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Estimating dredging volume at sunda pondok dayung dock using *s*-convex function-based curve fitting to ensure indonesian navy ship safety

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ABSTRACT

This study investigated the application of s-convex function-based curve fitting for estimating the dredging volume at Sunda Pondok Dayung Dock to ensure the safety of Indonesian Navy vessels. The research aimed to develop an alternative method to conventional numerical integration techniques by employing s-convex curve fitting using both two-point and three-point approaches and by comparing its performance with the trapezoidal rule, Simpson's 1/3 rule, and Simpson's 3/8 rule. Data from Pushidrosal's 2023 survey were utilized, and explicit analytical forms for definite integral estimation were derived by approximating the function with s-convex methods. The results demonstrated that although the trapezoidal method produced the smallest relative error, the s-convex approach yielded a comparable error margin, differing by only 0.038%, which indicated its viability as an alternative method for dredging volume estimation. Future research was suggested to extend s-convex curve fitting to more than three points to further improve accuracy.

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INTRODUCTION

Indonesia, as an archipelagic nation, has vast maritime territories, making maritime defense a crucial aspect of maintaining national sovereignty (Labandi & Haris, 2023). Within the naval defense system, Naval Bases (Lanal) play a vital role as primary infrastructure supporting the core duties of the Indonesian Navy (TNI AL) (Purnomo et al., 2020). Currently, there are 61 Naval Bases spread across Indonesia, one of which is Lanal Pondok Dayung in North Jakarta. A critical component of the Lanal Pondok Dayung complex is Sunda Dock, a berthing site for military vessels. The security and safety of these ships must be consistently maintained to prevent accidents, such as hull grounding due to shallowing caused by tidal sedimentation (Hasanspahić et al., 2021). Therefore, periodic seabed dredging is necessary to ensure safe navigational conditions for military ships (Sepehri et al., 2024).

Seabed dredging requires bathymetric surveys to determine water depth and calculate sedimentation volume for removal (Khomsin et al., 2023). In practice, dredging volume calculations are typically performed using software such as Surfer, Cross Section and Volume (CSV), and CIVIL 3D, which have been used in previous studies (E & I, 2024; Timirkhanov et al., 2022). The Indonesian Navy's Hydro-Oceanographic Center (Pushidrosal), responsible for navigational safety, employs Surfer to analyze bathymetric data and compute dredging volumes through numerical integration methods like Newton-Cotes, which was used by previous study by Šiljeg (2019). These methods include the Trapezoidal Rule, Simpson's 1/3 Rule, and Simpson's 3/8 Rule, which approximate definite integrals based on field survey data.

Although conventional numerical integration methods are widely used, their accuracy depends on the shape and characteristics of bathymetric data (Amante & Eakins, 2016). In certain cases, particularly for complex or irregular functions, conventional integration approaches may yield significant errors (Marinov et al., 2014). Thus, alternative methods with higher accuracy are needed for integral estimation. One promising approach is curve fitting using the s-convex function, as explored in recent work on signomial programming-compatible models. This function offers greater flexibility in adapting to data, potentially improving integral estimation accuracy and reducing errors compared to conventional numerical methods (Karcher, 2023; Zhan et al., 2024).

This research aims to develop a new method for estimating definite integrals through s-convex-based curve fitting. The method is expected to provide more accurate estimates than standard numerical techniques, particularly for calculating dredging volumes at Sunda Dock, Lanal Pondok Dayung. The study will compare dredging volume estimates using the s-convex function with results from the Trapezoidal Rule, Simpson's 1/3 Rule, Simpson's 3/8 Rule, and Surfer software. Through this research, a superior method for dredging volume calculation is anticipated, enhancing the effectiveness of dredging planning and execution to ensure the safety of military vessels docked in the area.

METHOD

This study consists of a literature review, bathymetric data collection and processing, the calculation of the dredging volume using S-Convex, Trapezoidal, Simpson's 1/3, Simpson's 3/8, and using Surfer Software, and then the results will be analyzed. This procedure shown by Figure 1.

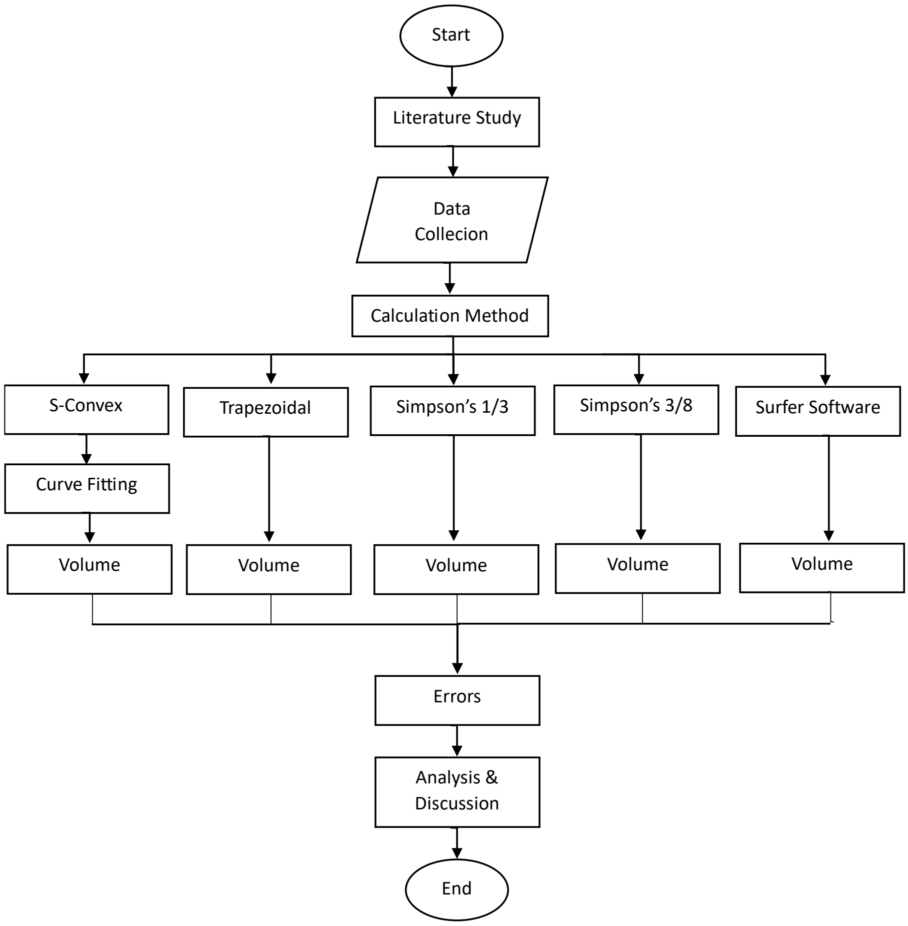


Figure 1. The Illustration of the Research Design

The study utilizes data from Pushidrosal's 2023 survey, which has been corrected for tidal variations, patch tests, and Sound Velocity Profiler (SVP). This corrected data enables direct calculation of dredging volume. The calculation process involves dividing the area into multiple segments to determine the area of each segment. The area of each segment is calculated by summing the areas of n+1 triangles, where n represents the number of points within each segment (Fauziyah et al., 2021). Figure 2 show the illustration of this calculation.

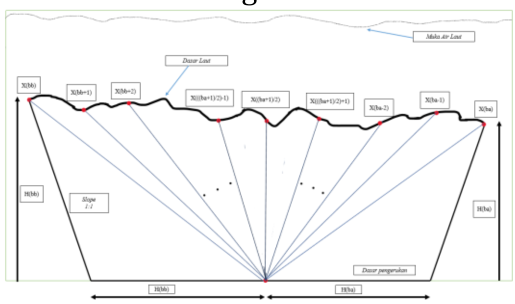


Figure 2. Sketch of Segment Area Calculation

The volume calculation employs the Trapezoidal, Simpson's 1/3, Simpson's 3/8, and S-Convex methods. These methods are similar to previous studies (Kashuri et al., 2020a; Slavinić & Cvetković, 2016). The results summarized in Table 4.1. The calculation process is outlined as follows:

1. Secondary data from Pushidrosal is collected as the basis for calculations.

2. The s-convex function is fitted to the analyzed function using the Trapezoidal, Simpson's 1/3, and Simpson's 3/8 methods. The definite integral formula is derived as the outcome of this process.
3. The volume is calculated via numerical integration by dividing the area into multiple segments using polynomial interpolation methods.

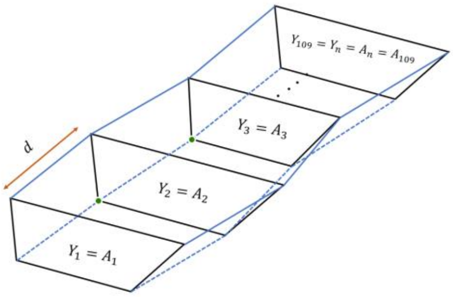


Figure 3. Sketch of Volume Calculation

4. The calculated volume is compared with results from Surfer software to assess the smallest relative error among the methods.

This volume calculation involves 109 points, where each point represents one segment. The number of points satisfies the requirements for estimation using the aforementioned methods. Data processing is conducted using MATLAB software, with results presented in Table 4.1. Notably, these results reflect the volume within the dredging area without accounting for slope volume, due to the limitation of Surfer software, which calculates volume only within predefined boundaries.

Through this methodology, the study aims to evaluate the extent to which the s-convex function can provide better approximations compared to conventional methods in estimating dredging volume at the Sunda Dock in Pondok Dayung.

RESULTS AND DISCUSSION

Before calculating the dredging volume using the s-convex function, the curve fitting of the function f on $\mathbb{R}^+$ is performed by employing the s-convex function at two and three points. This approach yields an explicit form of the definite integral estimate, which is subsequently used to compute the dredging volume at the pier.

Curve Fitting of the Function f on $\mathbb{R}^+$ Using the S-Convex Function

Curve fitting is used to find the curve that best fits a given function or data (Law et al., 2022). Curve fitting is performed using both two-point and three-point interpolation techniques, aiming to derive an explicit representation of the function $f(x)$. Recent approaches highlight the use of convexity-preserving and weighted interpolation methods to ensure accurate modeling of the underlying function. This was described in the study by Kyasov (2013, 2014). In the two-point case, the function $f(x)$ is approximated using an s-convex function, where the parameter $s \in (0,1]$ controls the curvature. This approach aligns with recent developments in the analysis of integral inequalities and function modeling using s-convexity (Kashuri et al., 2020b). The interpolation relies on the known values of fff at two distinct positive points, $\big(x_1, f(x_1)\big)$ and $\big(x_2, f(x_2)\big)$, with $x_1 \le x < x_2$, a common framework in shape-preserving interpolation models (Hussain et al., 2019).

Since $x_1 \le x < x_2$, it follows that

$$x = \alpha x_1 + (1-\alpha)x_2, \forall\alpha \in [0,1]. \qquad (1)$$

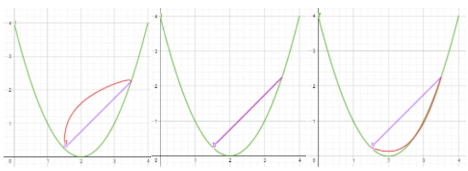
Based on the definition of an s-convex function (Hudzik & Maligranda, 1994), we have:

$$\begin{aligned} f(x) &= G(\alpha) \\ &= \alpha^s f(x_1) + (1-\alpha)^s f(x_2) \end{aligned} \qquad (2)$$

By utilizing the above relation, it is obtained that $\alpha = \frac{x_2 - x_1}{x_2 - x_0}$. Substituting this value of α into the previous, the two-point method approximates the function $f(x)$ as

$$f(x) = \frac{x_2 - x}{x_2 - x_1}^{s} f(x_1) + \frac{x - x_1}{x_2 - x_1}^{s} f(x_2) \qquad (3)$$

Here s is a flexible parameter. When s=1, the curve reduces to a linear function, which is equivalent to the trapezoidal method. for s> 0, the curve adapts to nonlinear data (see Figure 4).



0 < s < 1 s = 1 s = 3 > 1

Figure 4. Graph of ***S***-Convexity at Two Points

Using three points, the s-convex function is employed based on the concept of Simpson's 1/3 rule. This approach utilizes three points from the function *f*, namely $(x_0, f(x_0))$, $(x_1, f(x_1))$, and $(x_2, f(x_2))$ which form an upward concave curve.
Based on equation (1), it is obtained that:

$$f(x_1) = f(\alpha x_0 + (1 - \alpha)x_2) \qquad (4)$$

Considering the defintion of an s-convex function, we have

$$\begin{aligned} f(x_1) &= f(\alpha x_0 + (1 - \alpha)x_2) \\ &\leq \alpha^s f(x_0) + (1 - \alpha)^s f(x_2) \end{aligned} \qquad (5)$$

Let $G(\alpha) = \alpha^s f(x_0) + (1 - \alpha)^s f(x_2)$, so that

$$\begin{aligned} f(x_1) &= G(\alpha) \\ &= \alpha^s f(x_0) + (1 - \alpha)^s f(x_2) \end{aligned} \qquad (6)$$

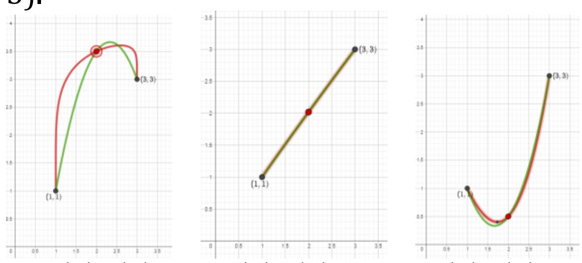
Utilizing equation (1) we obtain $\alpha = \frac{x_2 - x_1}{x_2 - x_0}$. Then substituting this value of α into the equation yields

$$f(x_1) = \left(\frac{x_2 - x_1}{x_2 - x_0}\right)^s f(x_0) + \left(\frac{x_1 - x_0}{x_2 - x_0}\right)^s f(x_2) \quad (7)$$

Since x_1 is the midpoint between x_0 and x_2, it follows that

$$f(x_1) = \left(\frac{1}{2}\right)^s f(x_0) + \left(\frac{1}{2}\right)^s f(x_2)$$
$$f(x_1) = \left(\frac{1}{2}\right)^s \left(f(x_0) + f(x_2)\right)$$
$$\frac{f(x_1)}{f(x_0) + f(x_2)} = \left(\frac{1}{2}\right)^s \qquad (8)$$

Subsequently, for the three-point method, the parameter s is explicitly defined as $s = log_2 \frac{f(x_0) + f(x_2)}{f(x_1)}$ where x_1 is the midpoint between x_0 and x_2. The value of s is then substitued into $f(x) = \left(\frac{x_2 - x_1}{x_2 - x_0}\right)^s f(x_0) + \left(\frac{x_1 - x_0}{x_2 - x_0}\right)^s f(x_2), \quad \forall x_0 < x < x_2, x_1 = \frac{x_0 + x_2}{2}$, dan $f(x_1) > 0$. This approach yields an upward concave curve that very accurately fits the original data (see Figure 5).



$1 < \frac{f(x_0)+f(x_2)}{f(x_1)} < 2$ $\frac{f(x_0)+f(x_2)}{f(x_1)} = 2$ $\frac{f(x_0)+f(x_2)}{f(x_1)} > 2$

Figure 5. Graph of ***S***-Convexity at Three Points

Explicit Form of the Definite Integral Estimate

The definite integral of the s-convex function is derived analytically by substituting the approximated function $f(x)$ obtained from both the two-point and three-point methods. This yields the following explicit forms for the definite integral estimates.

- **Two-Point Method**:
  $$\int_{x_1}^{x_2} f(x)dx = \frac{x_2 - x_1}{s+1}\left(f(x_1) + f(x_2)\right) \qquad (9)$$

- **Three-Point Method**:
$$\int_{x_0}^{x_2} f(x)dx = \frac{x_2 - x_0}{log_2 \frac{2(f(x_0)+f(x_2))}{f(x_1)}} \left(f(x_0) + f(x_2)\right) \quad (10)$$

Comparison of Dredging Volume Analysis

The dredging volume at the Sunda Pondok Dayung Wharf is calculated using four methods: the trapezoidal rule, Simpson's 1/3 rule, Simpson's 3/8 rule, and the s-convex method. The results are compared with those obtained using Surfer software (see Table 1). The comparison can be observed from the absolute error and relative error obtained from the results of the four methods compared to the results from Surfer software.

Table 1. Comparison of Dredging Volume and Error Analysis

Method	Volume (m^3)	Absolute Error (m^3)	Relative Error (%)
Trapezoidal	58987.01	5733.42	8,857
Simpson 1/3	58967.32	5753.10	8.889
Simpson 3/8	58987.01	5733.42	8.859
S-konveks	58963.56	5756.87	8.895
Surfer Software	64720.43	-	-

The trapezoidal method yielded the smallest relative error (8.857%), while the s-convex method exhibited a slightly higher error (8.895%). Nevertheless, all methods demonstrated comparable accuracy, with differences in relative error below 0.04%.

The methods of volume calculation such as the Trapezoidal Rule, Simpson's 1/3 Rule, and Simpson's 3/8 Rule have been widely applied in various studies. The studies shown in Table 2 indicate that these methods have been commonly used in many applications and produce relatively small errors.

Table 2. Previous Research of Trapezoidal and Simpson's Application

No	Author(s) & Year	Application Area	Results
1	Sulej & Murawski (2017)	Determining the stroke volume of the artificial ventricle	All methods produce appropriate results, but the Simpson's provides the highest accuracy determination.
2	Saleem (2024)	representing surfaces and calculating volumes between two surfaces	Advanced interpolation methods like Kriging and IDW yield accurate volumes by capturing complex terrain features.
3	Syah Amir & Yuwono (2023)	Volume Calculation of Sidoarjo Mud	Trapezoidal method is suitable; differences with Simpson's method are minimal.
4	Kareem et al. (2023)	Experimental investigation of holdup fraction	In bubble flow, all methods show low error (~9–11%)
5	Zhang et al., (2022)	Construction waste landfill volume estimation	The trapezoid, Simpson and Simpson 3/8 rules were suitable for estimating construction waste Volume.

In the context of this research, the S-Convex method has proven to deliver results with very small differences in relative error —less than 0.04%—when compared to these regular methods (Trapezoidal and Simpson's). Therefore, the S-Convex method holds potential as a more accurate and efficient alternative for integral estimation in volume calculations, particularly in applications such as dredging volume assessment at Sunda Pondok Dayung Dock.

CONCLUSIONS AND SUGGESTIONS

This study demonstrates that s-convex function-based curve fitting is an effective approach for estimating definite integrals, particularly in dredging volume calculations. Both two-point and three-point methods successfully approximated the function, with the three-point method using a predefined s parameter, while the two-point method allowed for flexibility. When applied to dredging volume estimation at Sunda Pondok Dayung Dock, the s-convex method yielded comparable results to conventional numerical integration techniques, with only a 0.038% error difference from the trapezoidal method. This suggests that the s-convex approach is a viable alternative for volume estimation, especially in cases where data flexibility is required.

Future research should explore extending the s-convex curve fitting method to more than three points to improve accuracy. Additionally, applying this approach to larger areas with a more flexible s parameter could enhance its adaptability. Given its precision in volume estimation, this method has the potential to support Pushidrosal in refining dredging calculations and assist the Naval Base Facilities Service (Disfaslanal) in optimizing budgets and ensuring navigational safety for Indonesian Navy vessels.

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