**Journal of Engineering Management and Systems Engineering**
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# Geometrical Modeling of Extruder Screws Utilizing the Characteristic Product Features Method in CAD

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**Received:** 04-12-2024 **Revised:** 05-18-2024 **Accepted:** 05-25-2024

**Citation:** N. Vitkovic, M. Manic, S. Randjelovic, N. Korunovic, R. Turudija, A. Trajkovic, and J. Arandjelovic, "Geometrical modeling of extruder screws utilizing the characteristic product features method in CAD," *J. Eng. Manag. Syst. Eng.*, vol. 3, no. 2, pp. 93–99, 2024. https://doi.org/10.56578/jemse030204.



**Abstract:** Computer-Aided Design (CAD) is employed extensively to facilitate design processes through software tools, serving as an indispensable component in Reverse Engineering (RE) across various sectors. This study elucidates the integration of RE and CAD in constructing generic product models for the manufacturing industry, particularly through the enhancement of the Feature-Based Design (FBD) approach. The Characteristic Product Features (CPF) methodology, pivotal in this research, enhances FBD by enabling the creation of parametrically defined generic features. Such features encapsulate a range of parameters including geometrical dimensions, topological constraints, and requirements for material properties and functionality, all dictated by the parametric model established. The methodology affords mechanical engineers enhanced capabilities to devise specific or customized manufacturing processes, applicable in domains spanning CAD, Computer-Aided Manufacturing (CAM), and Computer-Aided Engineering (CAE). The practical application of CPF within CAD is exemplified through the development of a three-dimensional geometrical model of an extruder screw utilized in polymer extrusion, illustrating the potential for tailored process innovation in manufacturing.

**Keywords:** Computer-aided design (CAD); Reverse engineering (RE); Feature-based design (FBD); Characteristic product features (CPF); Parametric modeling

## 1 Introduction

The primary objective of CAD [1] is to optimize and streamline the workflow of designers, thereby enhancing productivity and elevating the quality of designs. Additionally, CAD facilitates improved communication through documentation and often contributes to establishing a comprehensive manufacturing design database. "Geometric modeling" revolutionized engineering practices, enabling the examination of construction sequences, behavior, strengths, weaknesses, and various characteristics of engineering models before their physical construction. Subsequently, the introduction of Feature-Based Modeling (FBM) equipped engineering designers with tools that facilitated the integration of design and manufacturing processes. This integration established a connection between CAD and CAM and automated procedures [1], increasing production efficiency and reducing capital costs. Feature definitions are numerous, but one more applicable to this scenario is: "Features encapsulate the engineering significance of portions of the geometry of a part or assembly, and, as such, are important in product design, product definition, and reasoning, for a variety of applications" [2]. Further exploration initiated a convergence between object-oriented design/models and features. Salomons suggests that 'features can be considered as design objects, part of a broader class inheriting traits from other classes.' Due to the nature of features, diverse information can coexist, altering their primary role based on different application contexts. Various types of features include functional features [3], assembly features [4], analysis features, tolerance features, technological features, geometrical features [5], material features, precision features, mating features, abstract features, and physical features [6]. Feature extraction refers to the process of identifying the features of any model, analyzing them, and accurately interpreting the model [7]. The contemporary use of features has evolved to integrate recent advancements. Features serve as control tools, leveraging dynamic engineering knowledge to assist engineers in design, reuse, and manufacturing. Their utilization spans various methods, consistently leading to the generation of engineering models. Literature broadly divides feature definitions into two main categories: design features and manufacturing features. Design features typically comprise geometric entities representing specific shapes, patterns, or embedded information, while manufacturing features are sections of a workpiece that are generable through metal removal or other processes. In essence, a feature constitutes a physical element of a part, making parts physical constituents of assemblies. Consequently, any attribute of a feature characterizes parts and their assemblies.

RE, as a complex technique, is often connected to reverse modeling, which presumes gathering information regarding an object's shape or geometry using scanning and model reconstruction in CAD software. Scanning involves utilizing a 3D scanning device to capture geometric data about the product, employing different scanning technologies—non-contact or contact scanning devices. This process generates a point cloud comprising numerous points from the product's surface or interior. Subsequently, this point cloud becomes instrumental in the remodeling process for the creation of a 3D geometrical model. Several methods, such as NURBS patches or SubD surfaces, are utilized for remodeling, primarily focusing on the resulting model surface's strict geometrical, mathematical, or numerical representation [8–14]. A novel approach to remodeling the surface of a product founded on CPF is presented in the study [15]. CPFs represent crucial geometrical or functional entities specific to particular parts, such as holes, crests, fillets, or rebars. These features are pivotal in defining the model's geometry from a more product-oriented perspective. Each designated product feature undergoes a geometric definition, resulting in the creation of an appropriate 3D model. Moreover, additional properties are integrated into the model description, encompassing functional attributes, manufacturing technology, or material specifications. This comprehensive feature definition comprises multiple descriptions, including geometric representation (point cloud, STL, IGS, STEP), material definition, and technological specifications. This approach significantly enhances 3D model creation, ensuring improved geometrical accuracy, topological correctness, and functional relevance. Part remodeling constitutes a fundamental stage within the RE process, creating a geometrically accurate and topologically correct 3D model [8–12]. Various procedures and methods are employed in this process, categorized based on the quantity and quality of the scanned data [9]. Remodeling can be executed using complete or insufficient data concerning part geometry, where deficiencies in data can arise from hardware (e.g., scanner) or software limitations (e.g., scanner software) [9, 10]. The precision of the model's geometry and topological correctness depends on specific requirements, potentially influencing the complexity of constructing a particular part's 3D model [13, 14].

Polymer extrusion is a commonly employed high-volume manufacturing technique that involves melting and continuously shaping a polymer material with the desired components. The process begins by feeding raw material into a hopper, usually in granulated form. From there, it moves through a feed throat onto a rotating screw powered by an electric motor. The screw's design varies depending on the material and the intended final product design [16]. As the screw turns, it pushes the plastic through a heated barrel. The screw's channel, or thread, gradually decreases in size along the barrel, compressing the plastic. Three or more independent Proportional Integral Derivative (PID) controllers control the barrel's temperature, creating zones with progressively increasing temperatures. The plastic melt temperature typically exceeds the set temperatures of these controllers. This excess heat results from a mix of compressive force and shear friction, known as shear heat. When the plastic reaches the end of the screw, it passes through a screen pack positioned by a breaker plate. This stage effectively filters out contaminants and removes the material's rotational memory. After filtration, the liquefied plastic is pushed through a die, shaping the final product according to the desired profile and form. Subsequently, the material produced through extrusion is pulled out and subjected to a cooling procedure tailored to the specific profile and shape of the extruded material [17–20].

This study introduces a novel approach to FBD by integrating different techniques for CAD and manufacturing technologies, together with CPF methodology, which refers to engineering feature-based methods for product redesign. By using this approach, the parametric model(s) of the specific product are developed. These model(s) incorporate different parameters for different features or the whole product. Forming the complete product definition as parametric enables the creation of different product models depending on the specific requirements (e.g., functional, material, geometrical). The construction of the extruder screw 3D parametric model is used as an example of methodology application and verification.

## 2 Methodology

The CPF methodology depicted in Figure 1 includes several sequential steps, commencing with importing a point cloud and culminating in the comprehensive definition and implementation of selected product features. Initially, the point cloud constitutes a collection of points obtained from the scanning process, wherein each point represents a minimal geometric description of the scanned product. Subsequently, in Process 2 (P2), each product feature of interest undergoes semantic description, creating a feature list represented through plain text or visual forms, such as sketches. The subsequent step, Process 3 (P3), provides a holistic definition of feature properties. This phase, fundamental within the methodology, encompasses various feature definitions, extending beyond the confines of those illustrated in Figure 1. These definitions span geometrical, mathematical, and functional attributes, among others. Importantly, this methodology remains open-ended, allowing further feature definitions or descriptions to be added.

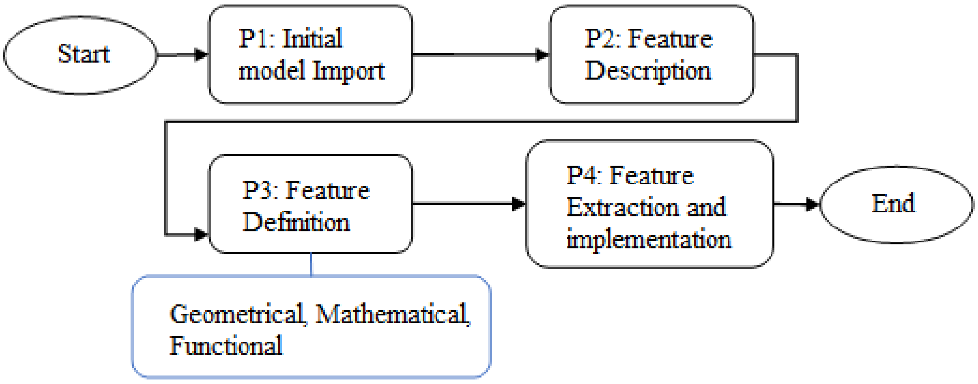


**Figure 1.** CPF basic schematic

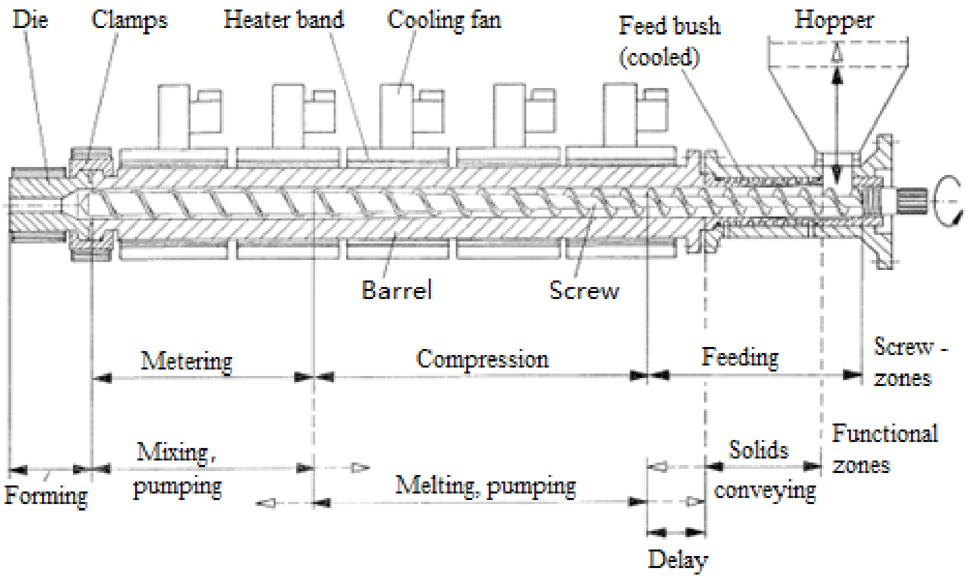


**Figure 2.** Polymer single screw extrusion and zones [14]

Defining the feature and associated points represents a crucial stride in the methodology typically executed during the point cloud analysis phase. However, this process is not restricted solely to that activity, as modifications to the product feature and its points are possible. These point clusters are outlined and exported into a distinct file alongside the point cloud file. Subsequently, these point clusters can undergo further processing in subsequent remodeling steps, such as mesh creation, shaping geometrical components like curves, and culminating in the development of 3D models (either surface or solid). Each sequential step generates outputs that contribute to the refined definition of product features. For instance, the mesh element can be exported into an STL file and combined with the product's point cloud file, generating a set of files for an individual feature—comprising a point cloud (.txt) and mesh file (.stl). The assembly of all product Features of Interest (FoI) may entail numerous files for each component. These individual files can be utilized separately or combined to form the entire product, serving as a part model if required. Crucially, an essential capability of a product feature lies in the parametrization of its point set. The stated parameterization enables the creation of a parametric point cloud model for a distinct feature, adaptable to various parameters—expanding beyond geometrical aspects to encompass functional, technological, and other relevant attributes [15]. To conclude, the CPF methodology enables the creation of geometrically defined FoI with additional data stored in different files that reflect stated requirements, like functional, material, and technological. The following activity in methodology is to define FoI as CAD features and to incorporate them in FBD. This is possible because FoI are geometrical entities defined in CAD software, and as such, they can be defined as one type of feature. To integrate them and enable FBD, it is crucial to properly define initial geometrical areas, or FoI, on the

CAD model. The first step is to define a specific CAD model as a set of FoIs and enable further parameterization. The FoI can be defined by considering the shape and topology of the specific model, and their number can vary from one to the required number (defined by model complexity and requirements). To demonstrate the application of the methodology, an extruder screw is selected as an example that combines different requirements and properties. The extruder screw is the most crucial component in polymer extrusion, and it enables the flow of plastic from the material source (hoper) to the die. To define extruder screw parametric models, it is essential to describe the process and define the main characteristics of the process itself and the screw. Polymer Extrusion (Figure 2) is a commonly used high-volume manufacturing technique involving the melting and continuous shaping of a polymer material infused with specific additives. The process begins by introducing the raw polymer material in granular form into a hopper, which then gravity-feeds it through a feed throat onto a rotating screw driven by an electric motor. The screw's design is tailored to the material and the intended product design. As the screw turns, it propels the plastic through a heated barrel. The channel or thread of the screw gradually decreases along the barrel, compacting the plastic as it progresses. The barrel is divided into sections heated by three or more independent PID controllers. These controllers create zones with increasing temperatures along the barrel. Typically, the plastic's temperature exceeds the set temperature of the controllers due to additional heat generated from the combined effects of compressive force and shear friction (shear heat).

As the plastic melt reaches the screw's end, it undergoes thorough mixing and passes through a screen pack supported by a breaker plate. This screen pack filters out contaminants and erases any rotational memory from the materials. Subsequently, the filtered melt is forced through a die, shaping the final product according to the desired profile and form. Once extruded from the die, the material—known as extrudate—is drawn and cooled. The cooling process employed is chosen based on the extrudate's profile and shape. Screws in extrusion typically encompass three distinct zones [17, 20]:

-Feed Zone: This initial zone, also known as the solids conveying zone, is responsible for introducing resin into the extruder. Here, the channel depth remains constant throughout this section. Zone length is up to 50% of the screw length.

-Melting Zone: Often termed the transition or compression zone, this segment primarily facilitates the polymer's melting. As the material progresses through this zone, the channel depth gradually diminishes. Zone length up to 30% of the screw length.

-Metering Zone: This area, known as the melt conveying zone, is where the last remnants of particles are melted, leading to a consistent temperature and composition. Similar to the feed zone, the channel depth remains consistent within this zone. Zone length is up to 20% of the screw length.

The zones are transferred to the 3D model by selecting surfaces in the adequate screw area, and they are presented in Figure 2. The zones are defined as surfaces on the screw, composed of NURBS patches created over the set of points, which are the basis geometrical elements for CPFs.

The length of the screw is often measured in relation to its diameter, referred to as the L:D ratio. Common L:D ratios range around 25:1, although some machines utilize ratios of up to 32:1 for enhanced mixing and higher output at the same screw diameter. Each zone incorporates thermocouples or RTDs in the barrel wall to control temperature. This "temperature profile" significantly influences the quality and characteristics of the final extrudate. The screw, essentially a conveyor, operates by turning while resisting backward movement out of the barrel, facilitated by a bearing. The material needs to soften to pass through the die, a transformation achieved through heat. While some preheating of the feed occurs (usually for drying purposes), the bulk of the heat is generated internally due to friction against the barrel walls and screw surfaces. Exceptions exist, such as certain twin screws, smaller machines, high-temperature resins, and PE coatings, where barrel heat plays a crucial role. The screw operates on a three-zone principle: the feed zone, compression zone, and metering (pumping) zone. Each serves specific functions in material processing, ensuring proper melting, mixing, and consistency. Factors like channel depths, screw length, flight pitch, hollow screws, and materials used for construction all play pivotal roles in the efficiency and effectiveness of the extrusion process. These considerations directly impact heat generation, mixing, conveying capabilities, and the overall quality of the final extruded product. The length-to-diameter ratio (L:D) serves as a critical metric for screw dimensions. For example, 24:1 is the standard ratio, while 20:1 is considered short due to its impact on melting time and temperature. More extended screws aid in melting but require higher temperatures, leading to a trend favoring larger screws over extended lengths. Flight pitch, typically maintaining a square angle, corresponds to a helix angle of 17.6° if "unwrapped." Flight thickness affects heat development and material conveyance per turn—thicker flights result in more heat area but less conveyance, while thinner ones lead to less pumping but more mixing. Screw variations include hollow designs that allow passage for substances like water, oil, or air, impacting mixing and preventing tip degradation. Varying the radius of channel corners influences channel volume and material stagnation. Screw materials predominantly involve machinable steel with hardened flight surfaces, achieved through methods like welded caps or nitriding. Chrome plating is standard and claims to reduce frictional heat and minimize degradation. Specialized metals cater to abrasive or corrosive feeds, ensuring durability and efficiency [17–20].

## 3 The Formation of the Parametric Models as Object-Oriented Features

The initial parametric models of the defined object are developed based on the screw geometry, defined zones, and process requirements. The parametric models are formed using Unified Modeling Language (UML) [21] notation and class definition. The UML approach to parametric modeling is used because it can define (to model) different use cases and system responses to them. It also enables a universal approach to software development because the UML diagrams can be transformed into different programming languages, i.e., they are not related to strictly one programming language. The properties of the parametric models are defined separately for the geometry, zones, and process requirements. In Figure 3, the parametric models defined as UML objects are presented. The first model, or geometry model, is defined by using the following parameters: screw profile, screw dimensions, and an array of additional properties set as objects - addObjects. The last property enables adding additional geometrical parameters as objects to the defined geometrical model. The possibility of using these kinds of models is diverse. Each of the defined parameters in the geometrical model is defined as a separate object, which can reflect its complexity. For example, the screw dimensions parameter is an array of dimensions defined for the screw, like screw length and screw diameters (Figure 4). These parameters are also set in the form of a CSV table to be easily imported into CAD, which is standard procedure for setting parameters of the CAD model through Excel or CSV format. The screw 3D model presented in Figure 5, can be geometrically altered by using CSV structure (Table 1).

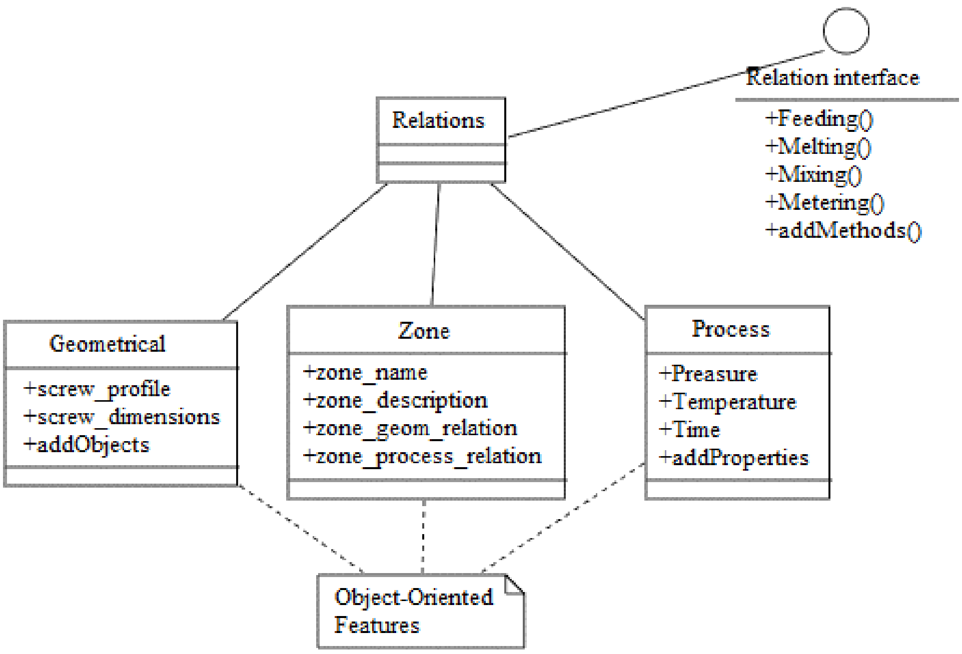


**Figure 3.** The parametric models defined as object-oriented features

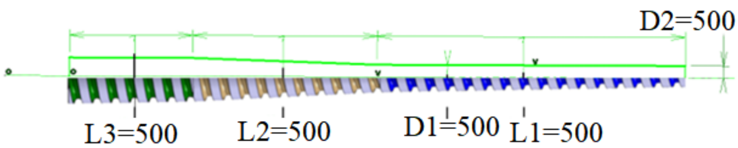


**Figure 4.** The screw basic geometrical parameters


**Figure 5.** Extrusion zones presented on screw 3D model by using CPFs definitions

**Table 1.** Key parameters of our model

| L | L1 (% of L) | L2 (% of L) | L3 (% of L) | D1 (mm) | D2 (mm) |
|---|---|---|---|---|---|
| 500 | 50 | 30 | 20 | 50 | 60 |
| 600 | 40 | 30 | 30 | 60 | 70 |

The second model, or zone model, is defined as a descriptive model related to geometrical and process models in the sense that defined zones are related to the defined geometrical parameters. Of course, the descriptive model enables the additional process definition in the sense that zones can vary from three to five, and geometrical parameters reflect that. The screw zone model is defined as an object with attributes defined as zone name (String), zone description (String), zone geometrical relation (array of related geometrical parameters), and zone process relation (array of related process parameters).

The third model is a process model, which contains an array of process parameters, and it is a dynamical model, which means that additional parameters can be added. Initially, the pressure(s), temperature(s), material properties, and timings are added as starting parameters, but the possibility of model extension is unlimited. This model also contains the addObjects parameter, which enables the user to add additional parameters that can influence the process.

The relation model enables mathematical and functional relations between the created individuals' models. Users can add relations between models' parameters. The relations are added as class methods, with functions as part of the method definition. The relation model interface can also be added as an entity that enables strict method implementation in connected classes. If the interface is implemented in the relation model object, the interface methods must be used. Therefore, it will enforce the integration of different model properties and their relation. In the initial development, this model only has the methods to set the zones and geometrical models by imposing the length parameters and zone descriptions, as presented in Figure 4.

These parametric models are defined as object-oriented features with parametric properties. Related software objects must be developed and correlated with the adequate CAD/CAM application to implement these new features. In this case, this is done by using the parametric properties of the CATIA V5 part modeler and MS Excel as a CSV creator tool. The parameters and their relations are described using a VBA script for CATIA software, but any other software solution (programming language or framework) can also be implemented.

To conclude, the initial parametric model's definition includes three different and related models, geometry, zones, and process, defined as generic features. They are connected by parameter relations, and the relation model is defined through the interface and objects that implement it. To apply generic features, it is essential to define process parameters and basic screw geometry. For example, in Figure 4, the geometrical model of the screw can be geometrically altered by using one row of the geometrical model CSV table defined like [L, L1, L2, L3, D1, D2] = [500, 50, 30, 20, 50, 60], which will produce a screw with a length of 500 mm, L1 = 250 mm, L2 = 150 mm, L3 = 100 mm; and D1 = 50 mm, D2 = 60 mm. The relation model will be used to connect L1, L2, and L3 to the screw zone model. Similarly, the process model can be used to define material and other process parameters and relate them to the other models if needed.

## 4 Conclusions

In this paper, the new Object-Oriented Features model is presented and demonstrated for the extruder screw definition. It extends FBD by introducing parameterization of different processes and model parameters. The relation model is introduced as the connection model, which contains different methods related to different processes conducted in different technological processes. Three parametric models are developed (geometry, zones, and processes) and connected, to enable the formation of object-oriented features that can be implemented in CAD/CAM. Therefore, applying the developed feature system to create and control different manufacturing technologies is possible. The future work implies an extension of the parametric model to include additional parameters and to conduct additional testing and validation of the proposed Object-Oriented Features model.


## Funding

This work has been supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Grant No.: 451-03-47/2023-01/200109).


## Data Availability

Not applicable.

## Conflicts of Interest

The authors declare no conflict of interest.

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