International Journal of Researches on Civil Engineering with Artificial Intelligence

www.ceai.reapress.com

Int. J. Res. Civ. Eng. AI. Vol. 3, No. 2 (2026) 107–121.

Paper Type: Original Article

An Analytical-CAD Framework for Automated Optimum Blank Design of Rectangular Deep-Drawing Components with Minimum Material Waste

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Citation:

Received: 20 June 2025 *Revised: 15 September 2025* *Accepted: 26 December 2025*	Faghihmaleki, A., & Angouraj Taghavi, H. (2026). An analytical-CAD framework for automated optimum blank design of rectangular deep-drawing components with minimum material waste. *International journal of researches on civil engineering with artificial intelligence*, *3*(2), 107-121.

Abstract

Deep drawing is one of the most widely adopted sheet metal forming processes for manufacturing lightweight, high-strength, and dimensionally accurate components used in the automotive, aerospace, household appliance, and packaging industries. Among the numerous parameters affecting the quality of deep-drawn products, the geometry of the initial blank plays a decisive role in controlling material flow, flange deformation, trimming allowance, thickness distribution, and the occurrence of common forming defects such as wrinkling, tearing, and excessive earing. Although extensive research has been devoted to the optimization of circular blank geometries, the design of optimal blanks for rectangular deep-drawn components remains considerably more challenging because of the non-axisymmetric material flow and the highly non-uniform strain distribution developed along the flange and corner regions. This study presents a computational methodology for the optimal design of the initial blank geometry for rectangular deep-drawn parts with the objective of minimizing trimming waste while maintaining satisfactory forming quality. An analytical material-flow formulation based on curvilinear coordinates is implemented within a SolidWorks environment through a customized Visual Basic application that automatically generates the optimum blank contour directly from the three-dimensional geometry of the desired component. The developed algorithm calculates the initial blank profile, reconstructs its geometry in Cartesian coordinates, and compares the optimized blank with several conventional blank configurations, including rectangular, elliptical, octagonal, and diamond-shaped blanks. The generated geometries are subsequently validated using nonlinear finite element simulations performed in ABAQUS to investigate material flow characteristics, deformation behavior, and the final trimming profile.Simulation results demonstrate that the proposed methodology significantly reduces trimming waste while improving material utilization compared with conventional blank geometries. Furthermore, the optimized blank exhibits a more uniform material flow toward the die cavity, resulting in a more homogeneous strain distribution and a noticeable reduction in localized deformation. The comparison between different blank geometries confirms that although octagonal blanks outperform other conventional alternatives, the proposed optimized contour consistently provides the minimum trimming allowance and the highest material efficiency. The developed computational framework offers a practical and computationally efficient tool that can readily be integrated into industrial computer-aided design environments for rapid blank design in deep drawing applications involving rectangular geometries.

Keywords: Deep drawing, Initial blank optimization, Rectangular cup, Sheet metal forming, Finite element analysis, Material flow, Trim reduction, ABAQUS, SolidWorks, Design optimization.

1 | Introduction

The increasing demand for lightweight structures, improved mechanical performance, reduced manufacturing costs, and sustainable production methods has significantly enhanced the importance of sheet metal forming

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https://doi.org/10.48314/ijrceai.v3i2.57

processes in modern manufacturing industries. Sheet metal forming provides several advantages, including high material utilization, high production efficiency, excellent repeatability, and the ability to manufacture complex thin-walled components with accurate geometrical characteristics. Among various forming technologies, deep drawing is considered one of the most important processes for producing components with complex shapes and high dimensional accuracy in automotive, aerospace, electronic, appliance, packaging, and other industrial applications [1–3]. Due to its capability for large-scale production with relatively low material waste, deep drawing remains an essential manufacturing process for advanced industrial applications [2], [3].

The quality and performance of deep-drawn components are strongly influenced by the interaction between material properties, die and punch geometry, friction conditions, lubrication, Blank Holder Force (BHF), forming velocity, and initial blank configuration. These parameters govern the material flow behavior, stress and strain development, thickness distribution, and occurrence of forming defects during deformation [1], [4], [5]. Improper selection of forming conditions may lead to undesirable phenomena such as wrinkling, tearing, excessive thinning, springback, and dimensional inaccuracies, which reduce product quality and increase manufacturing costs [4], [6]. Therefore, controlling material flow and determining appropriate forming conditions remain among the major challenges in sheet metal forming research.

Among the different factors affecting deep drawing performance, the initial blank geometry plays a fundamental role because it determines the initial material distribution before deformation. The blank contour directly influences the movement of material from the flange region into the die cavity and consequently affects strain distribution, thickness variation, deformation uniformity, and final dimensional accuracy [4]. An inappropriate blank shape can cause non-uniform material flow, excessive trimming allowance, localized thinning, and premature failure. Conversely, an optimized blank contour can improve material utilization, reduce forming defects, and enhance the overall efficiency of the manufacturing process [4], [7].

From an industrial perspective, efficient material utilization is one of the most important factors influencing the economic and environmental performance of sheet metal manufacturing. In mass-production industries, even small reductions in excess material and trimming waste can result in considerable savings in raw material consumption and energy usage. Furthermore, reducing material waste contributes to sustainable manufacturing objectives by decreasing the environmental impacts associated with metal production and processing [2], [3]. Consequently, optimum blank design has attracted considerable attention as an effective strategy for improving resource efficiency and reducing production costs.

The determination of optimum blank geometry has been extensively studied for axisymmetric components, particularly cylindrical cups, where deformation occurs relatively uniformly due to the symmetrical distribution of material flow. Analytical formulations and experimental investigations have successfully predicted suitable circular blank geometries for these components under simplified deformation conditions [5], [8]. However, these approaches cannot be directly extended to non-axisymmetric components because their deformation behavior is considerably more complex. Rectangular components, in particular, exhibit different material flow characteristics in straight wall regions and corner areas, resulting in non-uniform stress and strain distributions throughout the blank [4], [7].

Rectangular deep drawing is therefore regarded as one of the more challenging sheet metal forming operations. During forming, bending, stretching, and material redistribution occur simultaneously in different regions of the workpiece. The corner regions experience severe deformation due to concentrated material accumulation and complex flow paths, while the straight wall regions undergo different deformation mechanisms [4], [7]. As a result, the optimum blank contour for rectangular components usually deviates significantly from simple geometrical shapes such as rectangles or ellipses. Accurate prediction of the initial blank shape remains a critical challenge for improving forming quality and minimizing material waste in non-axisymmetric deep drawing processes [7], [9].

Traditionally, optimum blank design has been performed through experimental trial-and-error methods based on engineering experience. Although these methods may provide acceptable solutions for simple geometries, they are generally expensive, time-consuming, and unsuitable for modern manufacturing systems requiring rapid design optimization [10]. The development of Finite Element Analysis (FEA) has significantly changed the approach toward sheet metal forming analysis by enabling prediction of material flow, forming forces, thickness distribution, strain localization, and failure mechanisms before manufacturing physical dies [10–12]. Numerical simulation has therefore become an essential tool for analyzing complex forming operations and improving industrial process design.

Finite element methods have also been widely applied for blank shape optimization. Compared with analytical techniques, numerical simulations can consider realistic material behavior, nonlinear deformation, friction effects, and complex boundary conditions. Several researchers have developed iterative optimization procedures in which the initial blank geometry is modified based on the difference between the predicted and desired final component geometry [13], [9]. These methods have demonstrated significant potential for improving blank prediction accuracy, especially for complex non-axisymmetric components.

However, simulation-based optimization approaches generally require a large number of nonlinear finite element analyses. Since each modification of the blank geometry requires additional forming simulations, the optimization process can become computationally expensive and time-consuming [13]. This limitation reduces the applicability of conventional numerical optimization methods in industrial environments where rapid and efficient design solutions are required.

To overcome these limitations, researchers have investigated analytical approaches, numerical optimization algorithms, and computational intelligence techniques for improving the efficiency of sheet metal forming design. Evolutionary algorithms, response surface methodology, and other optimization techniques have been employed to determine suitable process parameters and improve forming performance while reducing the number of required simulations [7], [14], [15]. In recent years, artificial intelligence and machine learning approaches have also attracted increasing attention due to their capability to establish relationships between process variables and forming responses using computational models and experimental or numerical databases [16], [17].

Despite considerable progress in analytical modeling, finite element simulation, and optimization techniques, optimum blank design for rectangular deep-drawn components remains an unresolved research problem. Many previous studies have concentrated mainly on optimizing process parameters such as BHF, friction conditions, and tool geometry rather than directly generating the optimum initial blank contour [13], [14]. Furthermore, existing numerical optimization methods often depend on repeated finite element simulations, which limits their efficiency for practical industrial applications.

Another important limitation of previous studies is the limited integration between analytical blank prediction methods and commercial CAD environments. In industrial applications, engineers require automated design tools capable of generating optimized blank geometries directly from the final component geometry. Such integrated approaches can reduce design time, decrease material consumption, and improve the efficiency of sheet metal manufacturing processes.

Therefore, the objective of the present study is to develop an analytical-computational framework for automatic generation of optimum blank geometries for rectangular deep-drawn components. The proposed methodology combines analytical material-flow modeling with CAD-based automation through a Visual Basic algorithm implemented in the SolidWorks environment. Unlike conventional simulation-driven optimization methods, the developed approach predicts the optimum blank contour directly from the final component geometry, reducing computational requirements while maintaining acceptable prediction accuracy.

The effectiveness of the proposed methodology is evaluated using nonlinear finite element simulations performed in ABAQUS. The optimized blank geometry is compared with conventional blank shapes, including rectangular, elliptical, octagonal, and diamond-shaped configurations. The effects of blank geometry on material flow behavior, thickness distribution, deformation characteristics, and trimming allowance are investigated to demonstrate the capability of the proposed method for improving material utilization and reducing manufacturing waste.

The main contributions of this study are summarized as follows.

I. Development of an analytical algorithm for automatic prediction of optimum blank geometry in rectangular deep drawing processes.

II. Integration of the proposed optimization procedure into the SolidWorks CAD environment using a Visual Basic-based automation framework.

III. Validation of the predicted blank geometries through nonlinear finite element simulations in ABAQUS.

IV. Comparative evaluation of optimized and conventional blank configurations under identical forming conditions.

V. Demonstration of improved material utilization and reduced trimming waste through optimized blank design.

The proposed framework provides an efficient engineering approach for intelligent blank design and establishes a foundation for future integration with advanced optimization techniques, machine learning models, and digital manufacturing systems for sustainable sheet metal forming applications.

2 | Literature Review

Deep drawing has been extensively studied as one of the most important sheet metal forming processes due to its ability to manufacture lightweight and complex components with high dimensional accuracy and good mechanical performance. The complexity of this process originates from the nonlinear interaction between material properties, tooling geometry, friction conditions, lubrication, BHF, and initial blank configuration. These factors strongly influence material flow, stress development, strain distribution, thickness variation, and the final quality of formed components. Therefore, numerous analytical, experimental, and numerical investigations have been conducted to understand deformation mechanisms and improve the reliability of deep drawing processes [1], [4], [8].

Among the various parameters affecting deep drawing performance, the initial blank geometry has been recognized as one of the most influential factors controlling material distribution and deformation behavior. The blank contour defines the initial amount and location of material available for deformation and directly affects the movement of material into the die cavity. An inappropriate blank shape may result in excessive material accumulation, non-uniform deformation, increased trimming allowance, thinning, wrinkling, and premature fracture. In contrast, an optimized blank geometry promotes uniform material flow, reduces forming defects, and improves material utilization [4], [6], [7].

Early investigations on optimum blank design were mainly based on analytical methods developed from geometric relationships, deformation theory, and simplified assumptions regarding material flow. These approaches attempted to establish a relationship between the final component geometry and the required initial blank shape. Analytical methods provided rapid solutions with relatively low computational cost and contributed significantly to the fundamental understanding of sheet metal deformation. However, their accuracy was often limited due to assumptions such as ideal plastic deformation, simplified stress states, negligible friction effects, and uniform material behavior [4], [5].

For axisymmetric components, analytical approaches have shown considerable success because the material flow occurs relatively uniformly around the circumference of the component. Classical studies demonstrated that circular blank geometries could be effectively predicted for cylindrical cups under suitable forming conditions [5], [8]. The relatively simple deformation pattern of axisymmetric components allows analytical models to provide reliable results with limited computational effort. However, these methods become considerably less accurate when applied to non-axisymmetric geometries, where local deformation mechanisms and material redistribution become significantly more complex [4], [7].

Rectangular deep drawing represents a more challenging forming problem due to the simultaneous occurrence of bending, stretching, and non-uniform material flow in different regions of the blank. Unlike circular cups, rectangular components contain straight wall regions and corner areas with significantly different deformation characteristics. The corners experience higher deformation intensity due to material accumulation and complex flow paths, while the straight regions undergo different strain histories. Consequently, the optimum blank contour for rectangular components cannot be accurately represented by simple geometric shapes and requires more advanced prediction methods [4], [7].

Naceur et al. [7] investigated blank optimization in sheet metal forming using evolutionary algorithms and demonstrated that optimization of the initial blank contour can significantly improve forming performance. Their results highlighted the importance of considering the actual material flow behavior during deformation rather than relying only on geometric approximations. The study showed that optimization algorithms could provide improved blank predictions for complex forming operations where conventional analytical solutions are insufficient.

Kishor and Ravi Kumar [9] applied FEA for optimization of the initial blank shape to minimize earing defects in deep drawing processes. Their research demonstrated the capability of numerical simulation in predicting the influence of blank geometry on the final component quality. The study confirmed that finite element-based optimization methods could effectively improve forming accuracy by considering realistic deformation behavior and material response.

With the development of computational mechanics, FEA has become one of the most widely used approaches for investigating sheet metal forming processes. Numerical simulations enable researchers and engineers to predict forming forces, stress and strain distributions, thickness variations, deformation patterns, and potential failure locations before performing physical experiments or manufacturing dies [10–12]. The application of finite element methods has significantly reduced development time and provided a deeper understanding of complex forming phenomena.

Makinouchi [10] emphasized the important role of numerical simulation in industrial sheet metal forming applications and demonstrated that finite element methods provide an effective tool for predicting forming behavior and optimizing manufacturing processes. The increasing availability of advanced computational techniques has allowed engineers to analyze complex geometries and investigate the influence of different process parameters under realistic forming conditions.

Finite element simulations have also been widely applied in blank shape optimization problems. Park et al. [18] proposed a numerical optimization approach for determining optimum blank designs in sheet metal forming. Their methodology demonstrated that iterative modification of the initial blank geometry based on numerical predictions could significantly improve the final component accuracy. However, the study also highlighted an important limitation of simulation-based optimization approaches: the requirement for multiple nonlinear finite element analyses, which increases computational cost and limits their application in rapid industrial design processes.

In addition to blank geometry optimization, several studies have focused on controlling process parameters such as BHF, friction conditions, lubrication, punch geometry, and die design. Among these parameters, BHF has received significant attention because it directly controls the amount of material entering the die cavity. An insufficient BHF may lead to excessive material movement and wrinkling, whereas excessive force restricts material flow and increases the probability of fracture [4], [8].

Optimization of forming parameters has been investigated using various statistical and computational methods. Response surface methodology, design of experiments, and evolutionary optimization algorithms have been applied to identify suitable combinations of process variables while reducing the number of required experimental or numerical evaluations [14], [15]. These methods have demonstrated considerable potential for improving forming performance by establishing relationships between input parameters and final process responses.

Valente et al. [13] developed an integrated methodology for parameter identification and shape optimization in metal forming applications. Their work emphasized the importance of combining numerical simulation with optimization techniques to achieve improved forming performance. However, similar to many simulation-based approaches, their methodology depends on repeated numerical evaluations, which may become computationally expensive when applied to complex industrial components.

Recent developments in computational intelligence and machine learning have introduced new possibilities for optimizing manufacturing processes. Artificial intelligence-based approaches can establish relationships between process parameters and forming responses using numerical databases and experimental results. Machine learning techniques, including artificial neural networks, surrogate models, and other data-driven approaches, have been increasingly applied to reduce computational effort and accelerate optimization procedures [16], [17].

Kalita et al. [16] discussed the application of computational intelligence methods for optimization of manufacturing processes and highlighted the potential of intelligent algorithms for improving process efficiency and reducing computational requirements. Similarly, Shang et al. [17] demonstrated the capability of machine learning-based optimization methods for predicting and improving manufacturing process performance. These studies indicate that data-driven approaches can provide effective solutions for complex optimization problems where conventional analytical or numerical methods become inefficient.

Although significant progress has been achieved in analytical modeling, finite element simulation, and intelligent optimization methods, several challenges remain in the field of optimum blank design for rectangular deep-drawn components. First, a large proportion of previous investigations have focused on axisymmetric components, while rectangular geometries remain comparatively less studied due to their complex material flow behavior. Second, many existing optimization approaches require numerous finite element simulations, resulting in high computational costs and limiting their practical application in industrial environments [7], [9].

Furthermore, most previous studies have concentrated on optimizing individual process parameters rather than developing integrated methodologies capable of directly generating the optimum initial blank contour. While optimization of parameters such as BHF and friction conditions can improve forming quality, the initial blank geometry remains a fundamental factor determining material distribution and overall forming efficiency [4], [13].

Another important research limitation is the lack of integration between analytical blank prediction methods and commercial CAD environments. In practical manufacturing applications, engineers require automated tools capable of converting a final component geometry into an optimized blank shape with minimal manual intervention. Such systems can significantly reduce product development time, decrease material waste, and improve manufacturing sustainability.

Based on these limitations, the development of analytical-computational frameworks for automatic blank generation represents an important research direction. Combining analytical material-flow models with CAD-based automation can provide an efficient alternative to conventional simulation-driven optimization methods. Such approaches can reduce computational requirements while maintaining acceptable prediction accuracy.

Therefore, the present study focuses on developing an integrated analytical and computational methodology for optimum blank design of rectangular deep-drawn components. The proposed approach combines a curvilinear analytical material-flow model with CAD automation through a Visual Basic algorithm implemented in SolidWorks. The generated blank geometries are subsequently validated using nonlinear finite element simulations in ABAQUS to evaluate material flow behavior, thickness distribution, deformation characteristics, and trimming reduction. This framework aims to provide a practical engineering solution for efficient and sustainable sheet metal forming design.

3 | Analytical Formulation and Prediction of Optimum Blank Geometry

This section presents the mathematical framework used for modeling the optimum blank contour. The coordinate systems employed in the formulation, the transformation between different coordinate systems, and the development of the analytical model are described in detail. The proposed formulation is based on a curvilinear coordinate system, which enables a more accurate representation of material flow during the deep drawing process, particularly for non-axisymmetric components.

3.1 | Curvilinear Coordinate System (η–ξ)

To determine the initial blank contour, an appropriate curvilinear coordinate system $(\eta - \xi)$must first be defined, as illustrated in *Fig. 1*. This coordinate system consists of the tangent and involute curves generated from a predefined base curve. The ξ-axis is obtained by constructing tangent lines along the base curve, while the η-axis represents the arc length measured along the base curve.

The arc length parameter $s$is defined as the distance along the base curve from a reference point O' to the intersection point between the base curve and the corresponding involute curve. In this coordinate system, it is assumed that all material flow paths during the deep drawing operation are tangent to the base curve. Therefore, the ξ-coordinate lines represent the principal material flow trajectories during deformation.

The main advantage of introducing the curvilinear coordinate system is that it simplifies the mathematical description of material movement and blank contour evolution during the forming process. In contrast, expressing the same deformation relationships using conventional Cartesian coordinates results in highly complex equations due to the non-uniform flow patterns associated with rectangular deep drawing. Therefore, the $(\eta - \xi)$ coordinate system provides an efficient analytical framework for describing material redistribution and predicting the optimum initial blank geometry.

The use of curvilinear coordinates is particularly beneficial for non-axisymmetric deep drawing processes, where material flow cannot be represented accurately by radial deformation assumptions commonly used for circular cup drawing. By following the actual flow directions of the material, the proposed coordinate system enables a more realistic representation of deformation compatibility conditions and provides a suitable basis for analytical blank contour prediction.

Accordingly, the developed model utilizes the relationship between the final component geometry and the material flow lines defined in the $(\eta - \xi)$ coordinate system to determine the optimum blank boundary. This approach reduces the complexity of the mathematical formulation and provides a computationally efficient alternative to conventional iterative finite element-based blank optimization methods.

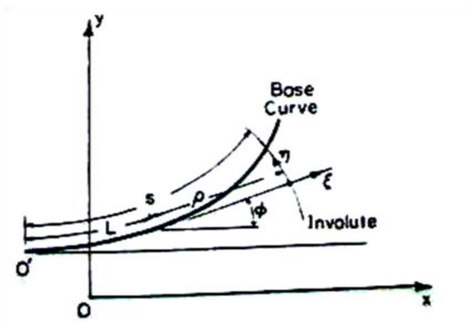

Fig. 1. Illustration of the Curvilinear Coordinate System $(\eta - \xi)$ [3].

To define the velocity field during the deep drawing process, it is necessary to determine the material flow behavior within the flange region, as illustrated in *Fig. 2*. Curve $s = s_0(\varphi)$ represents the initial flange boundary (initial blank contour). Curve $s = s_1(\varphi)$ indicates the starting position of the die, while curve $s = s_2(\varphi)$ corresponds to the end of the die radius and represents the final geometry of the drawn cup.

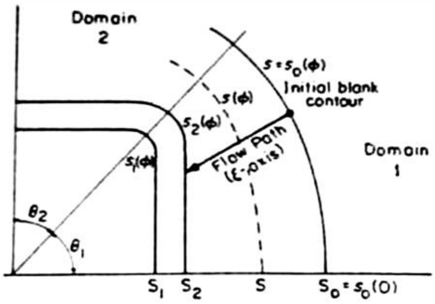

Fig. 2. Geometrical representation of material flow [3].

3.2 | Transformation of the Curvilinear Coordinate System $(\eta - \xi)$ into the Cartesian Coordinate System

The equations presented in the previous section were formulated based on the curvilinear coordinate system $(\eta - \xi)$. To obtain the initial blank contour in the Cartesian coordinate system, the transformation from the $(\eta - \xi)$ coordinate system to the Cartesian coordinate system $(x - y)$ must be established.

For this purpose, the base curve is assumed to have an elliptical shape. After solving the governing equations in the curvilinear coordinate system, the resulting contour points are transformed into Cartesian coordinates to obtain the actual coordinates of the initial blank geometry.

According to *Fig. 3*, the equation of the elliptical base curve can be expressed as follows.

$$\left(\frac{x - x_0}{d}\right)^2 + \left(\frac{y - c}{c}\right)^2 = 1. \tag{1}$$

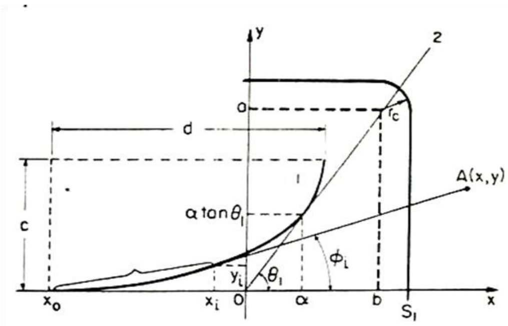

Fig. 3. Geometrical representation of the ellipse as the base curve [3].

The elliptical representation of the base curve provides a suitable mathematical approximation for describing the material flow path during the deep drawing process. By applying the coordinate transformation, each point defined in the $(\eta - \xi)$ coordinate system is converted into its corresponding Cartesian coordinates (x, y), allowing the optimum initial blank contour to be generated in a conventional coordinate system.

This transformation establishes a direct relationship between the analytical material-flow model and the practical implementation of the predicted blank geometry. Consequently, the obtained blank contour can be directly transferred to a CAD environment for automated geometry generation and subsequently evaluated through finite element simulations.

The *Eq. (2)*, which passes through the origin of the Cartesian coordinate system $x - y$ and the corner point of the component, can also be expressed as follows.

$$y = x \tan\theta_1 . \quad (2)$$

If λ is defined as the ratio of the minor diameter to the major diameter, then:

$$\lambda = \frac{c}{d}. \quad (3)$$

Consequently, x_0 and y_i x_i *s*are expressed by *Eqs. (4)-(6)*.

$$x_0 = \frac{c}{\tan\theta_1}\left\{1 - \left[1 + \left(\frac{\tan\theta_1}{\lambda}\right)^2\right]^{1/2}\right\}. \quad (4)$$

$$x_i = x_0 + \frac{\dfrac{c\tan\theta_i}{\lambda^2}}{\left[1 + \left(\dfrac{\tan\theta_i}{\lambda}\right)^2\right]^{1/2}}. \quad (5)$$

$$y_i = c\left\{1 - \left[1 + \left(\frac{\tan\theta_i}{\lambda}\right)^2\right]^{-1/2}\right\}. \quad (6)$$

The transformation from the $(\eta - \xi)$ coordinate system to the Cartesian $(x - y)$ coordinate system is expressed as follows.

$$x = x_i + (s - L)\cos\theta_i . \quad (7)$$

$$y = y_i + (s - L)\sin\theta_i . \quad (8)$$

However, the maximum value of c is obtained when the; therefore, the limiting factor of c, denoted as c_0, can be defined as follows.

$$c_0 = \frac{(b + r_c\cos\theta_1)\tan\theta}{1 - \left[1 + \left(\dfrac{\tan\theta_i}{\lambda}\right)^2\right]^{-1/2}}. \quad (9)$$

To nondimensionalize c, the parameter υ is defined as follows.

$$\nu = \frac{c}{c_0} \le 1. \quad (10)$$

Therefore, by determining the two parameters λ and υ, the base curve and consequently the curvilinear coordinate system can be established. The values of λ and υ were obtained experimentally as $\lambda = 0.1$ and $\upsilon = 0.8$, respectively [3].

3.2 | Calculation of the Sheet Contour Equation as a Function of Time

By neglecting thickness variation during the deformation process and assuming incompressible material behavior, the sheet contour equation at time $t = T$ can be obtained by solving the strain rate and material flow velocity equations and applying the corresponding boundary conditions. The resulting relationship is expressed in terms of the initial blank contour C_0 and the die cavity contour C_2 as follows.

$$T = \frac{\frac{s_0^2 - s^2}{2} - L(s_0 - s)}{s_1 - L}. \quad \textbf{(11)}$$

This equation describes the evolution of the sheet contour during the deep drawing process and establishes the relationship between the initial blank geometry and the final formed component. By using this formulation, the optimum initial blank contour can be determined based on the required final geometry and the predicted material flow path.

The distance from the reference point to the intersection points between the base curve and its corresponding tangent lines is considered as the arc length parameter. To obtain the optimum initial blank geometry from this equation, the equation of the initial blank contour must be determined under the condition that, at the end of the deep drawing process, the blank contour coincides with the die cavity contour ($s = s_1$). The forming time T is calculated from the ratio of the drawn component depth to the punch velocity. Therefore, by substituting $s = s_1$ into the above equation and solving the resulting relationship with respect to s_1, the optimum initial blank contour can be obtained.

Eq. (11) is subsequently employed for determining the flange contour of a given blank, designing blanks for components with a uniform remaining flange, and designing blanks for components with uniform height distribution.

3.3 | Development of the Initial Blank Design Program

The equations presented in the previous sections were implemented and solved using a Visual Basic programming environment. The developed program receives the three-dimensional model of the rectangular component as input and automatically calculates its optimum initial blank geometry.

After determining the optimum blank contour, the program generates several conventional blank geometries, including rectangular, circular, octagonal, and diamond-shaped blanks, which are tangent to the predicted optimum contour. The material waste percentage associated with the use of each blank configuration is then calculated and compared.

The user interface (UserForm) of the developed program is illustrated in *Fig. 4*. The developed computational tool provides an automated approach for optimum blank generation and enables direct evaluation of material utilization efficiency for different blank geometries. This integration between analytical modeling and CAD-based programming reduces the need for conventional trial-and-error procedures and provides an efficient solution for industrial blank design applications.

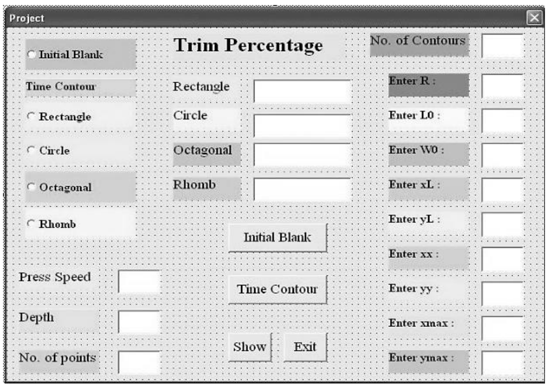

Fig. 4. Illustration of one of the program user interface pages.

3.4 | Program Implementation and Blank Contour Generation Procedure

At the beginning of the developed program, the required variables are defined. These variables include primary tree variables, numerical variables, and array variables. The main tree variables are introduced according to the requirements of the program and are subsequently assigned appropriate values.

In the next stage, the commands associated with the operation button are developed. This section represents the main computational part of the program. The initial part of these commands is dedicated to extracting the final component contour and determining its geometrical dimensions. This process is performed by storing the coordinates of the points defining the lines and arcs of the final geometry into two array variables.

Subsequently, the mathematical equations presented in the previous sections are implemented and solved within the program. After obtaining the required contour points, the optimum initial blank contour is generated by connecting adjacent points using spline curves. The spline generation process is performed through an iterative loop to ensure smooth and continuous representation of the predicted blank boundary.

Following the generation of the optimum blank geometry, additional commands are developed for creating and calculating the material waste percentage associated with different conventional blank shapes. Rectangular, circular, octagonal, and diamond-shaped blanks tangent to the optimum initial blank contour are generated, and the corresponding waste ratios are calculated for comparison.

For a rectangular component, as shown in *Fig. 5*, the calculated material waste percentages obtained for different blank configurations are presented in *Fig. 6*. These results demonstrate the capability of the developed program to automatically generate optimum blank geometries and evaluate material utilization efficiency for various blank design strategies.

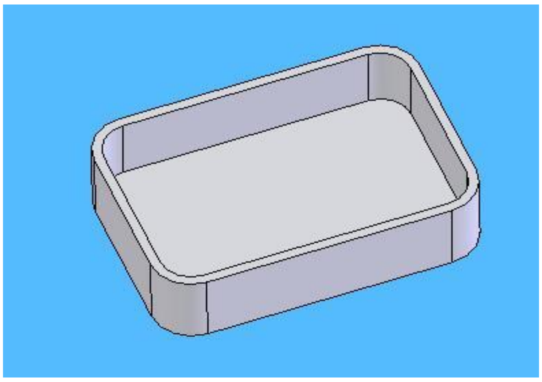

Fig. 5. A rectangular component.

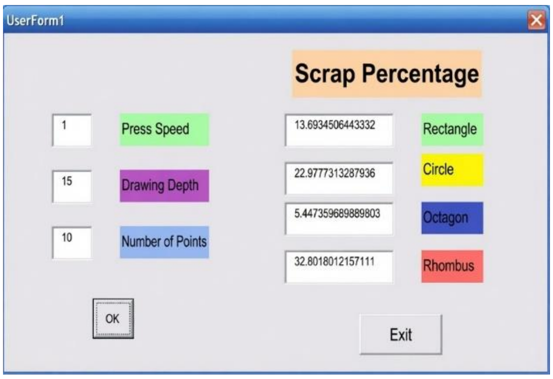

Fig. 6. Results of material waste percentage.

It can be observed that, for this component, the octagonal blank geometry provides the minimum material waste, with a sheet waste percentage of 5.5%. The generated blank configurations are illustrated in *Fig. 7*.

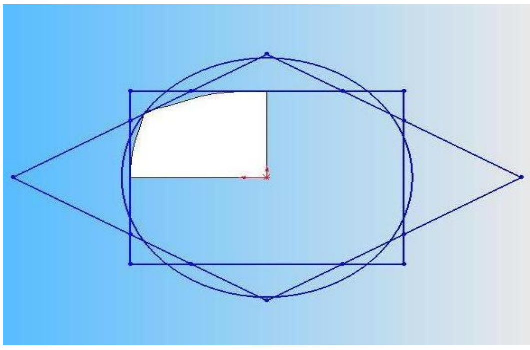

Fig. 7. Initial blanks for a rectangular-shaped part.

4 | Results Verification and Analysis

To validate the theoretical results obtained from the proposed analytical model, the deep drawing process of the rectangular component was simulated using the ABAQUS finite element software. For the numerical investigation, the optimum initial blank geometries generated by the developed Visual Basic program for the component shown in *Fig. 5* were modeled, and the deep drawing operation was performed on each blank configuration (*Figs. 8–12*).

The finite element simulations were conducted to evaluate the accuracy of the predicted blank contours and to investigate the influence of different blank geometries on the forming behavior. The numerical results were analyzed in terms of material flow characteristics, deformation behavior, and final component geometry to verify the effectiveness of the proposed analytical approach. The comparison between the analytical predictions and finite element results provides a comprehensive assessment of the capability of the developed framework for optimum blank design in rectangular deep drawing processes.

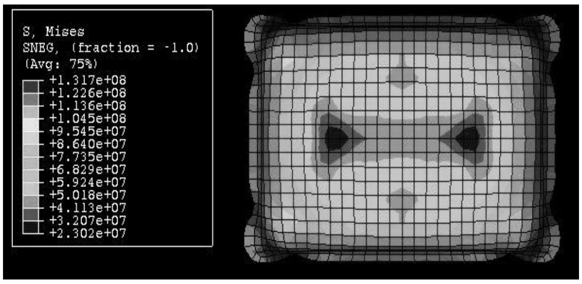

Fig. 8. The rectangular part after drawing with the optimal initial blank obtained from the program.

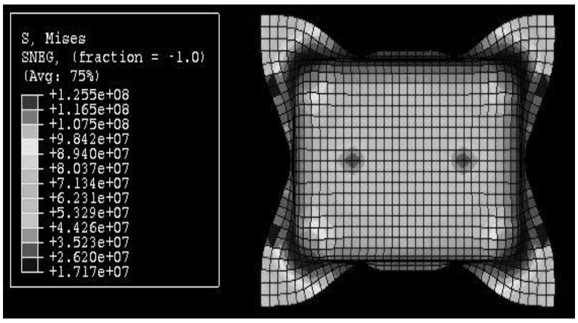

Fig. 9. The rectangular part after drawing with the rectangular initial blank obtained from the program.

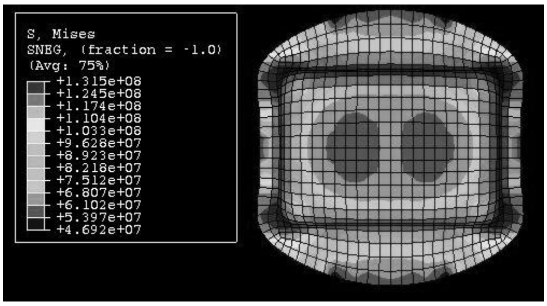

Fig. 10. The rectangular part after drawing with the elliptical initial blank obtained from the program.

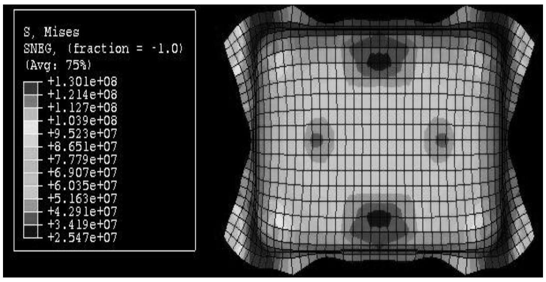

Fig. 11. The rectangular part after drawing with the octagonal initial blank obtained from the program.

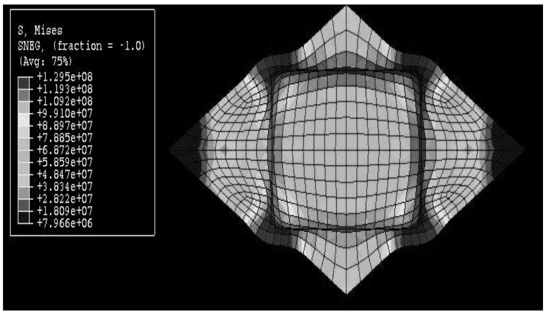

Fig. 12. The rectangular part after drawing with the diamond-shaped initial blank obtained from the program.

4.1|Verification of the Optimum Blank Geometry

Figs. 8–12 demonstrate that the application of the predicted optimum blank contour results in minimum trimming waste at the end of the deep drawing process. The final formed component obtained from the optimized blank exhibits improved material utilization and reduced excess flange material compared with conventional blank geometries. These results confirm the effectiveness of the proposed analytical formulation and provide numerical evidence supporting the optimality of the generated initial blank contour.

The agreement between the predicted blank geometry and the final component obtained from finite element simulation indicates that the developed analytical model can accurately describe material flow during rectangular deep drawing. Furthermore, the ABAQUS simulations confirm that the optimum blank design successfully minimizes trimming requirements while maintaining acceptable forming quality. Therefore, the proposed analytical-CAD framework can be considered an efficient approach for reducing material waste and improving blank design accuracy in non-axisymmetric deep drawing processes.

5 | Conclusion

In this study, an integrated analytical-computational framework was developed for optimum blank design of rectangular deep-drawn components. The proposed approach aims to automatically determine the initial blank geometry from the final three-dimensional component shape while minimizing trimming waste and improving material utilization.

Based on the theoretical formulation of material flow during rectangular deep drawing, the governing equations for predicting the optimum initial blank contour were derived. The developed mathematical model considers the deformation characteristics of non-axisymmetric components and determines the blank geometry that provides minimum excess material at the end of the forming process.

The proposed formulation was implemented in a Visual Basic-based computational program integrated within the SolidWorks CAD environment. By receiving the three-dimensional model of the target rectangular component as input, the developed program automatically extracts the component geometry, calculates the optimum blank contour, and generates the corresponding initial blank geometry.

The accuracy and effectiveness of the proposed methodology were evaluated through nonlinear finite element simulations performed in ABAQUS. The deep drawing process of the generated optimum blank was numerically modeled, and the obtained results demonstrated that the optimized blank leads to minimum trimming allowance after forming. The simulation results confirmed that the predicted blank geometry provides efficient material flow and can successfully minimize material waste.

In addition, several conventional blank geometries, including rectangular, elliptical, octagonal, and diamond-shaped configurations, were generated around the optimum blank contour, and their corresponding material waste percentages were calculated. The comparison results showed that, among the conventional geometries investigated, the octagonal blank provides the lowest material waste after the optimum blank, demonstrating its superior material utilization capability compared with other simple blank shapes.

Overall, the developed analytical-CAD framework provides an efficient and practical engineering tool for automatic blank generation in rectangular deep drawing applications. By reducing dependence on trial-and-error procedures and minimizing the number of required numerical simulations, the proposed methodology offers significant potential for sustainable manufacturing, reduced material consumption, and improved efficiency in advanced sheet metal forming processes.

References

[1] Hosford, W. F., & Caddell, R. M. (2011). *Metal forming: Mechanics and metallurgy*. Cambridge University Press. https://books.google.com/books?id=x0GWAd7hNy0C

[2] Serope Kalpakjian, S. (2015). *Manufacturing, engineering and technology*. Pearson. https://repositori.mypolycc.edu.my/jspui/handle/123456789/5339

[3] Groover, M. P. (2010). *Fundamentals of modern manufacturing: Materials, processes, and systems*. John Wiley & Sons. https://books.google.com/books?id=QU-Qvud3OvoC

[4] Marciniak, Z., Marciniak, Z., Duncan, J. L., Hu, J., & Duncan, J. (2002). *Mechanics of sheet metal forming*. Elsevier Science. https://books.google.com/books?id=jsFkpWE5YacC

[5] Lange, K. (1985). *Handbook of metal forming*. McGraw-Hill Inc.

[6] Emmens, W. C. (2011). *A review of parameters and processes that control, limit or enhance the formability of sheet metal*. Springer. https://doi.org/10.1007/978-3-642-21904-7

[7] Naceur, H., Guo, Y. Q., & Batoz, J. L. (2004). Blank optimization in sheet metal forming using an evolutionary algorithm. *Journal of materials processing technology*, *151*(1), 183–191. https://doi.org/10.1016/j.jmatprotec.2004.04.036

[8] Altan, T., & Tekkaya, A. E. (2012). *Sheet metal forming: Fundamentals*. Asm International. https://doi.org/10.31399/asm.tb.smff.t53400233

[9] Kishor, N., & Ravi Kumar, D. (2002). Optimization of initial blank shape to minimize earing in deep drawing using finite element method. *Journal of materials processing technology*, *130–131*, 20–30. https://doi.org/10.1016/S0924-0136(02)00790-2

[10] Makinouchi, A. (1996). Sheet metal forming simulation in industry. *Journal of materials processing technology*, *60*(1), 19–26. https://doi.org/10.1016/0924-0136(96)02303-5

[11] Vollertsen, F., & Hu, Z. (2006). Tribological size effects in sheet metal forming measured by a strip drawing test. *CIRP annals*, *55*(1), 291–294. https://doi.org/10.1016/S0007-8506(07)60419-3

[12] Abdelhafeez Hassan, A., Küçüktürk, G., Yazgin, H. V., Gürün, H., & Kaya, D. (2022). Selection of constitutive material model for the finite element simulation of pressure-assisted single-point incremental forming. *Machines*, *10*(10), 1–16. https://doi.org/10.3390/machines10100941

[13] Valente, R. A. F., Andrade-Campos, A., Carvalho, J. F., & Cruz, P. S. (2011). Parameter identification and shape optimization. *Optimization and engineering*, *12*(1), 129–152. https://doi.org/10.1007/s11081-010-9126-y

[14] Li, Y., Lu, H., Daniel, W. J. T., & Meehan, P. A. (2015). Investigation and optimization of deformation energy and geometric accuracy in the incremental sheet forming process using response surface methodology. *The international journal of advanced manufacturing technology*, *79*(9), 2041–2055. https://doi.org/10.1007/s00170-015-6986-5

[15] Montgomery, D. C. (2017). *Design and analysis of experiments*. John Wiley & Sons, Incorporated. https://books.google.com/books?id=Py7bDgAAQBAJ

[16] Kalita, K., Ghadai, R. K., & Gao, X. Z. (2025). *Intelligent machining: Using computational intelligence to optimize manufacturing processes*. Apple Academic Press. https://books.google.com/books?id=ym2QEQAAQBAJ

[17] Shang, F., Chen, H., Wang, S., Zhao, J., Ma, Y., & Ba, Y. (2025). Machine learning-based process parameter optimisation and strip plate shape improvement in steel production. *Ironmaking & steelmaking*, *52*(8), 975–1010. https://doi.org/10.1177/03019233251359803

[18] Park, S. H., Yoon, J. W., Yang, D. Y., & Kim, Y. H. (1999). Optimum blank design in sheet metal forming by the deformation path iteration method. *International journal of mechanical sciences*, *41*(10), 1217–1232. https://doi.org/10.1016/S0020-7403(98)00084-8