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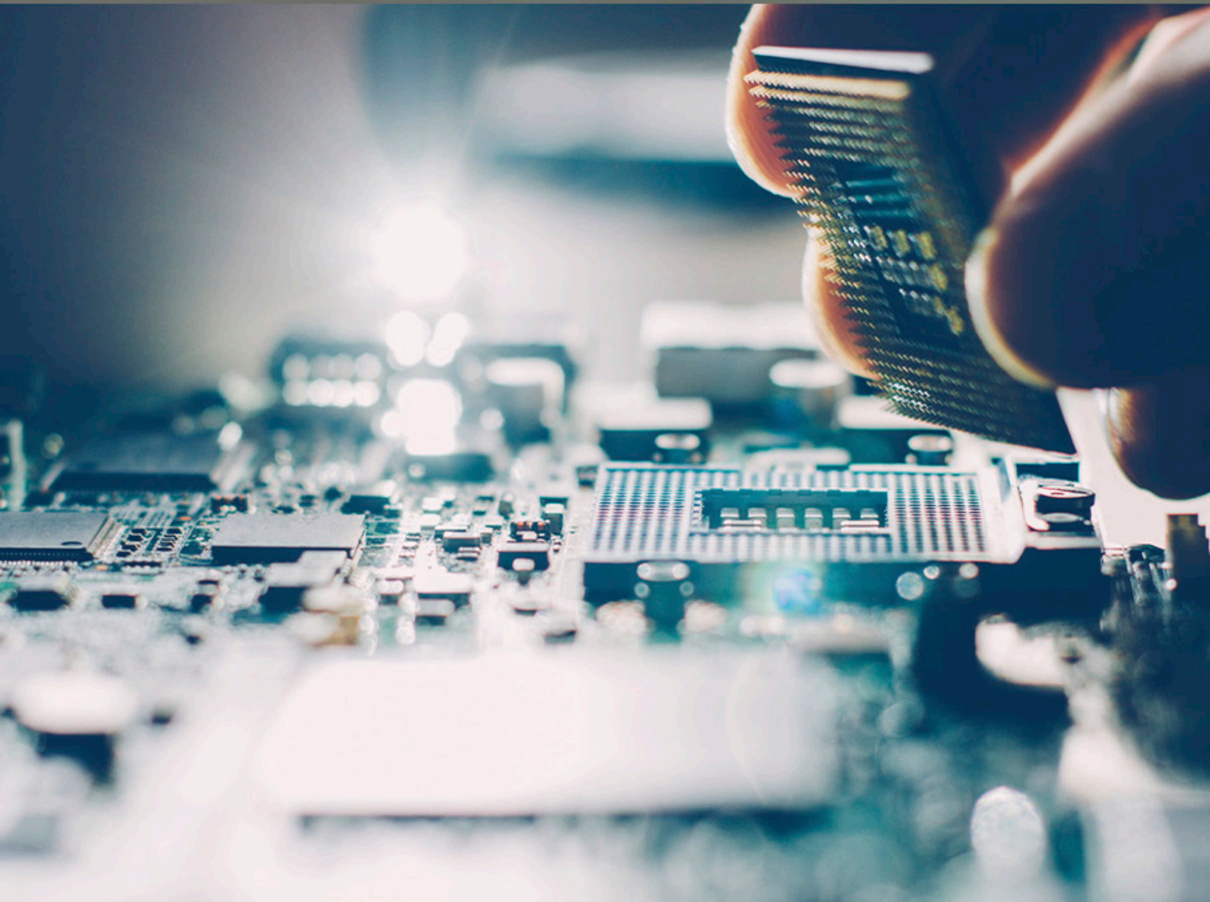
# DESAFIOS DAS ENGENHARIAS:

## ENGENHARIA DE COMPUTAÇÃO 2



ERNANE ROSA MARTINS
(ORGANIZADOR)

Atena Editora
Ano 2021

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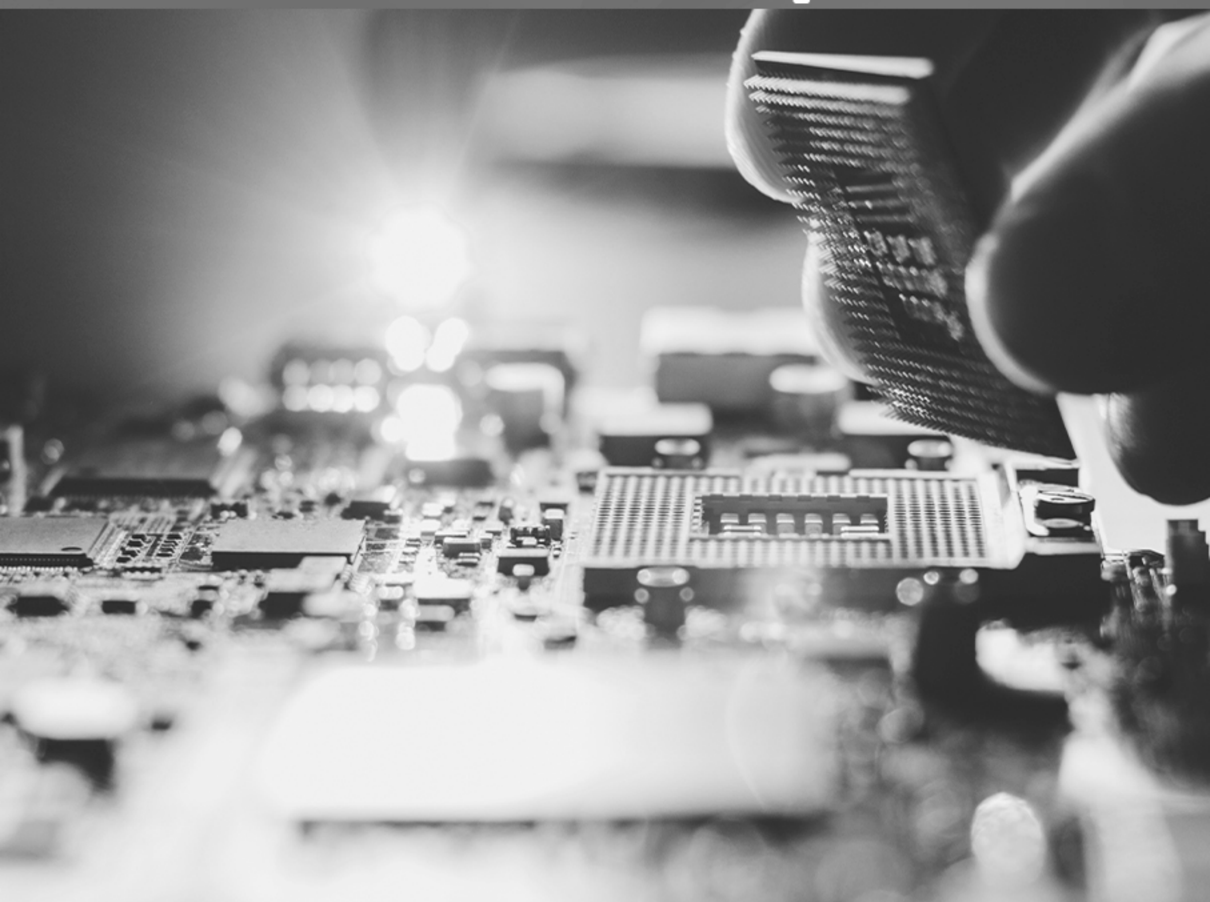

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Ciências Exatas e da Terra e Engenharias

# Coleção desafios das engenharias: engenharia de computação 2


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## APRESENTAÇÃO

A Engenharia de Computação é a área que estuda as técnicas, métodos e ferramentas matemáticas, físicas e computacionais para o desenvolvimento de circuitos, dispositivos e sistemas. Esta área tem a matemática e a computação como seus principais pilares. O foco está no desenvolvimento de soluções que envolvam tanto aspectos relacionados ao software, quanto à elétrica/eletrônica. Os profissionais desta área são capazes de atuar principalmente na integração entre software e hardware, tais como: automação industrial e residencial, sistemas embarcados, sistemas paralelos e distribuídos, arquitetura de computadores, robótica, comunicação de dados e processamento digital de sinais.

Dentro deste contexto, esta obra aborda diversos aspectos tecnológicos computacionais, tais como: implementação e modificações numéricas a serem feitas no algorítmo de Anderson (2010) para simular o escoamento sobre uma asa finita submetida a ângulos de ataque próximos ao estol; modelo distribuído para analisar a influência da formação e do adensamento de geada sobre o desempenho de evaporadores do tipo tubo-aletado, comumente usados em refrigeradores frost-free; um algoritmo de Redes Neurais Convolucionais(CNN) que identifica se a pessoa está ou não utilizando a máscara; potencialidades do M-Learning e Virtual Reality no curso técnico em Agropecuária; avaliação da qualidade da energia elétrica em um sistema de geração de energia fotovoltaica; uma abordagem para a segmentação de imagens cerebrais, utilizando o método baseado em algoritmos genéticos pelo método de múltiplos limiares; estudo numérico de uma âncora torpedo sem aletas cravada em solo isotrópico puramente coesivo, utilizando um modelo axissimétrico não-linear em elementos finitos; estudo acerca da análise numérica de placas retangulares por meio do método das diferenças finitas, obtendo soluções aproximadas para o campo de deslocamentos transversais bem como os correspondentes momentos fletores, para problemas envolvendo uma série de condições de contorno, utilizando-se o software Matlab® para simulação; desenvolvimento e aplicação da Realidade Virtual (RV) como Tecnologia de Informação e Comunicação (TIC) para auxiliar no processo de ensino-aprendizado de disciplinas do Ensino Médio; avaliação dos resultados obtidos em campanhas de medição de qualidade da energia elétrica (QEE) na rede básica em 500 kV; examinar o comportamento mecânico-estático de uma longarina compósita projetada para uma aeronave esportiva leve através de investigações numéricas, empreendidas em software (ANSYS Release 19.2) comercial de elementos finitos; construção de um sistema para monitoramento de ativos públicos; a relação da Sociedade 5.0 envolvida no contexto da Indústria 4.0 e a Transformação Digital; algoritmos de seleção e de classificação de atributos, identificando as vinte principais características que contribuem para o desempenho alto ou baixo dos estudantes; a Mask R-CNN, utilizada para a segmentação de produtos automotivos (parabrisas, faróis, lanternas, parachoques e retrovisores) em uma empresa do ramo de reposição automotiva; o nível de usabilidade do aplicativo protótipo para dispositivo móvel na área da saúde voltado ao auxílio do monitoramento móvel no uso de medicamentos em seres humanos.

Sendo assim, está obra é significativa por ser composta por uma gama de trabalhos pertinentes, que permitem aos seus leitores, analisar e discutir diversos assuntos importantes desta área. Por fim, desejamos aos autores, nossos mais sinceros agradecimentos pelas significativas contribuições, e aos nossos leitores, desejamos uma proveitosa leitura, repleta de boas reflexões.

Ernane Rosa Martins

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# CAPÍTULO 16

# PREVENTING SPURIOUS ARTIFACTS WITH CONSISTENT INTERPOLATION OF PROPERTIES BETWEEN CELL CENTERS AND VERTICES IN TWO-DIMENSIONAL RECTILINEAR GRIDS

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**ABSTRACT:** The finite element method (FEM) has been an essential tool in computational structural dynamics (CSD) as much as the finite volume method (FVM) has been in the field of computational fluid dynamics (CFD). These numerical methods and many other scientific applications (such as sedimentary process simulations, reservoir modelling, digital terrains) rely on cell-centered (CC) or cell-vertex (CV) meshes. For two-dimensional meshes, it is rather simple to interpolate property values from CV to CC maintaining local property coherence and continuity. However, the opposite is not valid. When applying the same interpolation approach on properties from CC to CV, spurious artifacts may emerge due to the topologically independent characteristic of the interpolation. In this study, we discuss how to interpolate property values from CC to CV for two-dimensional rectilinear grids and present an algorithm which produces property value distributions that are numerically exact, locally coherent and smooth.

**KEYWORDS:** Interpolation, Rectilinear grids, Artifact prevention, Value projection.

## PREVENÇÃO DE ARTEFATOS ESPÚRIOS ATRAVÉS DE UMA INTERPOLAÇÃO CONSISTENTE ENTRE AS PROPRIEDADES NOS CENTROS E NOS VÉRTICES DAS CÉLULAS EM GRIDS RETILÍNEOS BIDIMENSIONAIS

**RESUMO:** O método de elementos finitos (MEF) tem sido uma ferramenta essencial na dinâmica de estruturas computacional (DEC) tanto quanto o método dos volumes finitos (MVF) tem sido no campo da dinâmica de fluido computacional

(DFC). Esses métodos numéricos e muitas outras aplicações científicas (como simulações de processos sedimentares, modelagem de reservatório, terrenos digitais) dependem de malhas onde propriedades situam-se no centro de células (CC) ou sobre os vértices (CV). Para malhas bidimensionais, é bem simples interpolar valores de propriedade de CV para CC mantendo a coerência e continuidade da propriedade local. Entretanto, o oposto não é válido. Aplicando a mesma abordagem de interpolação de propriedades de CC para CV, artefatos espúrios podem surgir por conta da característica topologicamente independente da interpolação. Nesse estudo é discutido como interpolar valores de propriedade de CC para CV para malhas retilíneas bidimensionais e apresentar um algoritmo que produz distribuições de valores de propriedade que são numericamente exatos, localmente coerentes e suaves.
**PALAVRAS - CHAVE:** Interpolação, Malhas retilíneas, Prevenção de artefatos, Valor de projeção.

## 1 I INTRODUCTION

The finite element method (FEM) is a numerical technique used to solve engineering problems, such as fluid flows, mass transport phenomena and computational structural dynamics (CSD). It considers the discretization of the studied region and the problem's inherent governing equations using *finite elements*. In this sense, local element contributions are assembled into a global linear system that can be solved with the usual methods. This system of algebraic equations approximates the unknown function over the domain (Logan [1]). In turn, the finite volume method (FVM) is a method for representing and evaluating partial differential equations using algebraic equations (LeVeque [2], Toro [3]). Similar to the finite difference method (FDM) or the FEM, values are calculated at discrete places on a meshed geometry. Here, the term *finite volume* refers to the small volume surrounding each node point on a mesh. This method has been traditionally applied to solve computational fluid dynamics (CFD) problems. As exposed by Reddy [4], the subdivision of a whole domain into simpler parts has several advantages as follows: accurate representation of complex geometry, inclusion of dissimilar material properties, easy representation of the global solution and capture of local effects.

Grids underlie a wide variety of natural and familiar structures. Chessboards are grids. City blocks are typically arranged on a grid. The system of latitude and longitude defines a grid over the Earth, albeit on a surface of a sphere instead of a plane. Grids are ubiquitous because they are the most natural way to subdivide space into regions so that locations can be identified. Pushing to the limit, the cells of a grid can be individual points, although, for computational applications, these cells should be big enough to have a shape. In regular grids, each of these shapes is identical and they occur in a regular pattern. Triangle-based hexagonal grids have their importance for specific industry applications, but rectangular and rectilinear subdivisions are the most common grids, due to their simplicity (Skiena and Revilla [5]). These types of grid have an intuitive implicit topology and they are memory efficient, which makes them a nice fit for FEM, FVM and many other scientific applications, such as petroleum reservoir modelling, aerodynamics, digital terrain and geological sedimentation simulation.

Each cell in a regular grid can be addressed by index *(i, j)* in two dimensions or *(i, j, k)* in three dimensions, and each vertex has coordinates ($i \cdot dx, j \cdot dy$) in 2D or ($i \cdot dx, j \cdot dy, k \cdot dz$) in 3D for some real numbers $dx$, $dy$, and $dz$ representing the grid spacing. Figure 1 shows an example of 2D regular grid indexing for cells and vertices, while Fig. 2 shows the indexing for an individual arbitrary cell.

Though regular grids have been used in so many different ways, it's not always easy or safe to move them directly from one application to another without incurring compatibility, positioning and/or numerical errors. Depending on the application, different schemes of data storage are used to represent physical properties in these grids (Carvalho [6]). Conversions from one type of data storage to another may incur a few errors. There are many techniques that could be used to solve these numerical errors, but most of them may also introduce unusual data behaviors, resulting in spurious artifacts. Figure 3 shows an example of a rectilinear grid representing a height map. This grid stores data at the centers of its cells, thus all values at vertices are extracted from these centers to render the height map as a smooth surface.

Figure 4 shows the same rectilinear grid from Fig. 3 after data storage conversion from centers to vertices and several steps of numerical errors minimization. Although the errors were successfully minimized, the resulting surface is no longer smooth and now presents artificial artifacts.

These issues are the subject of this study. Therefore, in Section 3.3, we propose an algorithm that avoids compatibility problems and numerical errors as well as prevents the appearance of spurious artifacts after data storage conversion of two-dimensional rectilinear grids.

## 2 | MODELLING

In geological sedimentation simulations, two-dimensional rectilinear grids are intensively used for modelling, visualization and calculation on different methods, such as Navier-Stokes equations for fluid flow (Carvalho et al. [7]) and stratigraphic sedimentary inversion for mass transport (Raymond [8]). Some of these methods use the rectilinear grids taking into account that values are stored at the centers

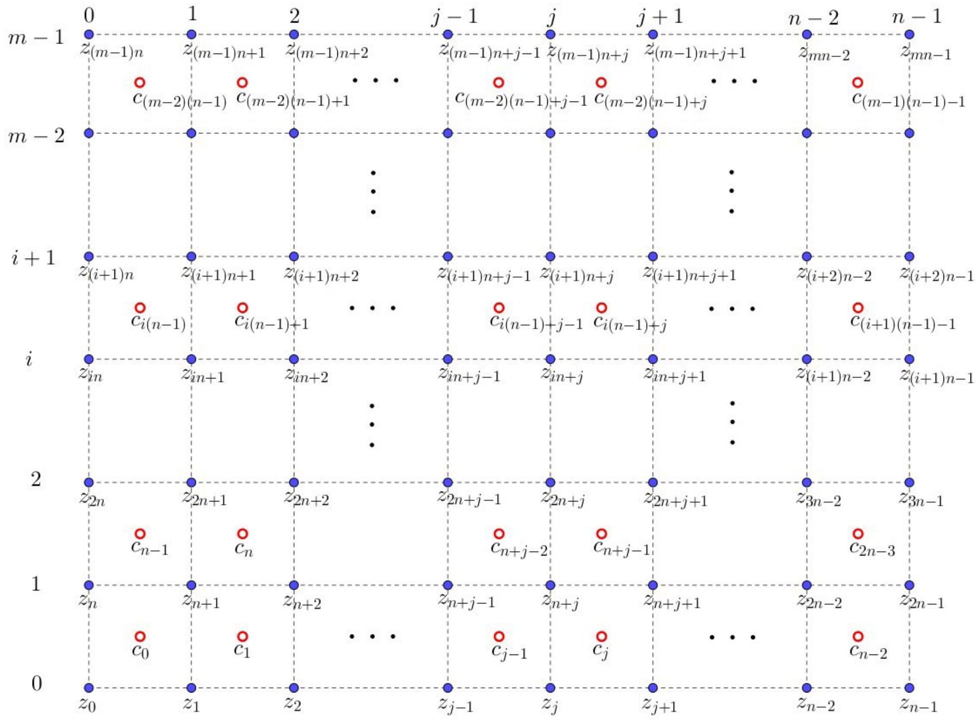


Figure 1. Indexing of two-dimensional rectilinear grid.

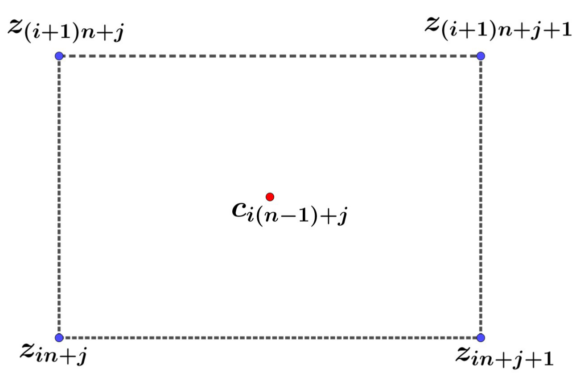


Figure 2. A closer look at the indices of an arbitrary grid cell.

of the cells, which is known as the cell-centered (CC) approach. A few other methods consider the values at the vertices of the grids, which is known as the cell-vertex (CV) (Demirdzic and Muzaferija [9]) or node-centered (NC) (Delis et al. [10]) approach. Blazek [11] discussed the pros and cons of cell-centered and cell-vertex formulations regarding spatial discretization. For some scientific applications, it is important to inter-operate between these two approaches and converting from one kind of grid to the other should not add numerical errors to the data.

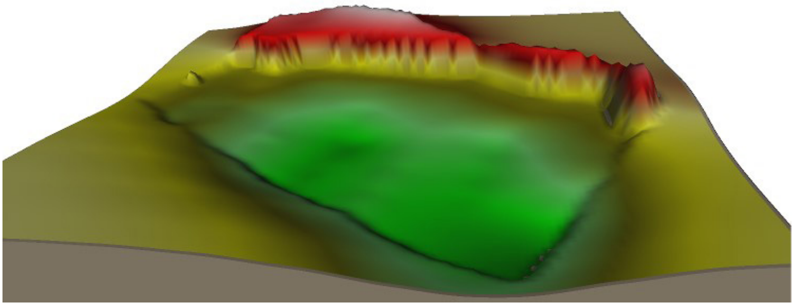

Figure 3. An example of a rectilinear grid representing a height map with data at the centers of grid cells.

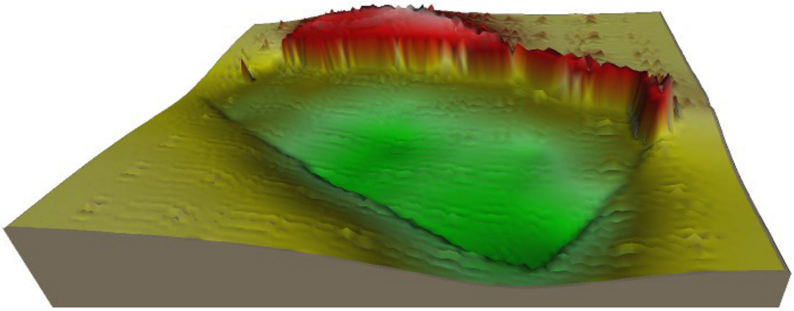

Figure 4. An example of height map presenting artifacts after data storage conversion.

## 2.1 Data positioning

The two data positioning approaches can be distinguished as:

- Cell-centered scheme (Fig. 5): property values are stored at the centroids of the grid cells. Thus, in FVM, the control volumes are identical to the grid cells.

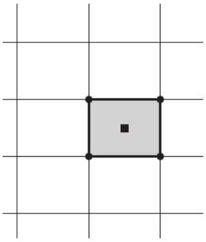

Figure 5. The gray area represents a single control volume of cell-centered scheme on a grid.

- Cell-vertex scheme (Fig. 6): property values are stored at the grid points. In FVM, the control volume can then either be the union of all cells sharing the grid point, or some volume centered around the grid point. In the former case, we speak for overlapping control volumes, in the second case of dual control volumes.

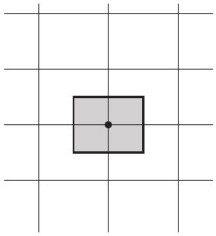

Figure 6. The gray area represents a single dual control volume of cell-vertex scheme on a grid.

The cell-centered approach has been the common method in CFD and it can efficiently support most of the computational codes for the simulation of fluid flows in an accurate and efficient manner. A continuum field which undergoes motion is governed by the Cauchy's equations, which is valid for both structural and fluid dynamics. The fact that the form of equations of Stokes flows is similar to the form of isotropic incompressible linear elastic solids has motivated many researchers to implement CFD methods, developed for the solution of incompressible fluids flows, for modelling displacement in solids (Demirdzic and Muzaferija [9], Henry and Collins [12]).

Unlike cell-centered approach, the origin of cell-vertex idea in CSD comes from traditional FEM, which uses shape functions for spatial discretization. In this approach, the solution points are the vertices of the numerical grid and the control volumes enclosing them are the median dual of the mesh (Hejranfar and Azampour [13]).

Although CV and CC methods have been largely developed, there are no extensive investigations in literature on the assessment of these two different approaches in terms of accuracy and performance. Fallah [14]'s study examined these aspects for CSD, while Delis et al. [10] and Diskin et al. [15] investigated it for CFD. However, the main goal of this study isn't to compare cell-centered and cell-vertex approaches or to determine which one is better for CSD, but to offer an algorithm to safely convert a cell-centered grid to a cell-vertex one without adding numerical error to the data and without generating artificial artifacts on the mesh.

## 2.2 Interpolation

Given a number of data points, obtained by sampling or experimentation, which represent the values of a function for a limited number of values of the independent variable, the interpolation is the estimation of the value of that function for an intermediate value of the independent variable. This is an essential tool for engineering and many of its aspects are relevant on the outcome of a method or a simulation, and are especially significant on data visualization, data interpretation and decision making. The choice of the interpolation to be used must consider the numerical error associated to it, the desired smoothness and the fact that several estimations may produce undesirable data behavior. There are cases where numerical errors are less important than smoothness (3d visualization). There are cases where numerical errors aren't tolerated at all and smoothness isn't even considered (well boring). Each field of study has its own characteristics and there isn't an interpolation method which can solve elegantly all estimation problems.

There are various techniques to perform these estimations and each one of them have their pros and cons. In the industry, the most common techniques are based upon a mathematical function (constant, linear, polynomial, spline) associated to a distance criterion between the location to be estimated and the sampled data set. The simplest interpolation method is to locate the nearest data point and assign its value. This method is unlikely to be used as it incurs a considerable numerical error and because linear interpolation is almost as easy, but in higher-dimensional multivariate interpolation, this could be a favorable choice for its speed and simplicity. Linear interpolation is intuitive, fast and easy to implement, but it is not very precise. Another disadvantage is that the interpolant is not differentiable at the sampled points. Polynomial interpolation is a generalization of linear interpolation where the interpolant is a polynomial and thus infinitely differentiable. However, polynomial interpolation also has some disadvantages. Calculating the interpolating polynomial is computationally expensive compared to linear interpolation. Furthermore, polynomial interpolation may exhibit oscillatory artifacts, especially at the end points like the ones seen on Runge's phenomenon (Schlomilch et al. [16]). Spline interpolation uses low-degree polynomials in each of the points intervals and chooses the polynomial pieces such that they fit smoothly together. The resulting function is called a *spline*. For instance, the natural cubic spline is piecewise cubic, twice continuously differentiable and its second derivative is zero at the end points. Like polynomial interpolation, spline interpolation is less efficient but incurs a smaller error than linear interpolation and the interpolant is smoother. Also, the interpolant is easier to evaluate than the high-degree polynomials used in polynomial interpolation. However, the global nature of the basis functions leads to ill-conditioning, though this effect can be mitigated by using splines of compact support (Kress [17]).

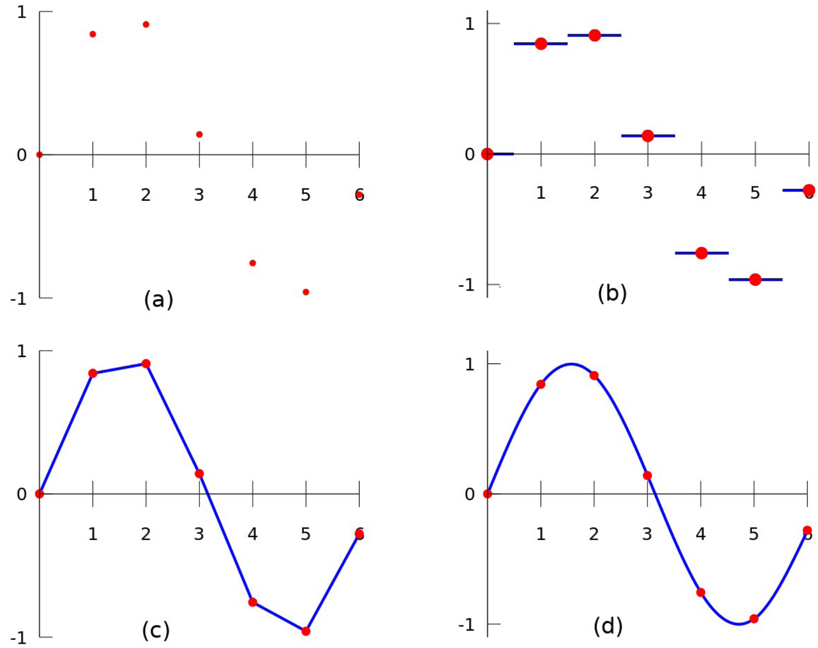


Figure 7. Three examples of interpolations using a given point set (a): nearest neighbor approximation (b), linear interpolation (c) and spline (d).

Converting a property values grid from CC to CV or vice-verse requires estimations of several values in different, usually internal, locations of the two-dimensional grid. In geological sedimentation simulations, every aspect of interpolation is taken into account when choosing the interpolation method. It is crucial to this sort of applications to have small numerical errors and to show natural surface smoothness, as well as it is mandatory to not present artifacts, once their appearances may ruin some patterns found in nature and lead to erroneous data interpretation. In this field, grids have high resolution and conversions are made over a considerable number of grids in various steps of the simulation process.

This means that interpolation is intensively used, thus it is also imperative that the chosen interpolation must be computationally efficient.

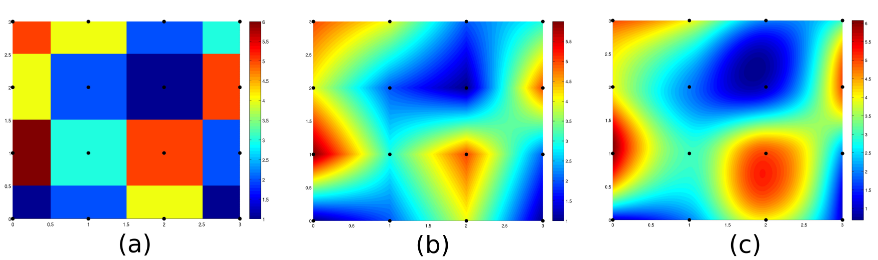


Figure 8. Interpolations in higher dimensions: nearest neighbor (a), bilinear (b) and bicubic (c).

For two-dimensional meshes, it is rather simple to interpolate property values from CV to CC maintaining local property coherence and continuity. For rectilinear grids, the centers of the cells correspond to the dual mesh vertices of CV grid, where each center lies at the same distance to each of the four cell's vertices. So, an estimated property value located at a cell center is simply the average value of the four property values correspondent to the cell's vertices. This interpolation generates a smooth and coherent distribution, maintaining local features and avoiding numerical errors.

However, the opposite operation doesn't generate a numerically exact distribution of property values for grid vertices. In previous conversion, all centers have necessarily four vertices to address when performing the interpolation. In this case, when converting from cell-centered to cell-vertex positioning scheme, the vertices on the borders of the CV grid don't have four cell centers to address, which implies a natural numerical error on the border. The border error could be eliminated by eroding the resulting grid, which is not always a satisfactory solution, depending on the grid resolution, the problem statements and the number of conversions to be realized. The numerical error in the border vertices could also be mitigated by spreading it through the whole grid, adjusting vertices values from outside in, degenerating local features and probably invalidating the entire grid for most cases. In addition to this border issue, when applying the same interpolation approach on data values from cell-centered to cell-vertex scheme and vice-verse, the values at vertices cannot be used to continuously convert from CV to CC to CV and so on in such a way that the same two grids are alternately produced. A different interpolation approach must be used to allow continuous conversions, grid structural maintenance and local property coherence.

## 3 I CONVERSION STRATEGIES

In this study, we present three conversion strategies for interpolating property values from CC to CV on two-dimensional rectilinear grids: a minimalist strategy, an iterative approximation strategy and an iterative analytic strategy. We also analyze their numerical errors, convergence, performance and visual results. For simplicity and visual evaluation purposes, we use two-dimensional rectilinear grids with cartesian z coordinate mapped as the property value for cell centers and vertices, although any physical scalar property could be used to produce similar results. Doing this allows us to visualize in three dimensions the surface smoothness and eventually some spurious artifacts that may emerge from the conversion process.

Figure 9 shows the rectilinear grid used on our examples. In this grid, the property data (z coordinates) are stored at cell centers and we perform conversions to vertices data according to the aforementioned strategies. Note that all grid cells are axis-aligned, but not all of them are valid. The invalid cells are not even drawn and they are treated separately from the valid ones during data storage positioning conversion. Every vertex adjacent to an invalid cell is treated the same way the vertices at the border of the grid. This feature allows us to simulate grid rotations while keeping all advantages of an axis-aligned grid, but it also implies that any border problems could occur in any grid position.

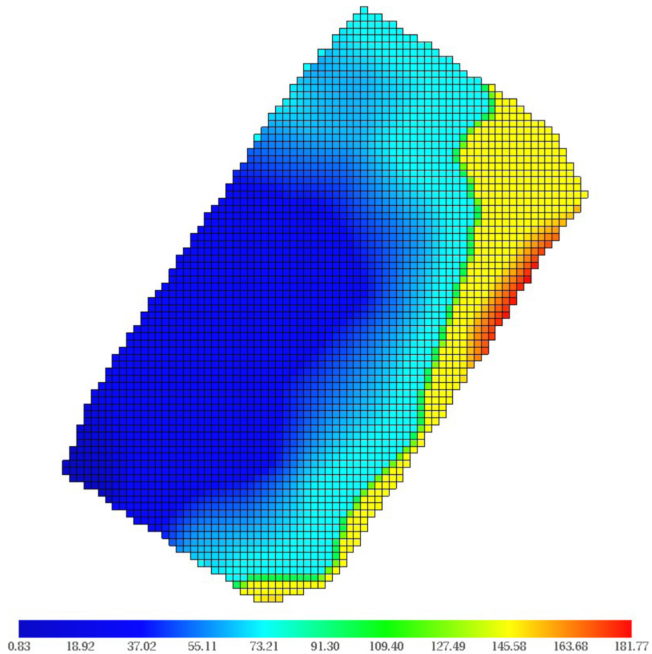


Figure 9. Two-dimensional rectilinear grid with data (height values) stored at cell centers.

### 3.1 Minimalist strategy

This strategy consists in calculating a vertex value based on closest cell center values. Each inner vertex has four adjacent cells whose centers are equidistant to it in a two-dimensional rectilinear grid. Corner vertices have only one adjacent cell, while other border vertices have two adjacent cells each, also equidistant to them. Considering this location property, the estimated vertex value is the average of all adjacent cell center values. No further processing is performed in this strategy. This estimation provokes slight numerical errors at the interior of the grid, as shown in Fig. 10, and coarse numerical errors on borders and near slopes, as illustrated on Fig. 11.

Figure 10 displays two surfaces with different colors. The green surface is the result of the minimalist strategy conversion from CC to CV scheme. The blue surface is the original surface with values stored at cell centers. Both surfaces should coincide, but they just overlap at a few certain spots.

Figure 11 shows the magnitude of this minimalist estimation approach's problems: near slopes, where the function gradient is very high, the algorithm introduces a considerable error to vertices data.

### 3.2 Iterative approximation strategy

This strategy is based on an error minimization technique. It is composed by an early processing phase and an iterative process with three steps in each iteration. Initially, the algorithm calculates all vertices values the same way minimalist strategy does, regarding the rectilinear grid's location property. Then, three steps of value adjustment are executed repeatedly until the error criterion is satisfied. The first step creates a cell-centered grid based on current estimated vertices values. Since all cells have four corresponding vertices on CV grid, the estimated value of a cell center is the average value of these four vertices values. The second step determines the errors by subtracting the original CC grid by newly created CC grid. The third step calculates and applies value adjustment on each vertex of CV grid based exclusively on both cell adjacency and the errors resulting from the second step.

This strategy offers fair convergence rate, minimizes both border problems and inner numerical errors, and produces smooth surfaces in most cases. Nevertheless, spurious artifacts may emerge re-

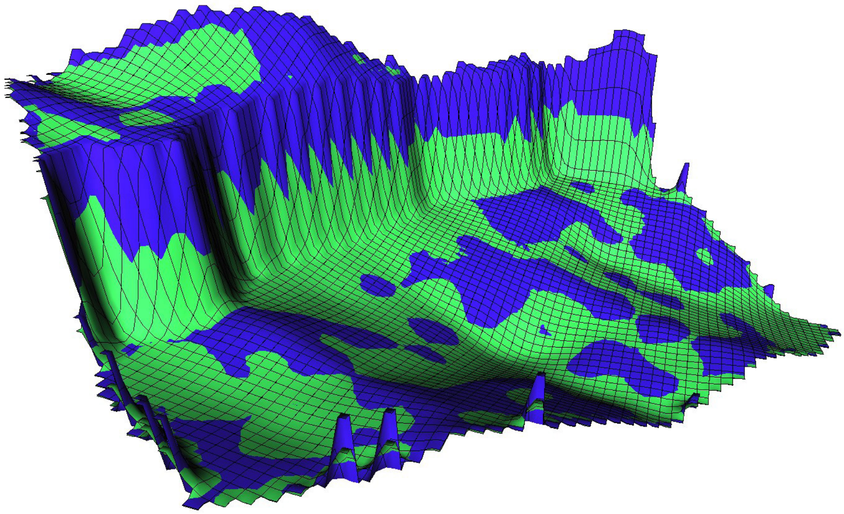

Figure 10. The result of minimalist strategy conversion from CC to CV compared to the original surface with values at cell centers. This image shows models scaled up vertically by 100 times.

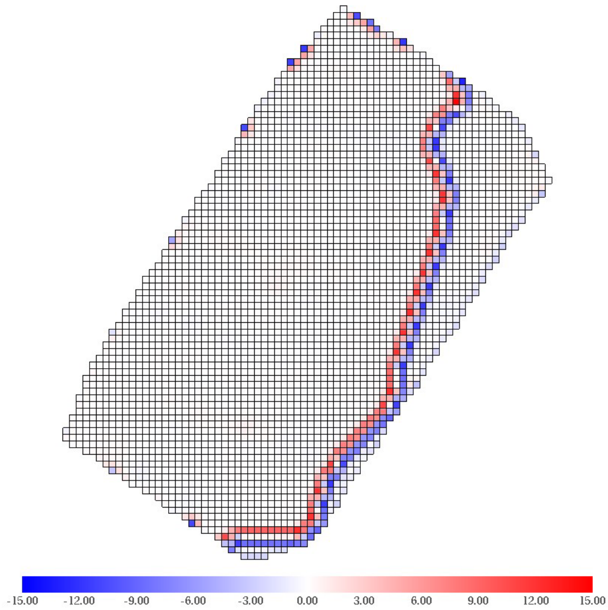


Figure 11. Error map from minimalist strategy conversion.

sulting from the topologically independent characteristic of the interpolation. Once the algorithm tries to approximate the vertex property values independently, two neighbor vertices may have their values adjusted in opposite ways. If this behavior occurs alternately along any direction, artifacts emerge in just a few iterations. This effect can be seen as wave patterns in Fig. 12.

In spite of spurious artifacts appearing in the grid data, this strategy produces low errors after a few iterations. These errors are spread over the whole grid, as one can see in Fig. 13.

In this example, we used 1024 iterations and its convergence is depicted in Fig. 14. The algorithm performance is acceptable, despite of its complicated nature for parallel design and development in the vertices' adjustment step.

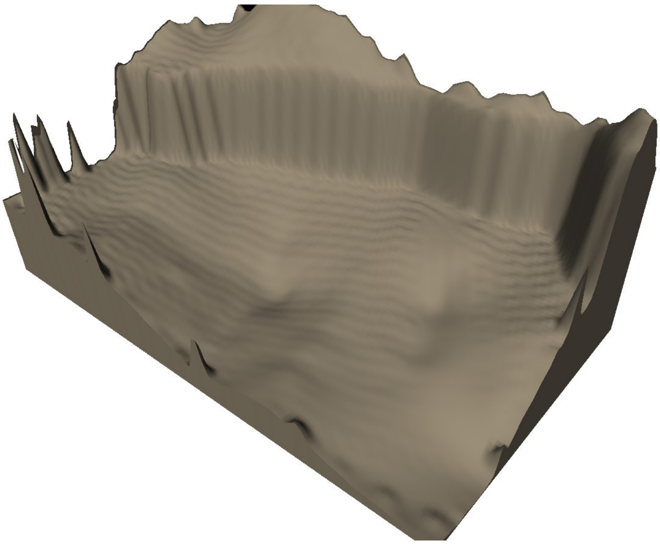

Figure 12. Result of iterative approximation strategy conversion from CC to CV scheme. This image shows a model scaled up vertically by 100 times.

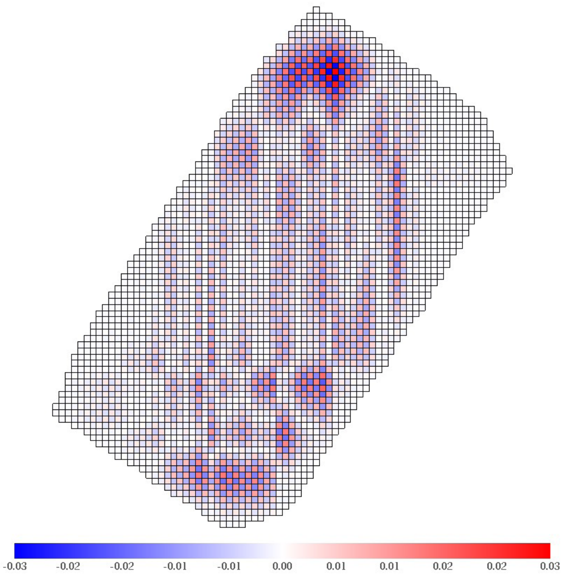


Figure 13. Error map from iterative approximation strategy conversion.

Artifacts become more evident when consecutive conversions are performed. To illustrate this undesirable effect, we executed three consecutive conversions on our example grid and the result can be seen in Fig. 15.

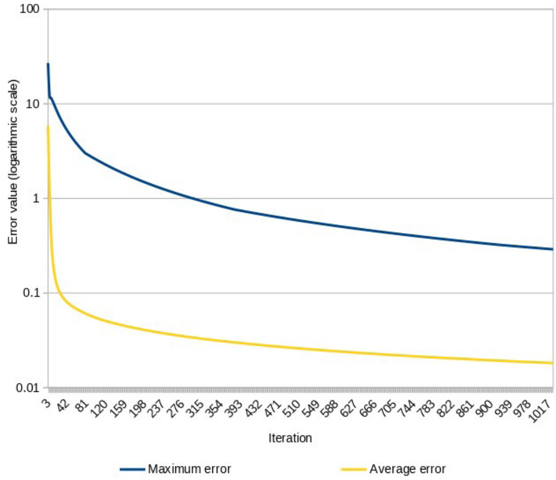


Figure 14. Iterative approximation strategy convergence chart.

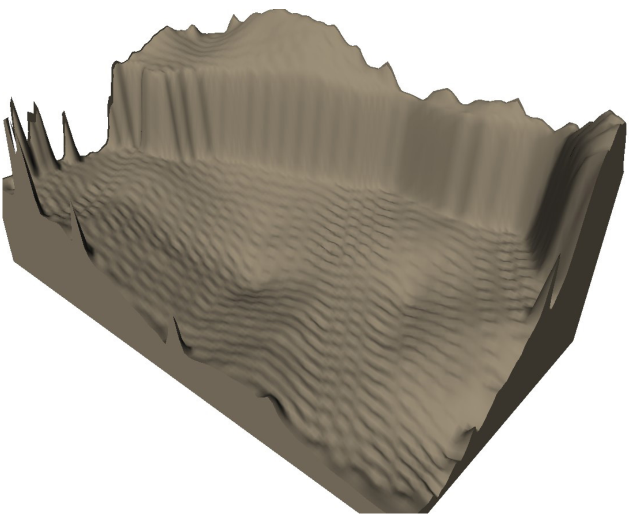

Figure 15. Result of three iterative approximation strategy conversions from CC to CV and vice-verse. This image shows a model scaled up vertically by 100 times.

### 3.3 Iterative analytic strategy

Previous strategies perform values estimations for grid vertices aiming to reach a scenario where calculated values at cell centers approximate the original cell-centered stored data as good as possible. It is an intuitive way to solve the problem and different algorithms may be used to achieve that. Unlike these approaches, the analytic strategy does not try to calculate the values at the vertices directly or by iterative approximation. Instead, it will use vertices/centers relations to create a system of linear equations and solve it.

There are two main relations among the vertices of a cell and its center. The first one dictates that a value at the cell center is composed by the average of the values at the four cell's vertices. This *locality property* is valid for every grid cell. Given the vertices and cells represented on Fig. 16, the following equations are obtained according to the mentioned relation:

$$
\begin{aligned}
4c_0 &= z_0 + z_1 + z_3 + z_4,\\
4c_1 &= z_1 + z_2 + z_4 + z_5,\\
4c_2 &= z_3 + z_4 + z_6 + z_7,\\
4c_3 &= z_4 + z_5 + z_7 + z_8.
\end{aligned}
$$

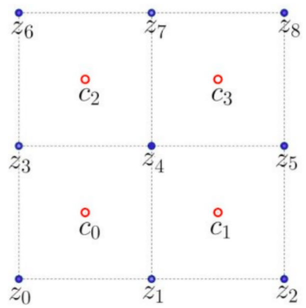


Figure 16. Indexing of two-dimensional rectilinear cell-centered grid.

The same relation and equations were used by previously described strategies on Section 3.1 and Section 3.2 to determine the value at vertex $z_i$ using values $c_i$ at cell centers. Generically, for a grid with dimensions $m \times n$, the system of equations is:

$$4c_k = z_{(k+i-1)} + z_{(k+i)} + z_{(\tilde{k}+i-1)} + z_{(\tilde{k}+i)} \qquad (1)$$

for $i = (0, 1, ..., m-1)$ and $j = (0, 1, ..., n-1)$,

$$A\mathbf{z} = 4\mathbf{c}, \qquad (2)$$

where $A \in \mathrm{R}^{m1 \times n1}$, the variables vector $\mathbf{z} \in \mathrm{R}^{n1}$ and the centers vector $\mathbf{c} \in \mathrm{R}^{m1}$, and $m_1 = m \times n$, $n_1 = (m+1) \times (n+1)$.

The second relation among grid vertices and cell centers can be seen as the *smooth criterion*, and it suggests that values at vertices can be calculated by values of neighboring centers. For corner vertices, we consider only the closest center. For other border vertices, we consider just two closest centers. For other grid vertices, we consider the four centers of the cells containing the vertex. Applying this relation to the grid depicted on Fig. 16 results in the following equations:

$$
\begin{aligned}
z_0 &= c_0, \\
z_1 &= \frac{c_0 + c_1}{2}, \\
z_2 &= c_1, \\
z_3 &= \frac{c_0 + c_2}{2}, \\
z_4 &= \frac{c_0 + c_1 + c_2 + c_3}{4} \\
z_5 &= \frac{c_1 + c_3}{2}, \\
z_6 &= c_2, \\
z_7 &= \frac{c_2 + c_3}{2}, \\
z_8 &= c_3.
\end{aligned}
$$

Similar equations were also used by the strategy describe on Section 3.2 when trying to approximate the values at grid vertices using an iterative technique. However, in the analytic strategy, the system of linear equations is created by combining the locality property to the smooth criterion, and it is constructed not to compute the values at grid vertices, but to compute the set of values at cell centers which satisfies both relations. In other words, using the smooth criterion equations, we calculate an artificial cell-centered grid whose values produce a CV grid which satisfies the locality property. The artificial grid equivalent to the CC grid illustrated of Fig. 16 can be seen on Fig. 17.

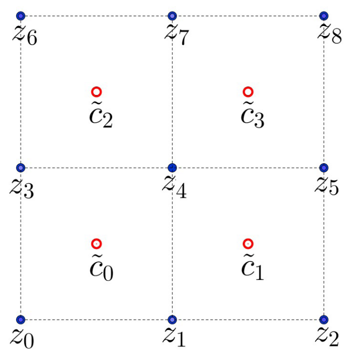


Figure 17. Indexing of two-dimensional rectilinear artificial cell-centered grid.

To accomplish the analytic strategy proposal, the original CC values are used only to satisfy the locality property, i. e. the average of all values at one cell's vertices will be equal to the original value stored in that cell. The smooth criterion is used to determine the system's variables, i. e. the set of cell-centered values which produce smooth values at vertices when applying the locality property equations. This approach generates the following equations:

$$16c_0 = 9\tilde{c}_0 + 3\tilde{c}_1 + 3\tilde{c}_n + \tilde{c}_{n+1},$$

$$16c_i = 3\tilde{c}_{i-1} + 6\tilde{c}_i + 3\tilde{c}_{i+1} + \tilde{c}_{n+i-1} + 2\tilde{c}_{n+i} + \tilde{c}_{n+i+1}, \text{ for } i = (1, 2, \ldots, n-2),$$

$$16c_{n-1} = 3\tilde{c}_{n-2} + 9\tilde{c}_{n-1} + \tilde{c}_{2n-2} + 3\tilde{c}_{2n-1},$$

$$\tilde{A}\,\tilde{\boldsymbol{c}} = 16\,\boldsymbol{c} \quad (3)$$

Matrix $\tilde{A}$ from the system of linear equations is positive and symmetric. This means that more elegant methods could be used to solve this system using the matrix $\tilde{A}$'s spectral characteristics, but initially we used a simple iterative approach to solve it. The analytical result of this system is the cell-centered grid whose vertices/centers locality property is assured. To retrieve the desired CV grid, we just apply the resulting solution to the smooth criterion equations.

As illustrated in Fig. 18, the resulting surface is very smooth and do not present artifacts.

As we didn't solve the system of linear equations analytically, but using an iterative processing, the resulting CV grid presented a few low errors as seen on Fig. 19. Once the purely analytic solution is provided, this strategy will produce exact solutions.

Although not producing exact solutions, the current iterative method utilized to solve the system has great convergence rate as shown in Fig. 20 and its performance is even better than the one seen on Section 3.2.

## 4 | CONCLUSION AND FUTURE WORK

Engineering applications make use of algorithms and data structures to represent real world events and elements. The data structures typically store data originated from sampling or experimentation, and they are the basics for most of current methods. Robust and reliable manipulation of these data structures

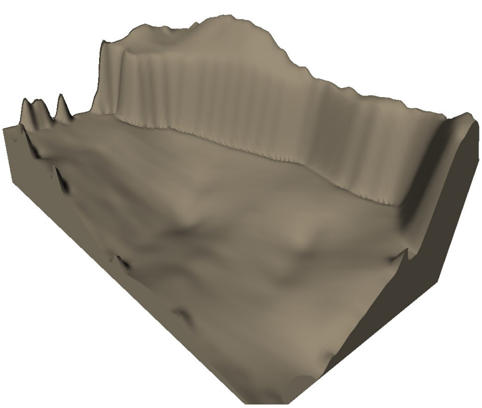

Figure 18. Result of iterative analytic strategy conversion from CC to CV scheme. This image shows a model scaled up vertically by 100 times.

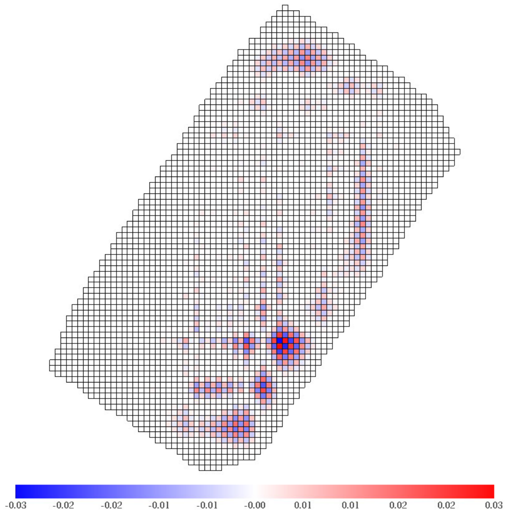


Figure 19. Error map from iterative analytic strategy conversion.

are fundamental, especially in areas where data precision is critical and visual results support natural events interpretation, such as Oil & Gas exploitation, geologic simulations and reservoir modelling. In this scenario, interpolation methods arise as significant mechanisms for data estimation over regions uncovered by sampled data.

We presented a new method for data positioning conversion on two-dimensional rectilinear grids. This new strategy solves complications created by either direct algorithms or purely mathematical methods. It minimizes numerical errors, presents good convergence rate and generates smooth values distribution, proving to be a valuable tool for scientific applications.

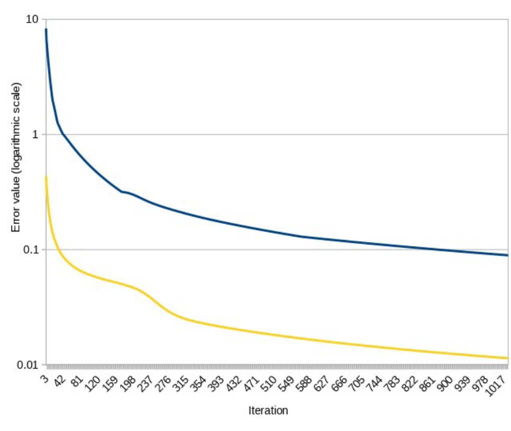


Figure 20. Iterative analytic strategy convergence chart.

The next natural step is to provide an analytic solution to the system of linear equations presented on Section 3.3. Although subjective and deeply related to data peculiarities, further artifact appearances could be avoided by using different smooth criteria which generate distinct systems of linear equations.

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