PolyMorph-2D

Help File & User Guide

An Open-Source GIS Plug-in for
Morphometric Analysis of Vector-based 2D Polygon Features

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Current version: 2.1

Release date: April 29, 2021

Webpage: https://github.com/burakbeyhan/morphometric-analysis

Citation: Güler, C., Beyhan, B., Tağa, H., 2021. *PolyMorph-2D: An Open-Source GIS Plug-in for Morphometric Analysis of Vector-based 2D Polygon Features (Version 2.1) Help File and User Guide*, 13 pp. https://github.com/burakbeyhan/morphometric-analysis/PolyMorph-2D_Help_File&User_Guide.pdf. https://doi.org/10.5281/zenodo.4726660

✦ **Last updated** ✦
April 29, 2021

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1. HOST PROGRAM (OpenJUMP)

The **PolyMorph-2D** plug-in, written in Java™ programming language, works as an extension of the OpenJUMP (Open-source Java Unified Mapping Platform) software, which is distributed under the General Public License version 2.0 (GPLv2) (OpenJUMP, 2021). The **PolyMorph-2D** plug-in has been tested to work with OpenJUMP 1.14 (released on January 01, 2019), OpenJUMP 1.15 (released on February 19, 2020) and OpenJUMP 1.16 (released on January 03, 2021) versions (http://ojwiki.soldin.de/index.php?title=Main_Page). OpenJUMP offers an integrated environment for a variety of vector and raster GIS analyses and it is freely available in **CORE** (the standard release, containing application core) and **PLUS** (an extended release, consisting of a wide variety of plug-ins) editions (OpenJUMP, 2021).

1.1. Installation of the Host Program (OpenJUMP)

OpenJUMP is an open-source project developed and maintained by a group of volunteers and can run on any operating system (e.g., Linux, UNIX, macOS, and Microsoft Windows) that supports Java™ (OpenJUMP, 2021). Available installers (free and no registration required) for the **CORE** and **PLUS** editions are as follows (* stands for the version and release numbers):

- OpenJUMP-Installer-*-CORE.exe (for Windows)
- OpenJUMP-Installer-*-PLUS.exe (for Windows)
- OpenJUMP-Installer-*-CORE.jar (for Linux and macOS)
- OpenJUMP-Installer-*-PLUS.jar (for Linux and macOS) or

Extract the portable zip file distribution:

- OpenJUMP-Portable-*-CORE.zip
- OpenJUMP-Portable-*-PLUS.zip

For the purposes of the morphometric calculations carried out by the **PolyMorph-2D** plug-in, **PLUS** edition of the OpenJUMP is **recommended**. Detailed guidelines regarding the installation of the OpenJUMP on different operating systems (e.g., Linux, macOS, and Windows) can be found in the webpage at: http://ojwiki.soldin.de/index.php?title=Installation.

1.2. Running the Host Program (OpenJUMP)

To start OpenJUMP, run the launcher for your platform from the <appfolder>/bin directory.

- On Windows: double-click on oj_windows.bat or OpenJUMP.exe
- On Linux/UNIX: launch oj_linux.sh
- On macOS: launch oj_mac.command or OpenJUMP.app

To learn more about OpenJUMP free and open-source software (FOSS), please visit the webpage at: http://www.openjump.org/.

2. THE PLUG-IN (PolyMorph-2D)

The **PolyMorph-2D** plug-in is designed as a free and open-source geographic information system (GIS) toolbox for morphometric analysis of vector-based two dimensional (2D) polygon features in OpenJUMP. Written in Java™ programming language, **PolyMorph-2D** plug-in allows researchers from various earth and spatial science-related disciplines (and also from others) to compute morphometric parameters of 2D input vector features forming a polygon (i.e., a closed curve) which may represent outer boundaries of various natural and/or man-made entities that differ in size, shape, complexity and drawing scale (e.g., craters, sinkholes, cirques, drainage basins, land parcels, buildings, lakes, ponds, peaks, pits, playas, pockmarks, coral mounds, seamounts, landslides, drumlins, islands, atolls, granular materials, mineral crystals, fossils, etc.). The **PolyMorph-2D** plug-in provides a selected set of the most common morphometric parameters that are used in the earth and spatial science studies, as well as in others, such as biology, mathematics, computer science, etc.

The **PolyMorph-2D** plug-in provides a practical and effective method to quantify object boundary characteristics, which would allow analysis of the interrelation of morphometric parameters and their covariation with external variables, leading to an improved understanding of the factors responsible for the formation of the shape (i.e., polygon feature). Historically, this task has been an arduous and time-consuming process. The **PolyMorph-2D** plug-in is also capable of performing morphometric calculations on overlapping polygon features with and/or without holes, provided they are topologically correct (see accompanying paper by Güler et al., 2021).

2.1. Installation of the Plug-in (PolyMorph-2D) and Its Components

The **PolyMorph-2D** plug-in provides an easy-to-use and user-friendly graphical user interface (GUI) for calculation of the morphometric parameters on vector-based 2D polygon features. The plug-in (**PolyMorph-2D.jar**) and the associated Help File & User Guide (PolyMorph-2D_Help_File&User_Guide.pdf) can be freely downloaded from the webpage at: https://github.com/burakbeyhan/morphometric-analysis. The benchmark files (in ESRI (1998) *.shp format) Regular_Geopolys.shp and Complex_Geopolys.shp can be downloaded from the webpage at: https://static-content.springer.com/esm/art%3A10.1007%2Fs10109-020-00325-3/MediaObjects/10109_2020_325_MOESM1_ESM.rar (Beyhan et al., 2020). The **PolyMorph-2D** plug-in (Güler et al., 2021) works in tandem with the MICGIS plug-in (Beyhan et al., 2020) developed for finding Maximum Inscribed Circle (MIC) that can be placed within a polygon feature. MICGIS plug-in is required for proper functioning of the **PolyMorph-2D** plug-in. MICGIS plug-in (**MICGIS.jar**) is available from the webpage at: https://github.com/burakbeyhan/maximum-inscribed-circle. Both the PolyMorph-2D and MICGIS plug-in files need to be added to OpenJUMP by placing them into the OpenJUMP **lib/ext/** folder, located inside the directory where OpenJUMP is installed. After re-starting the OpenJUMP, these plug-ins should be available as standalone (separate) tools under the "Plugins" menu (**Figure 1**).

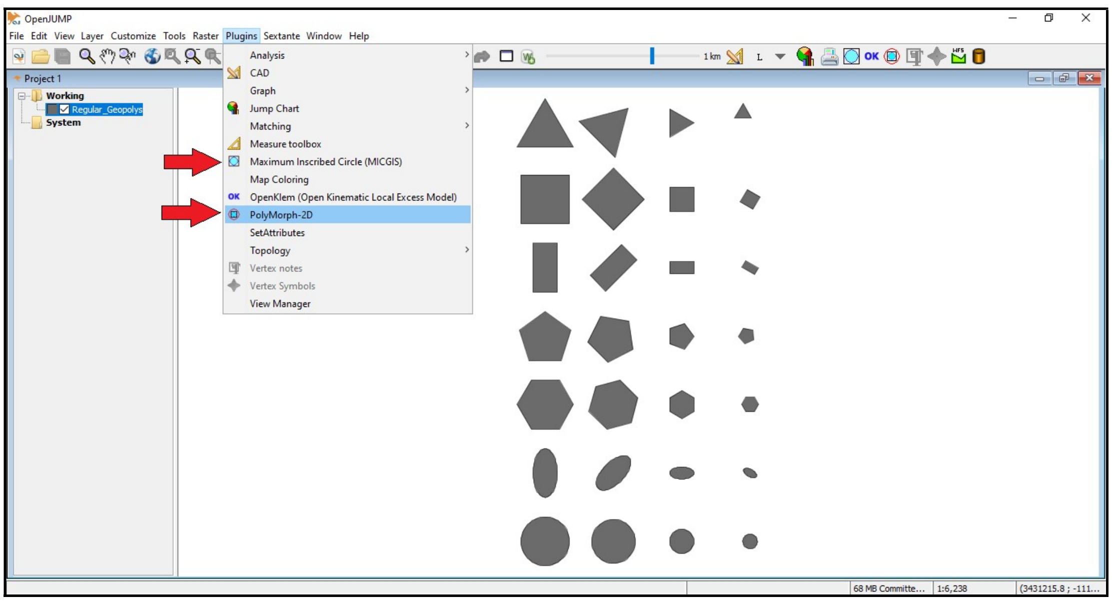

Figure 1. Screenshot of the "Plugins" menu to open **PolyMorph-2D** plug-in in OpenJUMP.

Important Note: Before proceeding with this document, it is suggested reading the papers below:

Beyhan, B., Güler, C., Tağa, H., 2020. An algorithm for maximum inscribed circle based on Voronoi diagrams and geometrical properties. *Journal of Geographical Systems*, v. 22, no. 3, 391–418. https://doi.org/10.1007/s10109-020-00325-3

Güler, C., Beyhan, B., Tağa, H., 2021. PolyMorph-2D: An open-source GIS plug-in for morphometric analysis of vector-based 2D polygon features. *Geomorphology, v. 386, 107755.* https://doi.org/10.1016/j.geomorph.2021.107755

2.2. Understanding Input Parameters and Running PolyMorph-2D Plug-in

Once the PolyMorph-2D and MICGIS plug-in files (i.e., **PolyMorph-2D.jar** and **MICGIS.jar**) are installed following the procedure outlined in Section 2.1, OpenJUMP should be re-started and afterwards the **PolyMorph-2D** plug-in link, as well as the **Maximum Inscribed Circle (MICGIS)** plug-in link should be visible under the OpenJUMP menu named "Plugins" (**Figure 1**). However, **PolyMorph-2D** and **MICGIS** menus will be inactive (appear grayed out) unless there is an open polygon vector file in the active Project window in OpenJUMP.

The **PolyMorph-2D** plug-in consists of two distinct but closely interdependent components, which enable users to perform specific actions found in the "**Basic Tasks**" panel and to execute commands found in the "**Derived Parameters**" panel. In these panels, if a particular menu item's checkbox is unselected (i.e., does not have a tick), it means that calculation will not be performed for this menu item unless the user makes a selection. The plug-in components and their functions are discussed in detail in the following parts. The screenshot of the plug-in's graphical user interface (GUI) is shown in **Figure 2**.

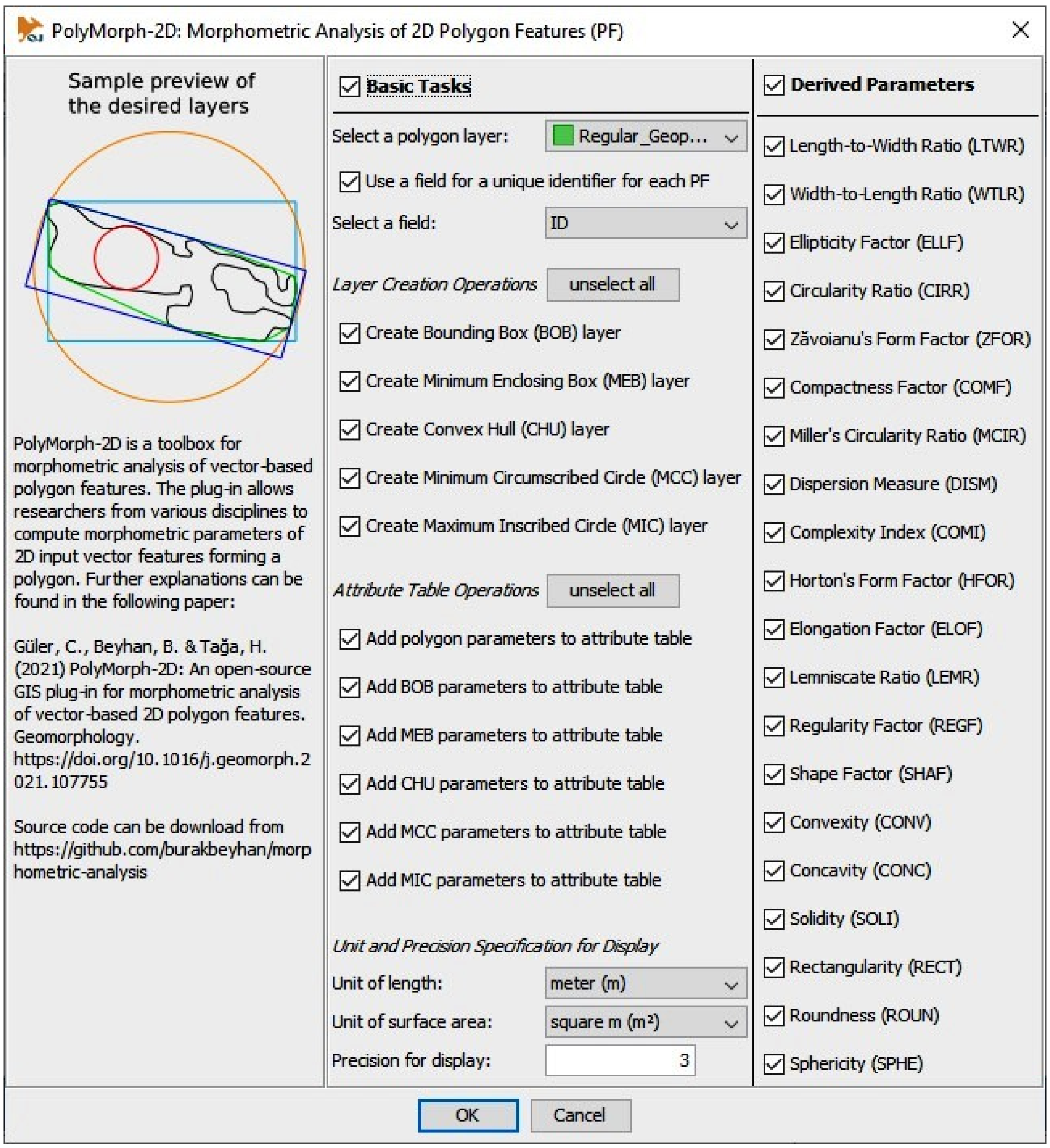

Figure 2. Screenshot of the **PolyMorph-2D** plug-in graphical user interface (GUI) used in OpenJUMP.

2.2.1. Basic Tasks panel

The method of obtaining morphometric parameters of polygon features (PFs) using the **PolyMorph-2D** plug-in (within the OpenJUMP environment) starts with the selection of an appropriate input vector file using "*Select a polygon layer*" drop-down list found in the **Basic Tasks** panel **(Figure 3**). The input file is assumed to contain a set of arbitrarily shaped and topologically correct 2D polygons (i.e., valid, closed and without self-intersections) representing outer boundaries of various natural and/or man-made 3D real-world entities. If it is desired, a "unique identifier" can be assigned to each polygon feature by activating the checkbox as shown below (**Figure 3**) and selecting an appropriate (existing) field from the vector file's attribute table. If this option is not selected, a new ID field (default is "ID" field) will be created in the original vector file's attribute table for the features in the layer starting from 1.

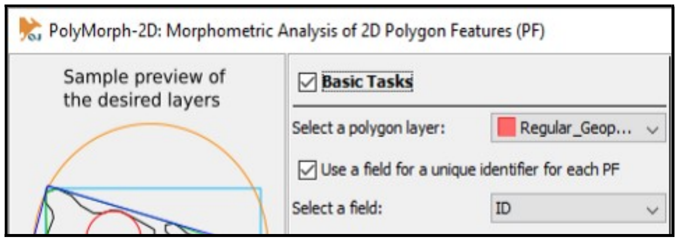

Figure 3. Option to assign a "unique identifier" to each polygon feature (PF) by activating the related checkbox.

Basic Tasks panel in the **PolyMorph-2D** plug-in interface includes a series of checkboxes that enable users to perform calculations related to *Layer Creation Operations*" and "*Attribute Table Operations*" (**Figure 2**). *Layer Creation Operations*, if it is desired, can be used to create separate layers (i.e., vector layers) for each polygon's bounding box (BOB), minimum enclosing box (MEB), convex hull (CHU), minimum circumscribed circle (MCC) and maximum inscribed circle (MIC) (see Güler et al., 2021). *Attribute Table Operations*, on the other hand, enables users to write calculated polygon parameters (to the attribute table) related to above-mentioned layers created for each polygon feature. However, it should be noted that creation of these layers and attribute table operations in relation to the calculation of their polygon parameters are not necessary for execution of morphometric calculations involving Derived Parameters (**Figure 2**).

Basic Tasks panel also performs some background calculations related to the location, size and orientation parameters of input polygon features, including centroid coordinates (XPOL and YPOL), area (APOL), perimeter (PPOL), length (LPOL), width (WPOL), and azimuth (AZIM), as well as areal and linear parameters (i.e., area, perimeter and radius) related to polygon's bounding box (ABOB and PBOB), minimum enclosing box (AMEB and PMEB), convex hull (ACHU and PCHU), minimum circumscribed circle (AMCC, PMCC and RMCC) and maximum inscribed circle (AMIC, PMIC and RMIC). All the parameters calculated by the plug-in are described in **Table 1**. The **Basic Tasks** panel also includes two separate drop-down lists for selection of units of length (i.e., mm, cm, dm, m, dam, hm, and km) and area (i.e., mm^2, cm^2, dm^2, m^2, daa, ha, and km^2) and a value box (i.e., input box) to indicate the precision for display purposes (i.e., the number of decimal places), where the default and maximum values are 3 and 15, respectively (see **Figure 4**).

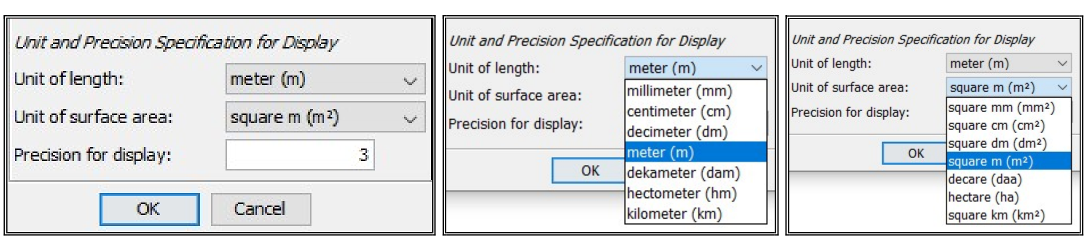

Figure 4. Drop-down lists for selection of units of length and area, and a value box for indicating measurement precision for display.

Table 1. List of morphometric parameters calculated by the **PolyMorph-2D** plug-in.

Basic parameters	
Symbol [a]	Brief Description
ID	A unique numerical identifier assigned to each polygon feature
XPOL	X coordinate of the polygon centroid or center of mass
YPOL	Y coordinate of the polygon centroid or center of mass
APOL	Area (A) of the polygon which is projected onto a horizontal plane
PPOL	Perimeter (P) length of the polygon boundary which is projected onto a horizontal plane
LPOL [b]	Major axis length (L) of the polygon
WPOL [b]	Minor axis length (W) of the polygon
AZIM [c]	Azimuth; degrees east of north, ranging from 0° to 179.9°
ABOB	Area of the bounding box (BOB) fully containing the polygon
PBOB	Perimeter of the bounding box (BOB) fully containing the polygon
AMEB	Area of the minimum enclosing box (MEB) fully containing the polygon
PMEB	Perimeter of the minimum enclosing box (MEB) fully containing the polygon
ACHU	Area of the convex hull (CHU) fully containing the polygon
PCHU	Perimeter of the convex hull (CHU) fully containing the polygon
AMCC	Area of the minimum circumscribed circle (MCC) which encloses the polygon
PMCC	Perimeter of the minimum circumscribed circle (MCC) which encloses the polygon
RMCC	Radius of the minimum circumscribed circle (MCC) which encloses the polygon
AMIC	Area of the maximum inscribed circle (MIC) that can be drawn inside the polygon
PMIC	Perimeter of the maximum inscribed circle (MIC) that can be drawn inside the polygon
RMIC	Radius of the maximum inscribed circle (MIC) that can be drawn inside the polygon

Derived parameters			
Symbol [a]	Name	Formula	Source
LTWR	Length-to-Width Ratio	L / W	Horton (1932)
WTLR	Width-to-Length Ratio	W / L	Zingg (1935)
ELLF	Ellipticity Factor	$\lvert L-W \rvert / (L+W)$	Buendía et al. (2002)
CIRR	Circularity Ratio	P^2 / A	Attneave and Arnoult (1956)
ZFOR	Zăvoianu's Form Factor	$(16 A) / P^2$	Zăvoianu (1978, 1985)
COMF	Compactness Factor	$P / (4 \pi A)^{0.5}$	Peucker (1894); Gravelius (1914)
MCIR	Miller's Circularity Ratio	$(4 \pi A) / P^2$	Cox (1927); Miller (1953)
DISM	Dispersion Measure	$1-[(4 \pi A)^{0.5} / P]$	Attneave and Arnoult (1956)
COMI	Complexity Index	$1-[(4 \pi A) / P^2]$	Shen et al. (1993)
HFOR	Horton's Form Factor	A / L^2	Horton (1932)
ELOF	Elongation Factor	$(4 A / \pi)^{0.5} / L$	Schumm (1956)
LEMR	Lemniscate Ratio (*k* Factor)	$(\pi L^2) / 4 A$	Chorley et al. (1957)
REGF	Regularity Factor	$(\pi L W) / 4 A$	Buendía et al. (2002)
SHAF	Shape Factor	$[(4 \pi A) / P^2] \times (L / W)$	Buendía et al. (2002)
CONV	Convexity	PCHU / P	Glasbey and Horgan (1995)
CONC	Concavity	ACHU–A	Landini (2010)
SOLI	Solidity	A / ACHU	Zunic and Rosin (2004)
RECT	Rectangularity	A / AMEB	Liu et al. (2001); Landini (2010)
ROUN	Roundness	$(4 \pi A) / (\mathrm{PCHU})^2$	Glasbey and Horgan (1995)
SPHE	Sphericity	$(4 A / \pi)^{0.5} / 2\,\mathrm{RMCC}$	Wadell (1935)

[a] Denotes abbreviations of morphometric parameters that are calculated by the plug-in and written to polygon layer's attribute table.
[b] Major and minor axis of the minimum enclosing box (MEB) of the polygon feature is used as a proxy for calculation of major axis and minor axis lengths of the polygon (see Güler et al., 2021).
[c] Azimuth (AZIM) is the angle (in degrees, north = 0) between north and the major axis of the minimum enclosing box (MEB) fully containing the polygon (see Güler et al., 2021).

2.2.2. Derived Parameters panel

In the literature, a wide variety of derived parameters (a.k.a. indices, measures, metrics, ratios, and factors) are proposed to quantitatively describe the morphometric characteristics of 2D polygon features, most of which derived from a limited number of primary measurements (e.g., length, width, perimeter, and area) pertaining to the polygon feature itself and/or the shapes enclosing or inscribed in the polygon feature. In the **PolyMorph-2D** plug-in, use of location (position), scale (size) and rotation invariant dimensionless parameters (see Derived Parameters panel) is preferred.

Twenty "Derived Parameters" that were employed for morphometric characterization of polygon features are listed in **Table 1**. These include, Length-to-Width Ratio (LTWR), Width-to-Length Ratio (WTLR), Ellipticity Factor (ELLF), Circularity Ratio (CIRR), Zăvoianu's Form Factor (ZFOR), Compactness Factor (COMF), Miller's Circularity Ratio (MCIR), Dispersion Measure (DISM), Complexity Index (COMI), Horton's Form Factor (HFOR), Elongation Factor (ELOF), Lemniscate Ratio (LEMR), Regularity Factor (REGF), Shape Factor (SHAF), Convexity (CONV), Concavity (CONC), Solidity (SOLI), Rectangularity (RECT), Roundness (ROUN), and Sphericity (SPHE) (see **Figure 2**). All these parameters are dimensionless and invariant to the polygon feature's location (position), scale (size), and rotation. Formulas that are used in the calculation of "Derived Parameters" in the **PolyMorph-2D** plug-in (see **Figure 2**) are listed in **Table 1** and described in detail in historical context in the following paragraphs.

Length-to-Width Ratio (LTWR): The simple ratio of a polygon's length (major axis, LPOL) to its width (minor axis, WPOL) is routinely utilized across a wide spectrum of earth science disciplines as a measure of elongation or overall form (e.g., Horton, 1932). This ratio commonly appears under different names in the literature, such as *elongation index* (Johansson, 1963), *axis ratio* (Aniya and Welch, 1981), *aspect ratio* (Riley et al., 2003), and *eccentricity* (Zhang and Lu, 2004). A polygon symmetrical in all axes, such as a circle or square, will tend to have a LTWR value equal to 1; whereas, a narrow and long (e.g., needle-shaped) polygon will have a LTWR value above 1.

Width-to-Length Ratio (WTLR): Less commonly, the ratio of a polygon's width (minor axis, WPOL) to its length (major axis, LPOL) is also used as a measure of elongation. This ratio also appears under different names in the literature, including *elongation index* (Zingg, 1935), *degree of elongation* (Diaconu and Lăzărescu, 1965), *index of planimetric shape* (Sperling et al., 1977), *aspect ratio* (Hentschel and Page, 2003), and *elongation ratio* (Roussillon et al., 2009). A polygon symmetrical in all axes, such as a perfect circle, will have a WTLR value equal to 1, whereas a non-equant and elongated polygon will have a value close to 0.

Ellipticity Factor (ELLF): This simple index of ellipticity is based on the ratio of the absolute value of the difference of polygon's length (LPOL) and width (WPOL) to the sum of the lengths of these axes (Buendía et al., 2002). Although it is easy to calculate, this index is not in general use in the earth science literature as a shape parameter. A polygon symmetrical in all axes (e.g., circle), will have an ELLF value equal to zero, whereas, an elongated polygon will have a value close to 1.

Circularity Ratio (CIRR): Circularity ratio, sometimes called *compactness* or *relative perimeter crenulation*, is defined as the ratio of the squared perimeter ($PPOL^2$) and the area (APOL) of a polygon. This parameter is a simple shape index measuring a polygon's departure from circularity (Attneave and Arnoult, 1956; Zhang and Lu, 2004). The value of CIRR reaches the minimum ≈12.566 (i.e., 4π) in a circular polygon and approaches infinity (∞) in thin and complex polygons. In the literature, square root ratio (e.g., $P / A^{0.5}$) (Attneave and Arnoult, 1956) and the inverse ratio (e.g., A / P^2) (Cox, 1927) are also commonly used as the measures of circularity.

Zăvoianu's Form Factor (ZFOR): This simple ratio takes as the reference figure a square whose perimeter is equal to that of the polygon. The ratio of the area of a polygon (APOL) to that of the reference square (given by $P^2/16$) will give a form factor with the square as a reference (Zăvoianu, 1978, 1985). The value of ZFOR is equal to unity when the polygon's shape is a square and decreases to zero as polygon becomes more elongated. For round polygons, the ratio becomes greater than unity, reaching 1.273 (i.e., $4/\pi$) in the case of a perfect circle (Zăvoianu, 1978, 1985).

Compactness Factor (COMF): The compactness factor is an expression of the degree of regularity or irregularity of the polygon boundary and it is very sensitive to both overall form (i.e., elongation) and surface roughness (i.e., convexity). COMF is defined as the ratio of the length of the polygon boundary (PPOL) to the perimeter (i.e., circumference) of a circle whose area is equal to that of the given polygon (Gravelius, 1914). If the polygon is a perfect circle then its value equals unity, whereas as the shape becomes more complex the value of COMF increases. Other names used in the literature include *shore development index* (Peucker, 1894), *compactness coefficient* (Luchisheva, 1950), *circularity ratio* (Aniya and Welch, 1981), *sinuosity index* (Bondesan et al., 1992) and *shape complexity index* (Hengl et al., 2003). The measure, called *Gravelius index*, is also implemented in GRASS GIS (https://grass.osgeo.org/) to find sliver polygons. For convenience, most subsequent researchers have modified the index by reversing and taking the square of both numerator and denominator or subtracting the value from one (e.g., see Miller, 1953; Attneave and Arnoult, 1956; Shen et al., 1993).

Miller's Circularity Ratio (MCIR): Even though this index is mostly credited to the Miller (1953) (in geomorphology literature), it was first defined by Cox (1927) (in the context of particle analysis) as the ratio of the area of a polygon (APOL) to the area of a circle with the same perimeter as that of the polygon. This shape parameter commonly appears under different names in the literature (e.g., *circularity*, *compactness*, *form factor*, *isoperimetric ratio*, *regularity ratio*, *roundness*, and *sphericity*). MCIR is used to measure how closely a polygon resembles to a perfect circle (Cox, 1927; Miller, 1953). Therefore, the value of MCIR is 1 for a perfectly smooth circular polygon and approaches to 0 for a polygon with strongly complex, irregular or elongated shape. The inverse ratio is also utilized as a measure of *circularity* or *compactness* in the literature (e.g., Bondesan et al., 1992; González and Romero, 2010).

Dispersion Measure (DISM): Dispersion measure (DISM) devised by Attneave and Arnoult (1956) is closely related to the compactness factor (COMF) defined by Peucker (1894) and Gravelius (1914). DISM can be obtained by taking the reciprocal of COMF and subtracting the obtained value from one. DISM values range between 0 and 1, where 0 value is assigned to the most compact polygonal shape possible, the circle. A deeply convoluted or jagged polygon and a very thin rectangle or ellipse will tend to have high dispersion values (Attneave and Arnoult, 1956).

Complexity Index (COMI): Shen et al. (1993) devised a modified measure of complexity (COMI) to restrict the range of the parameter to 0 and 1 and obtain increasing values with increase in complexity of the polygonal shape. This index closely resembles to the dispersion measure (DISM) devised by Attneave and Arnoult (1956). COMI can be obtained by taking the squared reciprocal of COMF and subtracting the obtained value from one. The value of COMI equals 0 for a circle, and increases with the complexity of the polygon to a maximum value of 1.

Horton's Form Factor (HFOR): This quantitative index was originally proposed by Horton (1932) to describe outline forms of drainage basins or watersheds. Horton's form factor (HFOR) is defined as the ratio of a polygon's area (APOL) to square of the polygon's length (i.e., major axis, $LPOL^2$). This index is equal to unity when the shape is a square, and decreases according to the extent of elongation. The value of HFOR would approach to ≈0.785 (i.e., $\pi/4$) if polygon has a perfectly circular shape; whereas, a smaller value indicate a polygon with an elongated shape. Other researchers have also used a ratio resembling Horton's form factor to characterize polygonal shapes (e.g., see Ogievsky, 1952; Gardiner, 1975).

Elongation Factor (ELOF): The shape of any polygon can be expressed by an elongation factor (ELOF), which is defined as the ratio of diameter of a circle with the same area as of the polygon to the polygon's length (i.e., major axis, LPOL) (Schumm, 1956). For a perfectly circular polygon, the value of ELOF equals unity, whereas for a polygon with an elongated shape, the value approaches to zero.

Lemniscate Ratio (LEMR): This parameter (a.k.a. *k* factor or *rotundity coefficient*) is used to describe the elongation of the polygons (Zăvoianu, 1985). The formula itself was previously used to relate areas of the streamlined shapes such as drainage basins and drumlins and their axial lengths (major axes) (Chorley et al., 1957; Chorley, 1959). We may note that LEMR is algebraically identical to the squared reciprocal of elongation factor (ELOF) defined by Schumm (1956). The value of LEMR equals 1 for an equidimensional polygon (circle) and increases above 1 with the elongation of the polygon (Chorley, 1959). In the literature, the inverse ratio called *form ratio* (Ebdon, 1985) or *roundness* (Cox and Budhu, 2008) was also used as a shape parameter.

Regularity Factor (REGF): The regularity factor (REGF) given by Buendía et al. (2002) simultaneously utilizes length (LPOL), width (WPOL) and area (APOL) measurements to derive an index of regularity for polygon features (used in biology). This index is calculated by dividing the product of polygon's length and width to the polygon area and multiplying it with a constant ($\pi/4$). The value of REGF equals unity for a perfect circle, 0.785 for a perfect square, and it is 1.571 for an equilateral triangle. The value of REGF will be much greater than unity, especially for narrow and long, L-shaped and bend polygon features.

Shape Factor (SHAF): The shape factor (REGF), given by Buendía et al. (2002), is the most complex parameter found in the literature (used in biology) simultaneously employing length (LPOL), width (WPOL), area (APOL) and perimeter (PPOL) measurements to derive a shape index for polygon features. This index equals to the Miller's circularity ratio (MCIR) multiplied by Length-to-Width ratio (LTWR) given previously. The value of SHAF equals unity for a perfect circle, 0.785 for a perfect square, and it is 0.698 for an equilateral triangle. The value of SHAF is above unity, especially for narrow and long (i.e., elongated) polygon features.

Convexity (CONV): Convexity can provide information about the overall roughness of a polygon's boundary (Glasbey and Horgan, 1995) and it is unaffected by overall form. A polygon is said to be convex if its boundary has no concave regions. In order to calculate convexity, a geometric shape known as the convex hull (CHU) is used. Convex hull (CHU) is the minimal convex shape that encloses a polygon, which can be visualized as an imaginary rubber band stretched around the polygon boundary (O'Rourke, 1998). This measure of convexity can be described as the ratio of the convex hull perimeter (PCHU) to the actual polygon perimeter (PPOL) (see **Table 1**). The more irregular the polygon, the greater is the difference from its convex hull (CHU). Therefore, the value of CONV will be close to 1 for a convex polygon with a smooth boundary and be close to 0 for a non-convex polygon with an extremely irregular or rough boundary (Glasbey and Horgan, 1995). The inverse ratio is also used in the literature as a measure of "*roughness*" (see Janoo, 1998).

Concavity (CONC): This concavity measure is also based on the convex hull (CHU) and it is calculated by subtracting the polygon area (APOL) from the area of convex hull (ACHU) enclosing the polygon (Landini, 2010). Therefore, the value of CONC will be 0 for a convex polygon with a smooth boundary and be much greater than 1 for a non-convex polygon with an extremely irregular or rough boundary. This parameter provides a value that is independent of shape anisotropy.

Solidity (SOLI): This dimensionless parameter is also based on the convex hull (CHU). The degree of difference between the polygon and its convex hull (CHU) is commonly utilized as a quantitative measure of the degree of irregularity (Zunic and Rosin, 2004). Solidity (SOLI), also called *density* and *convexity*, can be defined as the ratio of the actual polygon area (APOL) to the area of its convex hull (ACHU). A polygon with a very smooth boundary will have a solidity value close to 1, whereas a polygon with an irregular boundary will have a solidity value close to 0. That is, polygons with deeper and a greater number of concavities will have smaller values for SOLI.

Rectangularity (RECT): This shape measure is computed as the ratio between the polygon's area (APOL) and the area of the minimum enclosing box (AMEB) fully containing the polygon (Liu et al., 2001). The four boundaries of the rectangle are assumed to be parallel to the polygon's major axis and minor axis, respectively. The value of RECT is 0.785 for a perfect circle, equals 1 for square or rectangle and it is 0.5 for an equilateral triangle.

Roundness (ROUN): Roundness measures the degree of departure of polygon boundary from a circle, where an increase in the length of the polygon causes the shape to depart from a circle (Glasbey and Horgan, 1995). The roundness can be defined as the ratio of the area of a polygon

(APOL) to the area of a circle with the same perimeter. The value of ROUN equals 1 for a circular polygon and is less than 1 for a polygon, which departs from circularity, except that it is relatively insensitive to irregular borders (Glasbey and Horgan, 1995). Such quantitative index can be informative as, for example, a square has a relatively high degree of roundness.

Sphericity (SPHE): This is one of the first indices used to characterize the sphericity of polygonal features (i.e., particle boundaries) and relies on measuring the ratio of the diameter of a circle equal in area to the given polygon and the diameter of the smallest circle circumscribing the polygon (RMCC) (Wadell, 1935). Sphericity refers to the form of the polygon and reflects the similarity between the polygon dimensions (e.g., length and width). The value of SPHE is 1 for a perfect circle, 0.5 for an equilateral triangle and will be close to 0 for a polygon with an elongated shape.

2.2.3. Running PolyMorph-2D Plug-in

The following steps should be completed in order to start with the morphometric analysis of polygonal shapes in OpenJUMP utilizing the **PolyMorph-2D** plug-in:

1. Start OpenJUMP software (see Section 1.2).
2. Confirm that **PolyMorph-2D** and **Maximum Inscribed Circle (MICGIS)** links are available under the OpenJUMP menu named “Plugins” (see **Figure 1**). See Section 2.1, if they are not visible under the “Plugins” menu.
3. Open an existing polygon vector file from within OpenJUMP software using the “File” menu → “Open” command. For this, you can use the polygon shapefiles created (e.g., Regular_Geopolys.shp or Complex_Geopolys.shp) for benchmarking (testing) performance of the MICGIS plug-in. The benchmark files (in ESRI (1998) *.shp format) can be downloaded from the webpage at: https://static-content.springer.com/esm/art%3A10.1007%2Fs10109-020-00325-3/MediaObjects/10109_2020_325_MOESM1_ESM.rar (see Beyhan et al., 2020).
4. Click the **PolyMorph-2D** link located under “Plugins” in the OpenJUMP menu bar to activate **PolyMorph-2D** plug-in graphical user interface (GUI) (**Figure 2**).
5. If there is only one vector layer in the active Project window, it should be visible under the “*Select a polygon layer*” drop-down list found in the Basic Tasks panel in the plug-in GUI.
6. If there are more than one vector layers in the active Project window, select the appropriate input layer using the “*Select a polygon layer*” drop-down list (see **Figure 2**).
7. Select the morphometric (derived) parameters that you would like to be calculated by the **PolyMorph-2D** plug-in (by default, all options are pre-selected).
8. “*Layer Creation Operations*” can be selected to create separate layers for each polygon’s bounding box (BOB), minimum enclosing box (MEB), convex hull (CHU), minimum circumscribed circle (MCC) and maximum inscribed circle (MIC) (by default, all options are pre-selected). However, selection/creation of these layers are <u>not required</u> for execution of morphometric calculations related to Derived Parameters (see **Figure 2** and **Table 1**).
9. If it is desired, “*Attribute Table Operations*” can be selected to write various calculated polygon parameters related to polygon’s bounding box (BOB), minimum enclosing box (MEB), convex hull (CHU), minimum circumscribed circle (MCC) and maximum inscribed circle (MIC) to the polygon layer’s attribute table (by default, all options are pre-selected).
10. Click “OK” button to start the analysis.
11. When calculations are completed, a “Task Message” appears on screen to inform the user.
12. The calculation results are automatically written to the polygon layer’s attribute table (see **Figure 5**), which can be viewed by right clicking on the polygon layer’s name on the left panel (found in the Project window in the OpenJUMP) and selecting “View / Edit Attributes” command.

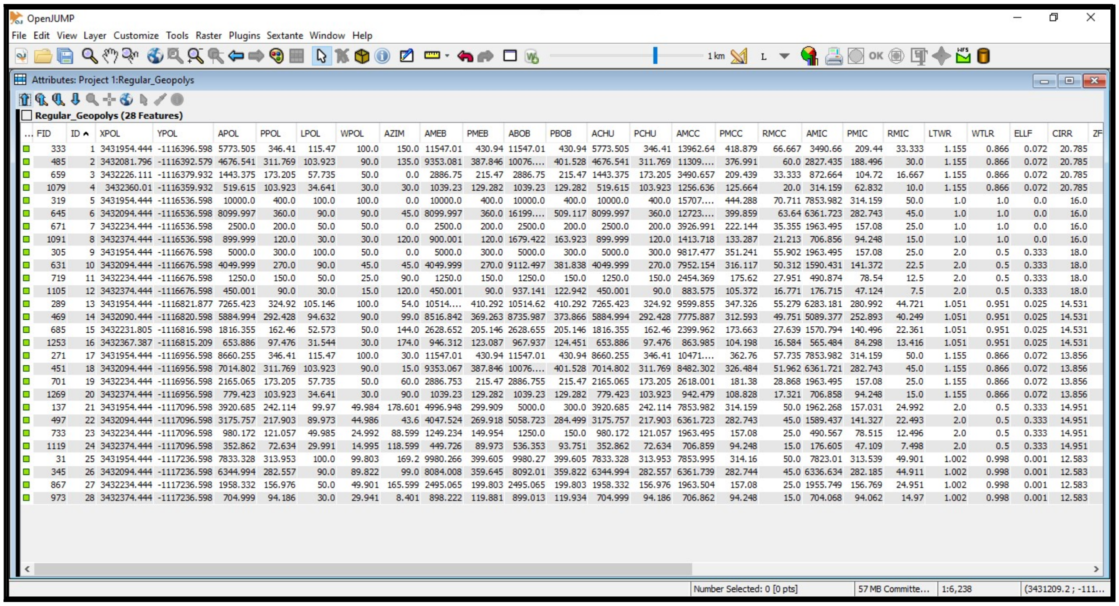

Figure 5. Screenshot of the output "attribute table" showing morphometric calculation results.

2.3. Output Files and Further Data Processing

Since, all options are pre-selected in the **PolyMorph-2D** graphical user interface (GUI), clicking the "OK" button will start the required morphometric calculations, which will yield two major types of datasets. One of them is the five additional shapefiles created for each polygon's bounding box (BOB), minimum enclosing box (MEB), convex hull (CHU), minimum circumscribed circle (MCC) and maximum inscribed circle (MIC) and the other one is the input polygon shapefile's attribute table where results of the all morphometric calculations are written (see **Table 1** for full list of parameters) (see Güler et al., 2021). After calculating the parameters, the layers concerned should be saved if they will be used for further data processing in another software environment. The results can be viewed by right clicking on the original polygon's layer name on the left panel (found in the Project window in the OpenJUMP) and by selecting "View / Edit Attributes" command. If the respective layer is saved, for example in .shp format (see ESRI, 1998), the attribute table (with .dbf extension) can be opened in or exported to a compatible spreadsheet/statistical program for further data processing. When all options are selected, **PolyMorph-2D** plug-in calculates a total of 39 morphometric parameters, which include 19 basic parameters and 20 derived parameters listed in **Table 1**.

3. HARDWARE & SOFTWARE REQUIREMENTS

OpenJUMP requires a minimum of 124 MB memory to run, however the best performance can be obtained with 256 MB memory. OpenJUMP can run on Linux, UNIX, macOS, Microsoft Windows 98 and later and any operating system that supports Java™. It is necessary to have installed at least a Java Runtime Environment (JRE) 1.5 on the computer. To check if you have Java™ installed, write "**java -showversion**" in the Command Prompt line after **C:\>**.

4. BENCHMARK (TEST) FILES

Two benchmark (test) files, i.e., shapefiles (in ESRI (1998) *.shp format) containing regular geometric shapes (Regular_Geopolys.shp) and complex polygonal shapes (Complex_Geopolys.shp) were utilized to test the performance of the **PolyMorph-2D** plug-in (see Güler et al., 2021). These benchmark files can be downloaded from the webpage at: https://static-content.springer.com/esm/art%3A10.1007%2Fs10109-020-00325-3/MediaObjects/10109_2020_325_MOESM1_ESM.rar (see Beyhan et al., 2020).

5. KNOWN ISSUES and BUGS

The **PolyMorph-2D** plug-in is provided "as-is", without any express or implied warranty. Although we have made every possible effort to make sure that plug-in runs as intended, there may be bugs and unexpected behavior in instances that we have not envisaged or tested.

The **PolyMorph-2D** plug-in (Version 2.1) has been tested under Microsoft Windows 10 (64-bit operating system) running on a computer with an Intel(R) Core(TM) i5-750 a quad-core CPU processor at 2.67 GHz clock frequency and 16.00 GB RAM and using the last three versions (1.14, 1.15 and 1.16) of the OpenJUMP software (https://sourceforge.net/projects/jump-pilot/files/OpenJUMP/).

6. ACKNOWLEDGEMENTS

The **PolyMorph-2D** plug-in makes use of several routines and scripts contributed as open source tools developed by the OpenJUMP community. We also utilized an OpenJUMP script named MICGIS.jar (see Beyhan et al., 2020) to calculate the parameters related to Maximum Inscribed Circle (MIC) that can be drawn inside individual polygon features. Without all these contributions, creation of the **PolyMorph-2D** plug-in would be an arduous task.

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