Research article

Fit-for-purpose conformal mapping for sustainable land administration in war-ravaged Syria

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ABSTRACT

Over the last nine years, the ongoing armed conflict in Syria has had a devastating impact on properties and infrastructure, making it necessary to rebuild everything from scratch. As spatial data are a pillar to enhance sustainable socio-economic development, it should be georeferenced and reformed to keep up with the tremendous growth in information and communication technology. On the other hand, the low-distortion conformal mapping contributes significantly to changing the position of any feature on the earth's surface onto a plane to create accurate large-scale spatial data. The current research conducts an analytical study using spatial statistics tools to investigate an optimal conformal projection for representing the Syrian area in a single zone that preserves angles locally, reduces linear distortions, and fulfills modern geospatial technologies' requirements. The findings have shown the applicability of the proposed model as an alternative solution to minimize the scale error over the interest area. In addition, the isograms pattern is close to the shape of the area, and better fits the quality criteria of the chosen projection.

1. Introduction

Modern advancements in geospatial technologies have opened a new horizon in the growth of data capturing techniques and depicting geographic features on a map. In general, the location of each point on a map is defined according to a specific reference system that should be selected carefully to achieve a high level of positional accuracy of geospatial data (Snyder, 1997; Kneisel et al., 2011). Map projection plays a vital role in converting the earth's curved according to an identified set of mathematical rules onto a developable surface that can be cut and flattened without stretching or tearing (Deetz and Adams, 1945; Kerkovits and Takáts, 2020; Lü, 2021). In contrast, distortion cannot be entirely avoided when transforming geodetic positions (latitude \( \varphi \), longitude \( \lambda \)) on an ellipsoidal datum to rectangular coordinates (E, N) on a chart, but it can be controlled and systematized to a certain degree (Mulcahy and Clarke, 2001). Euler (1778) reported that a spherical surface could not be projected into a flat sheet with zero deformation. Accordingly, any map involves some inevitable form of distortion in the shape, area, and distance that is expressed by the scale factor (Habib & A'kif, 2019). The difficulty of projection design is in developing a method for systematically drawing an ellipsoidal graticule on a map to guarantee specific desired characteristics as much as possible. The conformal property maintains angles locally and equalizes linear error in every direction around any point (Miller, 1953; Thomas, 1952). However, the shape of extended features will appear distorted due to changing the linear scale from one point to another (Vanicek and Krakiwsky, 2015). Conformal mapping is an active multidiscipline research topic for which it has been used in various applications, including surface parameterizations (Choi & Lui, 2015, 2018; Choi et al., 2020), stress intensity factor analysis (Li and Zheng, 2021), digital image correlation (Ye et al., 2022). Practically, understanding various projection characteristics is crucial for choosing an appropriate mapping system that highly affects the visualization and analysis of geographic information (Gosling and Symeonakis, 2020).

The digital transformation toward knowledge-based economies has encouraged many countries to create an e-government environment that delivers high-quality services. Building a paperless land administration system (LAS) within the context of the e-government paradigm is considered a critical component of geospatial information infrastructure (Basu, 2004; Van Oosterom et al., 2009). It is a powerful tool for land market valuation (Enemark et al., 2005), sustainable development (Pflüger, 2011), and security of property rights (Zevenbergen et al., 2013; Habib, 2020). Typically, geospatial information is data referenced to a place (Schade et al., 2020) that includes photogrammetry, surveying, geodesy, remote sensing, digital image processing, web mapping,
geographic information systems (GIS), cartography, global navigation satellite systems (GNSS), and decision support systems...etc. Therefore, all efforts must be devoted to unifying and modernizing the existing georeferencing systems, which rely on a single zone to establish a spatial data foundation that facilitates data sharing and integration. The multi-zone reference system hinders GIS applications through the necessity to switch between different stripes and originates spatially displaced points with the exact coordinates (Hartzell et al., 2002). The renewal of the adopted map projection must balance the benefits of retaining it against long-term expenses and risks.

Syria has employed two different geodetic datums to conduct military and civilian surveying and mapping activities (Habib and Pradhan, 2019). Transverse Mercator and Lambert projections were used in creating small-scale topographic maps for military purposes. Oblique stereographic projection was applied during the French mandate time in 1920 and consisted of the cultivated land and the country’s most important part to represent the geographic locations needed to produce cadastral and large-scale topographic maps (Habib, 2008). This situation has varied after land reclamation and oil exploration operations in Al Jazeera. The current form of adopted reference is not in line with the requirements of new technologies. Besides, the ongoing dispute in Syria has turned its cities into scenes of apocalyptic destruction and caused severe damage to human capital and geodetic infrastructure (Tan and Perudin, 2019). Accordingly, the central objective of this study is to propose a low-distortion conformal projection for modeling the complete area onto a unique flat surface that is sufficiently fit-for-purpose to be a keystone of an efficient e-LAS for conflict resilience in Syria.

2. Materials and methods

Sustainable development goals (SDGs) as a blueprint to build a better world for humanity must balance social, economic, and environmental dimensions (GA, 2015). Government policies, human capital accumulation, and technology diffusion are substantial for delivering these targets (Benhabib and Spiegel, 2005; Jenny et al., 2017). Spatial data infrastructure plays a pivotal role in e-government, and thus the investment in it will boost SDG achievement (Barbero et al., 2019). The most critical challenge in implementing geodatabases is to create accurate spatially referenced data from multi-sources that should be begun by establishing a fundamental geodetic base in which map projection remains its backbone. The ellipsoidal points can be converted into a plane by a double-conformal projection approach using the sphere as an intermediate surface. The scale factor changes from one place to another and is usually different in all directions. When designing a map projection, the primary purpose is to minimize the variation between geodetic and grid distances as much as possible (Gyorffy, 2018; De Genst and Canters, 1996). This paper focuses on analyzing the present status of applied conformal projection in Syria to identify its problems and faults to move towards the most appropriate grid coordinate system for the digital era based on the recommended quality standards and mainstream geospatial technology.

2.1. Case study description

The chosen test area is the Syrian Arab Republic in the Middle East region, consisting of 14 governorates, as described in Figure 1. It characterizes by gorgeous natural scenery and a heterogeneous landscape with high mountains, fertile plains, deserts, and the Mediterranean Sea to the western part. Syria desert (Badiyat al-Sham) covers parts of southeastern Syria by about two-thirds of the overall area. The country was the site of many early civilizations and home to different ethnic and religious gatherings. Damascus city is counted among the oldest continuously populated capital in the world. The geographical location of Syria is bounded by latitude 32° 30’ N - 37° 30’ N and longitude 35° 30’ E - 42° 30’ E, with a total area of about 184,479 km². The land lies at an average elevation of 514 m above mean sea level. Jordan is a neighbor of Syria to the south, Turkey to the north, Iraq to the east, and the Mediterranean Sea and Lebanon to the west.

In the country, three families of map projections represent real places on a flat piece of paper. They have been developed in different conditions according to the purpose for which the map is required. The territory utilizes a triple-zone rectangular coordinate system based on the transverse Mercator projection to sustain a 1:10000 precision between ellipsoidal and plane lengths. This system is characterized by minimal scale errors within a small band extending on either side of the central meridian, but areas further away will be more distorted. In any case, the transverse Mercator projection will no longer be considered in this research. The cone surface in Syrian Lambert conformal mapping is...
tangent to the country at the latitude of origin $\varphi_0 = 34° 39' N$ with the scale factor equals $0.9996256$, which makes it cut the earth at two standard parallels $33° 04' 24.36'' N$ in addition $36° 12' 59.20'' N$ and false easting and northing $E_0 = N_0 = 300000 m$. Distance precision of Lambert projection is constant in an east-west direction versus north-south for transverse Mercator.

The applied stereographic projection was devised to touch the area at $\varphi_0 = 34° 12' N$ and a longitude of the central meridian $\lambda_0 = 39° 09' E$ according to the political and economic importance of the territory and the level of accuracy required at that period. The mapping equations were derived for the forward problem using an infinite power series to convert directly from an ellipsoid to a plane. The scale factor $k_0$ has been introduced an accurate model to calculate direct/reverse transformation equations in the present stereographic system using a closed mathematical formula based on a double projection method. Furthermore, data sharing is not applicable as there is no integrated connection between various authorities, leading to duplication of effort and excess costs.

Presently, Syria suffers from large-scale violence that caused extensive devastation to every aspect of life. The importance of instituting a knowledge-based land administration system emerges to guarantee housing, land, and property rights issues and support sustainable development. Therefore, the reconstruction process should be devoted to updating geodetic infrastructure to keep in touch with advanced geospatial technologies and address property-related issues that may hamper economic and social promotion. On the other side, this transition in post-conflict Syria requires effective and meaningful participation from all relevant stakeholders to put forth suggestions to solve many legal, political, and technical matters.

### 2.2. Research methodology

Tellidis and Kappler (2016) indicated the importance of information and communications technology (ICT) in peacebuilding, achieving sustainable growth, and restoring war-torn countries. Hence, ICT-based innovative solutions are essential in establishing computerized geospatial data for various land administration applications. An accurate representation of the earth’s surface is needed using georeferencing systems, which describe the location of geographical entities in the world. This study endeavors to design an optimal map projection for building spatial data infrastructure within the context of e-government in post-conflict Syria, relying on the principle of reducing overall scale errors and representing the area in a single zone. Firstly, the current situation will be reviewed to highlight the deficiencies in the applied mapping systems through in-depth inspection and evaluation. This analysis will identify the key drivers and criteria for changing the existing projection to suit an electronic information environment. A low-cost tool will be developed to convert geodetic coordinates on spheroid to projected ones. Also, an evaluation of the proposed model will be performed to verify that it best meets the required quality criteria of the selected projection. Finally, the conclusions can be drawn based on the research findings. Accordingly, Figure 2 shows a methodology flowchart utilized in this research.

### 2.3. Selection of appropriate projection

Indeed, a large variety of projections allows the possibility of adopting the best one for depicting a portion of the earth on a flat surface while retaining the specific characteristics for a particular application. The quantity, kind, and pattern of distortions indicate the relationships between information on a map and features in the real world controlled by choosing a suitable mapping system (Brainerd and Pang, 2001). The selection of map projection depends on several factors such as characteristics and extent of an area, location, preserved properties, and the aim of spatial data (Nyerges and Jankowski, 1989). Also, implementing a single strip coordinate system in the country will eliminate the need for converting into another coordinate system outside zonal boundaries in a multi-band model. The fit-for-purpose conformal mapping system in war-torn Syria is designed to be highly compatible with the prevailing requirements of map-making and use and fill gaps in the current ones. Its parameters are defined by reducing the errors in linear scale and keeping the area in one belt. Figure 3 indicates a graphical diagram for determining a proper representation of spheroidal points upon a plane.

The visual appearance of the isogram surface is an effective procedure to describe the distance distortion pattern for assessing the suitability of a new projection to the area. Besides, statistics indices of linear error values are beneficial to detect high deformation at a global level. Distortion profiles are another technique to inspect locally significant distortion differences. Young’s formula specifies a class of projection by drawing two parallel lines that bound the considered domain in its

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**Figure 2.** Graphical illustration of the research methodology.

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**Figure 3.** Schematic flowchart to select a suitable map projection.
slightest spread direction (Young, 1920; Maling, 2013). According to this rule, Figure 4 shows a representative description to specify the most appropriate projection of the Syrian area. In practice, if the value \( \frac{\delta_2}{\delta_1} \) (\( \delta_1 \) distance between two parallel lines bounded the area, \( \delta_2 \) maximum extent of the area from its center) is less than 1.41, then the azimuthal projection should be used, but if the ratio is more significant than 1.41, a conic or cylindrical one is more suitable. As a result, the oblique stereographic projection has a superior status for mapping production.

Snyder (1997) advises applying a zenithal projection to the region whose shape is roughly circular. In addition, it has the property of slow variation in distortion away from the origin that allows depicting the extended area in one strip.

2.4. Proposed conformal mapping system in Syria

As stated before, projection is the foremost step in map production that is applied to portray physical features of the earth onto a plane through a specified set of mathematical functions, as written in Eq. (1) (Bildirici, 2003). The Cauchy - Riemann formula, Eq. (2), introduces an essential and sufficient theorem to construct a conformal mapping (Clendinning, 1939). The conformal transformation from spheroidal coordinates into grid ones is executed using complex numbers, as described in Eq. (3) (Canter, 1989; Deakin, 2004).

\[
\begin{align*}
E &= f_1(\varphi, \lambda) \\
N &= f_2(\varphi, \lambda) \\
\frac{\partial E}{\partial \lambda} &= -\frac{\partial N}{\partial \varphi} \\
\frac{\partial N}{\partial \lambda} &= \frac{\partial E}{\partial \varphi} \\
z &= E + iN \\
z' &= \psi + i\lambda \\
z &= f(z')
\end{align*}
\]

where \( z, z' \) complex number, \( i \) imaginary unit, \( \psi \) isometric latitude on an ellipsoid.

Although all projections are performed by calculating grid coordinates of geodetic ones, two mapping techniques, geometrical and mathematical, are used. In general, the geometric method consists of projecting a coordinate system that relies on the globe from a particular point directly onto a developable surface. On the other hand, the mathematical projection is an analytical style to deliver some characteristics. The conformal conversion from an ellipsoid into a sphere can be considered helpful in generalizing the derivation of projections corresponding to the spheroid, as clarified in Figure 5.

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Double-conformal projection is a simple process that yields a distance scale error much lower than changing from a sphere to a plane and returns precisely the same results based on turning geodetic positions on a spheroid onto a sphere and then to a flat surface as follows (Rose-nmund, 1903; Bentsen et al., 1999):

\[
\ln \tan \left(\frac{\pi}{4} - \frac{\phi}{2} \right) = \alpha \left[ \ln \tan \left(\frac{\pi}{4} - \frac{\phi}{2} \right) - \frac{e}{2} \ln \left(1 + e \sin \phi \right) \right] + \delta \tag{4}
\]

in reduced form it becomes:

\[
\psi' = \alpha \psi + \delta \tag{5}
\]

\[
\alpha = \sqrt{1 + \frac{e^2}{1 - e^2} \cos^2 \phi_0} \quad \tag{6}
\]

\[
e = \sqrt{1 - b^2/a^2} \quad \tag{7}
\]

parameter \(\delta\) is specified by replacing \(\psi' = \psi_0'\) and \(\psi = \psi_0\):

\[
\delta = \alpha \psi_0 - \psi_0' \tag{8}
\]

\[
\psi = \sin^{-1} \left( \tanh \psi \right) \tag{9}
\]
The importance of spatial data in decision-making on different land administration and management issues creates a growing demand to organize data across disciplines and institutions by establishing geospatial data infrastructures. One of the focal points in this regard is a design of an optimal map projection suitable for identifying a large-scale spatial database of the region in question. This study discusses the possibility of adjusting the oblique stereographic and applying Laborde projection to the territory of the Syrian Republic according to extremal and minimax criteria. The oblique stereographic is a conformal perspective mapping of the sphere whose origin is placed at any point except the north and south poles or the equator. The transformation equations of this projection were derived based on a sphere (Lee, 1974; Thomson et al., 1977; Glasscock, 1993). Determining a scale factor at the projection center remains problematic and needs more attention to balancing errors and defining a low-distortion conformal map grid. In the modified stereographic projection, its center varied into $\phi_0 = \frac{34}{30}$ N and $\lambda_0 = \frac{39}{30}$ E with $k_0 = 0.999499$ to keep the linear distortions in an acceptable range and a coordinate origin 250000 m east and 350000 m north to get only positive values. Laborde projection is utilized for a conformal depiction of countries with a skewed orientation that generates minimal errors based on reducing the sum of squares of distortions convenient to build a more realistic and consistent benchmarking surface for evaluating the other (Airy, 1861). It is described in mathematical equations and has no direct geometric interpretation (Driencourt and Laborde, 1932; Roggero, 2009; Geomatics...
The minor distortion in the Laborde can be implemented by initially drawing an ellipse of maximum scale error enclosing the Syrian area and giving the best possible fit to the border. The ellipse was oriented diagonally to coincide with the boundary roughly, as shown in Figure 6.

The center of Laborde projection locates at geodetic position \( \phi_o = 35^\circ 12' N, \lambda_o = 38^\circ 06' E \) and \( k_o = 0.9997 \), then its transformation equations are:

\[
E = k_o R \left( \psi - 0.07082016 \left( \psi^3 - 3 \psi \lambda^2 \right) - 0.043638614 \left( 3 \psi^2 \lambda - \lambda^3 \right) \right)
\]

\[
N = k_o R \left( \lambda - 0.07082016 \left( 3 \psi^2 \lambda - \lambda^3 \right) + 0.043638614 \left( \psi^3 - 3 \psi \lambda^2 \right) \right)
\]

(14)

\[
k = 0.9997 \left( 1 + 0.287039513 \psi^2 - 0.26183168 \psi \lambda + 0.212460486 \lambda^2 \right)
\]

(15)

2.5. Software development

A low-cost spatial tool, called "TopoGC", as a specialized software application, was developed in the Microsoft Visual Studio environment for calculating the projection equations. Figure 7 shows a schematic description of the developed software life cycle. The creation process involves six stages that begin with requirement analysis in relation to the context of the system usage and end with performance evaluation and maintenance against the design principles. The logic plan’s detail is stated in the design phase by achieving the flowchart and pseudocode algorithm and then coded using Visual C++ language. Some application dialog boxes are presented in Figure 8 that compute different map projections, grid-on-grid transformations, and conversions between local datums. The coordinates can be inserted manually or from MS-Excel/AutoCAD and modified before processing. The final result can be illustrated, printed, exported to MS-Excel, or drawn in an AutoCAD DWG format file.

2.6. Quality assessment

In this study, numerical criteria measures to investigate the projection performance are applied, including the maximum value (Max), average, standard deviation (STD), root mean square error (RMSE), and Jordan’s total distortion (JTD) of the linear distortions (Nestorov et al., 2020). Moreover, box plots (also known as whisker plots) are often used in descriptive data analysis to visually represent the distribution of numerical values, ranges, and skewness by displaying the data quartiles, medians, and averages, as shown in Figure 9. In reality, the optimal map projection should have the lowest possible values of all the distortion parameters in a variational sense. On the other hand, zonal statistics are a helpful tool for selecting the appropriate map projection by quantifying the relationship between the type of mapping and the resulted linear errors according to provincial divisions (Habib, 2021).

\[
Average = \frac{1}{n} \sum_{i=1}^{n} (d_i)
\]

(16)

\[
STD = \left[ \frac{1}{n} \sum_{i=1}^{n} (d_i - \bar{d})^2 \right]^{1/2}
\]

(17)
RMSE = \[ \sqrt{\frac{1}{n} \sum_{j=1}^{n} (d_j - \bar{d})^2} \]  

(18)

\[ JTD = \sqrt{\sum_{j=1}^{n} (k_j - 1)^2} \]  

(19)

where \( n \) denotes the number of grid points equally distributed along cross-sections of meridians and parallels at a specific over the area of interest, \( d \) linear distortion.

3. Results and discussion

All surveying and mapping activities need a unified reference frame to organize land use planning and development within countries. The present situation in the field of spatial information in Syria is stored in the traditional format with low accuracy fails to meet the requirements of decision-making, forecasting, and development planning. Syria has two different geodetic frames, military and civilian, with coordinates not available for public access, and approximately 90% of the control point markers have been disturbed or destroyed. In addition, the laws and regulations that control the legal aspects of real estate administration and details of working procedures have become outdated but still have to be followed. Figure 10 reviews the most significant problems in the coordinate systems used in Syria to modernize and harmonize them to resolve conflict and attain sustainable development. These issues will cause profound implications for the country's social and economic progress, especially after many people lost their property and housing rights during the ongoing war in Syria. The knowledge community is distinguished by an optimum investment of geospatial information to be used mainly in decision-making. Hence, reliable spatial data are valuable for creating a paperless LAS to conduct more social cohesion and enhance economic growth in war-torn Syria. The reconstruction after violence is pivotal, so...
patches according to administrative divisions of Syria. Statistical analysis will be employed to identify the distortion hot-spot Figure 11, according to regional importance. Hence, the ArcGIS zonal produces the most significant amount of distortion. The small average value in Laborde elucidates that the number of positive errors is near the negative one. Additionally, the sum of absolute errors is highly varied from the Laborde to other systems. The percentage of absolute distortions rises between applied stereographic projection and the proposed stereographic system by 12.6%, while it was 6.1% when using Lambert against the proposed stereographic projection. Overall, the appropriateness analysis of projections shows that the two reference systems, Laborde and proposed stereographic, most closely fulfilled the requirement for developing large-scale geospatial data, but each model has at least one undesirable feature.

Another investigation based on zonal statistics analysis was applied to quantify the distribution of the distortions. Table 2 indicates various error metrics in the addressed mapping systems based on territorial partitions. In addition, box whisker plots, Figure 12 provide statistical visualizations that can directly represent the center, spread, and overall range of a dataset and determine the dispersion, skewness, and outliers in inspected data. Figure 13 shows a class-based disparity between the reviewed projections according to different provinces through box plots. As a result, the distribution of the tested models in Damascus, Aleppo, Daraa, and Latakia zones shows similar performance. At the same time, the proposed stereographic projection in Al-Hasakah was significantly better than other ones since it was tuned to yield improved values at boundary places at the cost of reduced linear error in the desert areas (i.e., some parts of Homs and Deir Ez-Zor governorates). The distance error of the proposed approach mainly showed the highest trend than others in the Raqqa region due to the nature of the stereographic isolines. Figure 14 demonstrates the maximum absolute linear errors of each projection. The evaluation results give insights into the capability of the proposed stereographic surface compared to other ones. In general, it can be seen that the suggested coordinate system achieved controlled peaks in Damascus and Aleppo zones which are regarded as the most important cities in Syria since they are the administrative capital and economic capital, respectively. As pointed out earlier, the maximum error was also remarkably decreased at the Al-Hasakah extremity.
Figure 15 presents the comparative analysis of distortions values derived from the different tested surfaces for the considered zones in the country. The equality plot illustrates the distribution of the points below and above the perfect agreement, where the latter represents higher distortion in the y axis. Indeed, it can be seen from the comparison between the applied and proposed stereographic system that both models yielded similar performances, with the applied one having more points under the equality line, which means that it has higher distortions in more locations as compared to the proposed model. A similar conclusion can be seen in the case of Laborde vs. the proposed stereographic system, where the earlier had more errors in a significantly higher number of points. On the other hand, both the proposed stereographic and the Lambert model had similar performance.

4. Conclusions

The requirement of seamless geospatial data integration has caused the necessity of modernizing applied plane coordinate systems to be harmonious with computer-based mapping tools. Additionally, organizing information in GIS using a single zone grid reference system will enhance country-wide applications and facilitate data acquisition and retrieval. Map projection visualizes the pattern of an ellipsoidal graticule as it appears in the grid coordinate system. The main challenge of map-making is that it is impossible to accurately transpose the location of earth features onto a flat sheet without introducing some distortion. The unavoidable error value varies with respect to the projection’s type and its parameters. Conformality is needed for numerous large-scale surveying and mapping to preserve angles. Qualitative measures of scale error inherited in the projection are handled similarly to any other map variable. In this study, the isogram surfaces, distortion statistics, and zonal statistics analysis have been applied to evaluate and compare linear deformations on investigated map projections.

A single zone coordinate system is crucial in designing fit-for-purpose low-distortion projection for establishing spatial data infrastructure in Syria to fulfill SDGs. Indeed, with the availability of modern geospatial technologies, it has become no overriding factor in selecting projection. Hence, the study considers the modified stereographic appropriate to portray the country for two reasons. Firstly, it is currently applied and ideally satisfied for large-scale depictions of the whole area in one band. Secondly, linear errors are minimized over the given area and evenly distributed throughout the map beside the shape of the isograms that emulate the region frontier. The extreme linear distortion of this mapping system is about 45.3 cm/km, which is smaller than other projections. Renewing the map projection in Syria is an ambitious task that requires obtaining approval and contributions from relevant stakeholders. As a result, implementing an alternative mapping system will likely encounter numerous legal, financial, institutional, and technical obstacles that should be carefully addressed.

Declarations

Author contribution statement

Maan Habib: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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