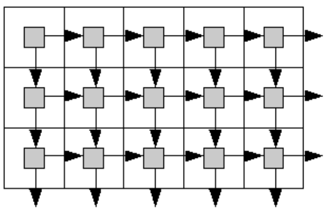
To compute the resulting sediment transport rates, which produce the observed morphological changes, an inverse finite volume procedure is developed. For simple geometries like a one-dimensional river with fixed boundaries (*dz=0*) the finite volume method can be easily inverted. In figure 8 it can be seen that the number of unknown values Q_i is the same as the number of the known depth changes Δz_i.



$$\Delta z_i = \frac{\Delta t}{\Delta x} \left(Q_{i-1} - Q_i \right)$$

Figure 8. Schematic 1-dimensional finite volume approximation

In general a simple inversion of the finite volume method is not possible. In the two dimensional case the number of the unknown values Q_{ij}, the sediment transport rates over the cell boundaries, are more than twice the number of the known depth changes Δz_{ij} over a time interval Δt at the cell centers. In figure 9 the schema of a finite volume method for a regular raster is illustrated.



$$\frac{A}{\Delta t} \Delta z_{i,j} = Q^x_{i,j} - Q^x_{i+1,j} + Q^y_{i,j} - Q^y_{i,j+1}$$

Figure 9. Schematic 2-dimensional finite volume approximation on raster-cells

To invert the finite element method an iterative procedure is developed. At first all sediment transport rates Q_{ij} are randomly initialized. In a second step the resulting depth changes are calculated by the finite volume method. Now the residuum between computed depth changes and observed depth changes are used to correct the estimated sediment transport rates Q_{ij}. This procedure is carried out as long as no changes to the sediment transport rates are calculated.

SEDIMENT TRANSPORT RATES AT THE NEAR SHORE AREA OF THE ISLAND OF LANGEOOG

For the near shore area of the island of Langeoog off the German coast of the North Sea regular bathymetric surveys, in time intervals of one to two years, are the basis of the following results. The basic data sets consist of a regular raster of 5m and are provided by the Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency (NLWKN).

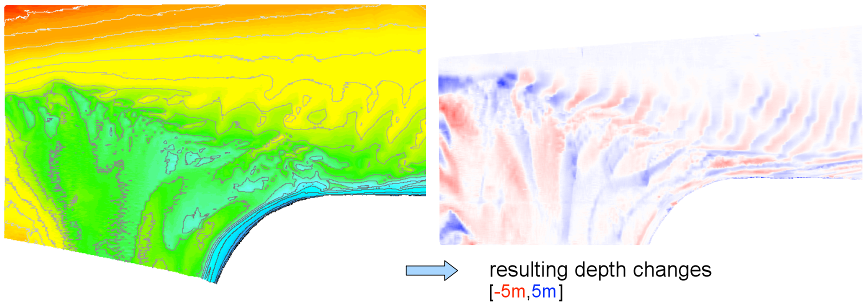


Figure 10. Depth distribution (isosurfaces 2002, isolinies 2003) and resulting depth changes between 2002 and 2003

In figure 10 on the left side, the depth distribution is presented with isolines for the year 2002 and with isosurfaces for the year 2003. The right picture shows the resulting depth changes, the red areas shows erosions and the blue ones sedimentations. The movement of the near shore structures, e.g. sand bars, which also are identified by the morphological velocities in figure 7 can be seen. Based on the bathymetries of the years 2002 and 2003 the resulting sediment transport rates can be determined by the inverse finite volume procedure (see figure 11).

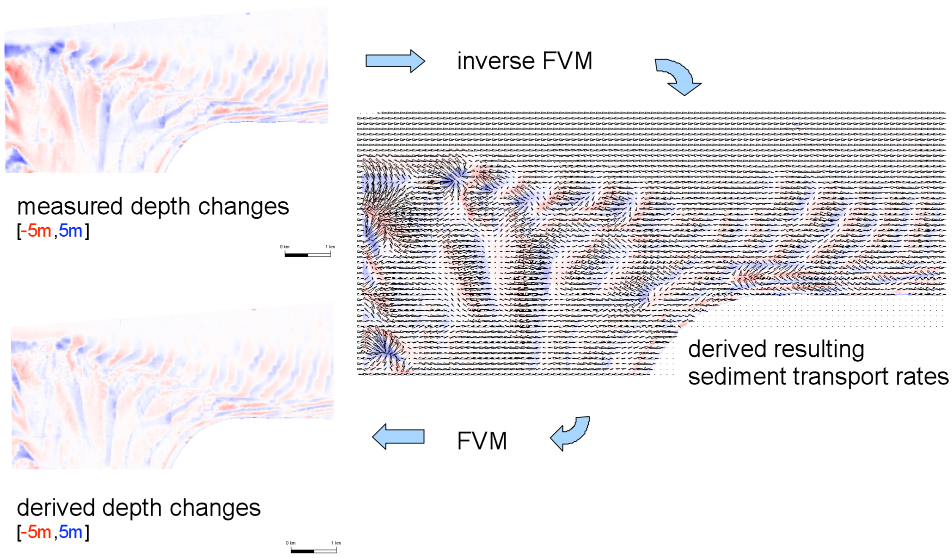


Figure 10. Inverse finite volume approximation

The determination of the sediment transport rate is unique. The constant streaming is not taken into account. Applying process-based morphodynamic simulations can do this.

ACKNOWLEDGMENTS

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REFERENCES

[1] Milbradt, P., Sellerhoff, F., Krönert, N., “*Konsistente Digitale Bathymetrien*”, KoDiBa Abschlussbericht, BMBF 03 KIS 042, (2005)

[2] Milbradt, P. and Dorow, C. “*Identifikation morphologischer Tendenzen und Geschwindigkeiten im Küstennahbereich*“ IMTG-Zwischenberichte (2008)

[3] Shepard, D.: “A two-dimensional interpolating function for irregularly spaced data“, *Proc. ACM. nat. Conf*., (1968), pp. 517-524

[4] Sibson, R.: “A brief description of natural neighbour interpolation“, in Barnet, V. (ed) *Interpreting Multivariate Data*, Wiley: Chichester., (1981), pp. 21-36

[5] www.db4o.com