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3D Model Reconstruction from Vector Perpendicular Projections

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3D MODEL RECONSTRUCTION FROM VECTOR PERPENDICULAR PROJECTIONS

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Abstract

This scientific monograph deals with the issue of 3D model reconstruction of a rotation part from its orthogonal projections recorded on a digitalized drawing in vector format and with computer-aided automation of the process. The topic is a partial task of the domain focused on generating the 3D part model or product from a technical drawing.

The introduction comments on the analysis of the current state of information in the field. The rules of projecting the parts in a technical drawing are described as well as the related terminology and methods in computer graphics, mathematics and geometry. The computer-aided ways of modeling solids are analyzed. The introductory part is complemented by an overview of existing solutions by other authors and by the possibilities of my own method development.

The monograph core is focused on the proposal of proceedings and algorithms for transformation process automation of 2D vector record comprising orthogonal projections representing the rotation part on a 3D model. The pilot implementations of algorithms and their verification by testing on the selected sample of geometric shapes are added.

Key words

technical drawing, orthogonal projection, Monge projection, 3D model, rotation solid, 3D reconstruction, CSG representation, vector figure, DXF

LIST OF ABBREVIATIONS

3D	Three-dimensional
2D	Two-dimensional
B-Rep	Boundary Representation
CAD	Computer Aided Drawing
CAM	Computer Aided Manufacturing
CNC	Computer Numerical Control
CSG	Constructive Solid Geometry
DXF	Drawing Exchange Format
IGES	Initial Graphics Exchange Specification
ISO	International Organization for Standardization
OOP	Object Oriented Programming
PLM	Product Lifecycle Management
PN	Company Standards
STEP	Standard for the Exchange of Product model data
STN	Slovak Technical Standard

INTRODUCTION

The process of part drawing is described in detail in related sources and standards. The technical drawing of a part is drawn by a constructor or generated by current CAD/CAM systems which can model the part as a 3D solid and prepare its drawing via known methods. Applying the methods and rules recommended, the result is legible and clearly comprehensible. It is obvious for someone who explains the technical documentation submitted. If the part drawing is described by a computer program, we will face a problem. For CAD system the projections drawn are only a group of lines drawn by a constructor though by the tools of CAD system given.

There are many technical drawings which were drawn long ago in paper or digital vector form. There is an effort to make these documents available to modern CAD/CAM systems and automate the whole process of 3D model design, however, these systems work only with 3D models. The reason why we deal with old drawings is that construction does not include only new parts design, but fitting, modifying and improving existing parts as well. The issue is not new, but it is topical, which is demonstrated by a number of papers focused on similar targets as this scientific monograph.

The concept of digital production assumes the application of digital technologies in the full life cycle of a product. Digital production is the key requirement for integrating the control system of product life management and production devices on the level of CNC systems. In digital production, the technical drawing is replaced by a product (part) model. The product model is represented by a data structure which comprises relevant information on generating the control program of its production. Regarding its significance, it becomes the integrating part of the digital production [65].

Due to the variety of parts shapes, the amount of standards for technical drawings and their continuous updates, and various inaccuracies on real technical drawings, etc., the whole process of transformation is quite complex, therefore it is necessary to divide the problem into self-contained parts and investigate them individually.

At present, we can face four main forms of archiving and exchange of parts documentation, they are: paper, raster, vector drawings and 3D model.

Because new parts development is mainly based on modifying, fitting and improving existing parts, there is an effort to make the older documentation available to modern CAD/CAM systems which work with 3D models and are able to generate the control program for machining CNC machines. Storing, simplification of production information and particularly the utilization improvement of such documentation which grows from left to right are the other reasons (Fig. 1). If we want to convert either one form to another in this direction, we face a lot of complex steps, especially further from the raster format [17]. The processing from right to left, from 3D model to paper drawing is commonly used by all modern CAD/CAM systems. The procedures are generally known and, compared with the opposite, also quite simple.

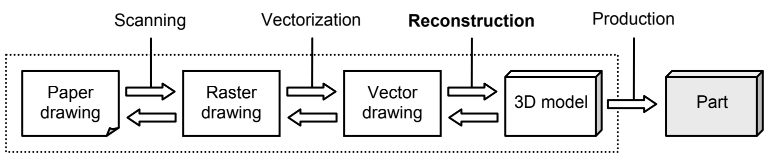


Fig. 1 *Forms of parts archiving*

The scientific world tries intensively to make the whole process automated. This monograph is aimed at contributing to the research in the field, particularly in the field of 3D model reconstruction from vector drawing.

Regarding the current state of analysis in the field (Chapter 1.3) the wide spectrum of parts type was reduced to rotation parts which were investigated only a little so far.

This scientific monograph is focused on the solution to the primary aim:

To propose the algorithm for generating rotation part 3D model from vector record of projections with maximum degree of single steps automation, while the resulting solid will be described by CSG representation. The aim can be divided into partial objectives:

- Definition of input limit criteria for technical drawing contents and shape of part construction elements.
- Proposal of algorithms for automation of rotation part 3D model reconstruction from vector record.
- Proposal of software structure regarding the possibilities of its application in various CAD/CAM systems.
- Implementation of the algorithms proposed and verification of their functionality.

1. OVERVIEW OF CURRENT STATE IN THE FIELD

1.1 Displaying parts in technical drawing

Technical drawing of a part as one of the technical documentation forms has to meet various requirements and rules for correct legibility, understandability and definiteness of information. The requirements are published in generally binding regulations and standards with different levels of validity on international, national and regional levels (e.g. ISO, STN, PN).

Technical drawing as a carrier of a technical idea is a communication means for individual components of technical and economic activities [68]. It comprises data of geometric shape and part dimensions, then information on material, surface finish, allowed deviations, etc. Then it has to meet formal requirements such as dimension, framing, scale, used types and thickness of lines, size of letters and other necessary data. All these regulations and recommendations can be found in related standards [55], [56] and publications dealing with technical drawings [12], [22], [38], [45], [68].

1.1.1 Selected elements and drawings properties

Technical drawings comprise many various text data and geometric shapes. For 3D model generation, however, only some of them are needed. The following part describes only those elements which are important for further digital processing of a vector drawing [15].

1.1.1.1 Scale of projection

Scale is the ratio of the element length depicted in the drawing to the length of the same element of a real object. The real size with the gauge ratio 1:1, gauge of magnification X:1 and scale of diminution 1:X are differed. From the point of processing, the gauge is the coefficient by which all length dimensions are multiplied.

According to recommendation of STN ISO 5455 Standard – *Technical Drawings. Scales.* We can use more kinds of scales, but it is necessary that the basic views are drawn in the same scale, then we can count on this by projection data analysis.

1.1.1.2 Lines

Lines are the basic building element of a technical drawing. ISO 128 Standard – *Technical drawings. General rules of display.* – and in its other parts, general rules for display and lines design for all kinds of documentation are defined. In the Standard, the lines are defined as geometric objects including elements and line segments. The ways of line connection and intersection are prescribed, in the point of longer segment of both lines. Suggestions for thin, thick and very thick lines are standardized; the recommended ratio is 1:2:4.

Regarding the complexity of the technical drawing, only selected kinds of lines and related drawing elements will be processed. Table 1 shows the numeric indications, titles and display of lines as well as the field of their use as defined by the Standard.

SELECTED KINDS OF LINES ON TECHNICAL DRAWINGS

Table 1

Line		Use of line
No.	Description and display	
01.1	Continuous thin line	Imaginary lines, auxiliary and dimension lines, reference lines, outlines of inclined projections, short axes, line of thread bottom depth, boundary of details, indication of repeating elements, projecting beams.
01.2	Continuous thick line	Visible outlines and edges, line of thread backs, boundary of thread length.
02.1	Dashed thin line	Hidden edges and outlines.
04.1	Long-dash dot thin line	Axes, lines for symmetry indication, spaced line of toothing, spaced line of holes.

1.1.1.3 Projections

In technical drawings, 3D solids are displayed onto 2D surfaces – planes. The method enabling 3D to 2D transformation is called projection. These projections provide full and clear images of exact shapes and dimensions of the products.

According to [22], [68] and other sources, for technical documentation design, the method of perpendicular projection is used for several planes of projection. Methods of axonometric display – technical (rectangular) isometry, technical (rectangular) dimetry and ortho-angular dimetry (cabinet axonometry) are used as complementary methods.

Orthogonal projection onto several planes of projections

As mentioned before, rectangular projection is the most widespread way of displaying parts in the drawing. We distinguish two basic methods of orthogonal projection, which differ on the mutual position of the observer, the part being displayed and the plane of projection.

To avoid confusion, the method depicted in the drawing will have a relevant indication in the title block or close to it.

Method of projection in quadrant 1 (E method)

This method, called E method (European), is defined [68] as orthogonal projection on mutually perpendicular planes of projection, by which the solid displayed is situated between the observer and related planes of projection.

From the point of the observer, the projection of what the observer sees is placed on the plane of projection behind the solid. To figure out better how the images of individual projection originate, it is possible to place the solid inside a cube with all walls as plane of projection (Fig. 2). The placement of views is binding, so that the one who describes the drawing documentation cannot be wrong. If for any reason it is not possible to keep the projections' placement stated, the projection given, as well as its direction, shall be indicated by an arrow and capital letter [22]. Then we will consider only standard projection placement.

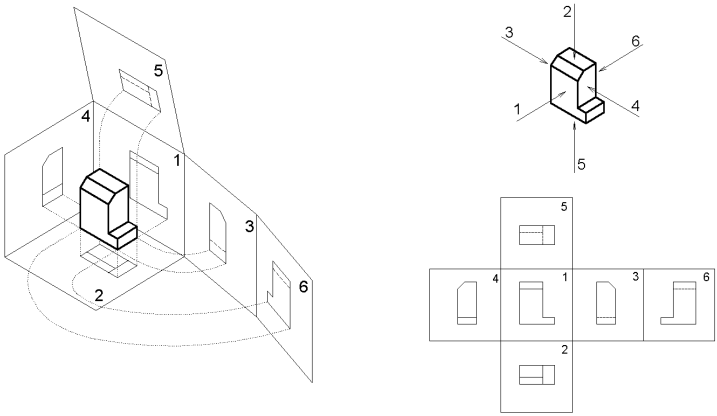


***Fig. 2** Principle of projection method in quadrant 1 and mutual position of projections [68]*

Auxiliary and partial views

Auxiliary projections are used when, by projecting into some of the main planes of projection, a misrepresented image inappropriate for providing dimensions origins. The auxiliary (oblique) view is placed in the direction of projection onto the plane of projection parallel with the part being projected. Mostly, it is combined with a partial view, when not the whole projection but only its part is displayed.

Sections and cross-sections

Display in sections and cross-sections is used especially by hollow solids, by which it is necessary to display the internal outline of hollows which as hidden (illustrated by a dashed line) appear as insufficiently distinct and the image of the solid is not comprehensible enough or not suitable for providing dimensions.

1.1.1.4 Other elements

A common technical drawing obviously comprises many other elements, such as dimensions, dimension lines, hatching, various marks, etc. These data are filtered out and used for specifying and complementing the information obtained from the projections in further processing according to needs. It is related to the input criteria for the decrease of complexity and demand in the processing of drawing data which are stated in the following chapters of the monograph. To filter out unwanted data or selection of only relevant data, we can use a tool which is at the disposal of all modern CAD systems, i.e. work in levels or layers.

1.1.1.5 Levels - layers

A system of preparing a drawing in different levels eases the work and makes it more transparent. Individual levels provide the separation of elements with the same or similar properties, such as contours, invisible edges, dimensions, sections. Each of the levels can have the common parameters of type, thickness and color of lines set. Suitable classification of drawing elements into relevant levels can significantly simplify the processing of drawn views. This is also one of the input criteria.

Color differentiation of various drawing elements can be used as an alternative or complement to the use of levels.

1.1.2 Projecting

Projecting is a special projection of the space onto the plane selected – plane of projection, which assigns each of the points of the space (pattern) by one projection in the plane of projection (image). In computer graphics, projecting is the transformation via which we can transfer 3D coordinates of each of the object points into 2D coordinates. In practice, two types of projections are used, parallel and central projections [41], [66], [69].

1.1.2.1 Central projecting

By this projecting, all projecting straight lines go through one point located in a specific distance behind the plane of projection. The distance of the projection centre influences the rate of misrepresentation of projected images to original patterns. The rate of misrepresentation is called a perspective and figures situated farther from the observer are projected as smaller ones. The method of central projection is utilized mainly where we want to display 3D objects or the whole scene in the plane more realistically. Paper drawings of buildings are typical examples. In computer graphics, it is used in virtual reality, most dynamically in games.

1.1.2.2 Parallel projecting

Parallel projecting is a special type of central projection, where the centre of projection is placed into infinity. The projecting straight lines are parallel and cross the plane of projection under the same angle. If the straight line rake angle determining the projection direction to the projection plane equals 90°, it is rectangular parallel projecting, in other cases it is ortho-angular parallel projecting.

Rectangular projecting

Rectangular projecting is such a parallel projecting by which all the projecting straight lines are perpendicular to the plane of projection. Perpendicular projecting into three planes of projection π, ν, μ (plan view, front view, sideview) can be expressed analytically by the following matrices:

$$\mathbf{P}_{\pi} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \begin{matrix} x' = x \\ y' = y \\ z' = 0 \\ h' = 1 \end{matrix} \qquad \mathbf{P}_{\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \begin{matrix} x' = x \\ y' = 0 \\ z' = z \\ h' = 1 \end{matrix}$$

$$\mathbf{P}_{\mu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \begin{matrix} x' = 0 \\ y' = y \\ z' = z \\ h' = 1 \end{matrix} \tag{1.1}$$

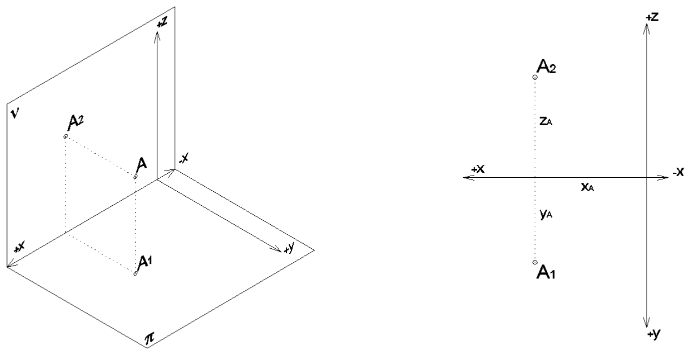
The properties of rectangular parallel projecting can be summarized into the following:

- Point is projected as a point and is located on the intersection of the plane of projection and projecting straight line going through the point.
- Point projection located on the line segment is on the projection of this line segment.
- Line segment perpendicular to the plane of projection is projected as a point.
- Line segment parallel to the plane of projection is projected as a line segment of the same length.
- Line segment inclined to the plane of projection is projected as its cosinus component.
- Parallel line segments which are not rectangular to the plane of projection are projected as parallel.
- Right angle is projected as right if at least one arm is parallel to the plane of projection and none is perpendicular to it.

- Plane perpendicular to the plane of projection is projected as a line segment of the same size.
- Plane parallel to the plane of projection is projected as a plane.
- U-figure projection located in the plane parallel to the plane of projection is the figure identical with U-figure.
- Line segment's division ratio is preserved.

Monge projection

Rectangular projection on two mutually perpendicular planes of projection – horizontal plane of projection $\pi = xy$ and frontal plane of projection $\nu = xz$, is called Monge projection [60], [67]. Each point A is assigned a couple of associated projections (A_1, A_2), where A_1 is the plan view of A point – the perpendicular projection into π horizontal plane of projection and A_2 is the front view of A point – the perpendicular projection into ν frontal plane of projection (Fig. 3a). In Monge projection, we associate two planes of projection by turning one of them into the other (horizontal to frontal plane of projection) around the common straight line – x-axis. The projection of coordinate x-axis is called associating x_{12} axis. For the couple of associated projections (A_1, A_2) of A point stands $A_1A_2 \perp x_{12}$. A_1 plan view is determined by coordinates x_A and y_A of A point and A_2 front view is determined by coordinates x_A and z_A of A point (Fig. 3b).



a) b)

Fig. 3 *Monge projection [60]*

Feedback process can be applied to Monge projection. If we consider the couple of points A_1, A_2 situated in ν plane of projection on the perpendicular to the associating x_{12} axis, then by spatial turning of the bottom half to the perpendicular to ν frontal plane of projection π horizontal plane of projection origins. By activating the projecting straight lines perpendicular to the planes of projection and going through points A_1, A_2, point A origins in their intersection.

For more complex parts, the projection into two planes of projection is not sufficient. Then we add other planes of projection as shown in Fig. 2 and Fig. 4. For each couple of mutual perpendicular planes of projection the same rules of Monge projection are in force as for frontal and horizontal planes of projection aforementioned.

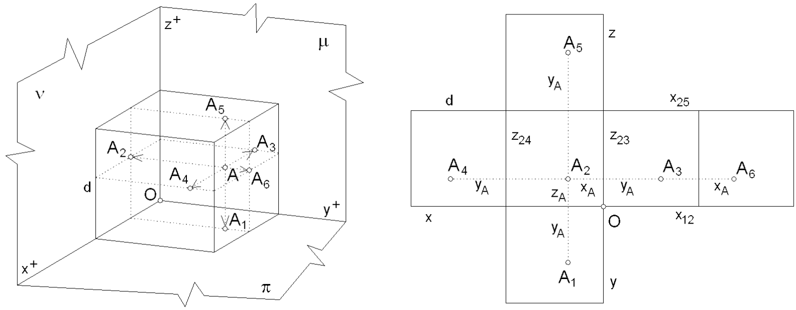


Fig. 4 *Projections in Monge projection [68]*

For analytical processing, Monge projection is represented by the following matrices of projection. If we state the distance of planes of projection $d \neq 0$, then:

$$\mathbf{P}_1 = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \mathbf{P}_2 = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \mathbf{P}_3 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{P}_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -d & 0 & 0 & 1 \end{bmatrix} \quad \mathbf{P}_5 = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & d & 0 & 1 \end{bmatrix} \quad \mathbf{P}_6 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ d & 0 & 0 & 1 \end{bmatrix} \qquad (1.2)$$

Individual projections of A point $A = [x_A, y_A, z_A, 1]$ expressed in homogeneous coordinates are shown in the following table:

CARTESIAN COORDINATES OF A POINT PROJECTIONS
IN ASSOCIATED PLANE OF PROJECTION Table 2

Plan view	$A_1 = [-x_A, -y_A]$	Left side view	$A_4 = [-y_A - d, z_A]$
Front view	$A_2 = [-x_A, z_A]$	Bottom view	$A_5 = [-x_A, y_A + d]$
Side view	$A_3 = [y_A, z_A]$	Back view	$A_6 = [x_A + d, z_A]$

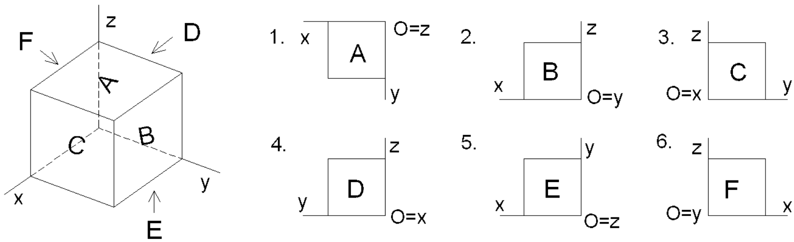


Fig. 5 *Views representation in Monge projection [69]*

1.1.3 Geometric transformations

Geometric transformations are the mostly used operations in computer graphics and many authors deal with the issue [24], [30], [36], [50], [52], [53], [67], [75], [77], therefore it is researched and described a lot. Transformation or display assigns to any individual point of one set exactly one point from the other set. If it is vice-versa in force as well, it is called unambiguous projection. If the straight line is projected as a straight line and the plane as a plane, it is linear projection.

By analytical processing the geometric linear transformations are expressed in the form of square regular matrix **T**, called transformation matrix of n+1 order (where *n* is the dimension of space). Figure U’ is obtained by the transformation matrix application to all points of U object, from which it consists of - $U' = U \cdot \mathbf{T}$. Transformation matrices were already mentioned in Chapter 1.1.2.2.

The record of linear transformations via matrix is possible due to the implementation of homogenous coordinates, which to inhomogeneous Cartesian coordinates add a complementary dimension $w \neq 0$, so called homogenizing factor or point weight which is mostly equal 1. Such an expression allows us to compose transformations as multiplication of matrices and inverse transformation is done by an inverse matrix.

for 2D $$\left[\frac{x}{w}, \frac{y}{w}\right] \equiv [x, y, w]$$

for 3D $$\left[\frac{x}{w}, \frac{y}{w}, \frac{z}{w}\right] \equiv [x, y, z, w] \tag{1.3}$$

If we consider $w = 1$, then the record of the point in homogeneous coordinates $[x, y, z, 1]$ is equivalent to the record in Cartesian coordinates $[x, y, z]$.

1.1.3.1 3D linear transformations

In Monge projection, 3D linear transformations are used, since they preserve metric, i.e. there is no change of shape or size. Such transformations are also called identical representations.

3D linear transformation of point $P = [x, y, z, 1]$ to point $P' = [x', y', z', 1]$ can be expressed by transformation equations or transformation matrix.

$$x' = a_{11}x + a_{21}y + a_{31}z + a_{41}$$
$$y' = a_{12}x + a_{22}y + a_{32}z + a_{42} \qquad \mathbf{T} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 \\ a_{21} & a_{22} & a_{23} & 0 \\ a_{31} & a_{32} & a_{33} & 0 \\ a_{41} & a_{42} & a_{43} & 1 \end{bmatrix} \qquad (1.4)$$
$$z' = a_{13}x + a_{23}y + a_{33}z + a_{43}$$

Monge projection utilizes mainly translation and rotation. In building individual projections, these transformations are composed into one transformation matrix, as shown in (1.2).

Composition of transformations

By gradual execution of individual transformations we come to their composition. The resulting transformation matrix is given by the product of matrices, i.e. by partial transformations, in progress from left to right. The composition of transformations is not commutative, i.e. the order of the multiplication of matrices is important [66], [75].

As it will be mentioned later, it will be not necessary to carry out individual transformations in the work with projections, it will be possible to build on the data form Table 2. These values are the result of the composition of more transformations coordinates of the point projection onto the projection cube, its development into a plane and transfer into Cartesian coordinate system.

1.1.4 Basic geometric elements of technical drawing

Straight lines (line segments) and curves (circle, arc, technical curves, etc.) are the basic elements of a technical drawing. For automated processing of vector drawings it is necessary to know their computer expression and the way of their mutual position determination [4], [6], [13], [44], [50], [69], [75], [77].

1.1.5 Areas and their expression for computer graphics

Part projections in the technical drawing are composed of lines (line segments, curves) which build closed areas. These areas are the projections of individual solid surfaces into a related plane of projection. According to the definition, the plane area is represented by a bounded, closed and continuous, not empty, set of points in a plane. The aforementioned properties are valid if:

- the whole set can be placed into a circle (bounded),
- the boundary is the part of the set of points and divides it from other parts of the plane (closed),
- each two points can be connected by a line situated within this set (continuous).

The area is simply continuous if its boundary is made by a closed line. If *k* of closed lines is the boundary, we cal the area *k-th* continuous. The area in which it is possible to connect two random points by a line segment lying within this area, it is convex. In case there are two such points which cannot be connected by a segment line within the area, we speak about an inconvex area.

By investigating the areas we pass along their boundaries. If the area is to the right from the motion direction on the boundary, we indicate it as negatively oriented, if it is on the left, it is positively oriented.

In case of processing the solid projections consisting only of plane surfaces, the individual projections will comprise only polygons.

1.2 Computer representation of solids

The set of information of an object which can describe it sufficiently as well as define its geometric properties such as shape, dimensions, orientation and mutual position of elements is the geometric model of the real object. A unified method to describe the solid is not stated, since it is not possible. Models have to meet very different and sometimes even antagonistic requirements. They should be simple, easy to build and modify. However, programs require a lot of information for calculations of static and dynamic object properties, i.e. extensive geometric information required by projecting algorithms. On the other hand, data structure should be economical so that it is possible to process in reasonable time. Many authors deal with the issue of data structure for representation [24], [43], [57], [63], [64], [75], [76], [77].

1.2.1 Boundary representation

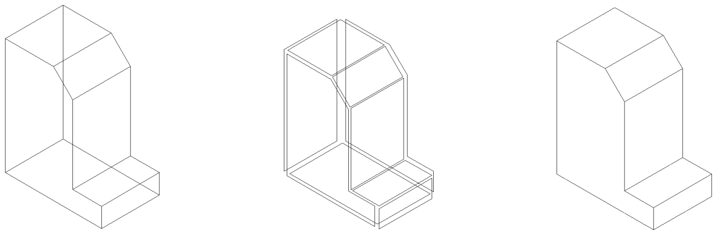
This way of solids representation is based on the description of the solid surface as its most important part, as it builds the boundary between the solid mass and surrounding space. It is indicated by abbreviation B-Rep (Boundary Representation). Boundary representation comprises geometric and topological information that can provide as exact solid description as possible.

1.2.1.1 Edge representation

The simplest and information-poorest solid representation is based on the description of edges, contours and peaks of a real object. It builds a so-called wire-frame which cannot be unambiguously described.

1.2.1.2 *Simple surface representation*

Via enhancing the wire-frame by surfaces a surface model origins which builds a shell copying only the surfaces of the object. Each surface is built only of the list of final edges points. The object drawed is unambiguously possible to describe, but it has little topological information for further processing.



a) b) c)

Fig. 6 *Boundary representation*
a) wire-frame, b) surface model, c) B-Rep

1.2.1.3 *Structured boundary representation*

Complete data structure describing B-Rep model has enough information for description and manipulation, as well with such a defined object. It's built from three lists:

- list of peaks and their coordinates,
- list of edges with edge peaks given,
- list of surfaces with given edges building the edge of the surface.

Boundary representation designed by Baumgart is the most used data structure, and it is known as widged-edge. The solid is described by three cyclic lists of surfaces, edges and peaks. Each edge has the most important topological information, i.e. with what surfaces it neighbors and which four edges are connected to its final points. The perfection of data in B-rep is possible to verify by Euler´s or Euler-Poincaré´s relations.

On the widged-edge structure we can notice the typical feature of data structures used in 3D graphics. Geometric information builds approximately 25%, the remaining three quarters provide the topology description and as fast processing of geometric information as possible.

1.2.2 Constructive solid geometry

This method of solids representation describes complex solids via combination of other simpler solids by means of set operations. It is indicated as CSG representation (Constructive Solid Geometry) and its data structure is built by a binary tree. Individual nodes represent the operations of 3D transformations (rotation, translation) or Boolean set operations (addition, subtraction and intersection). The basic objects or transformation parameters are the leaves of the tree. The basic solids are the following geometric objects: prism, cylinder, cone, sphere, toroid, half-space, etc. The description of solids is very economical, but it comprises almost no information on its surface. Therefore it is frequently combined with B-Rep data structure.

a) b)

***Fig.** 7 Constructive solid geometry:*
a) basic objects b) result model

1.2.3 Patterns

In using patterns, the solid is described by the profile and trajectory on which the profile is moving. Such a solid is indicated as 2.5D. According to the trajectory we can divide the patterning as follows:

- translation pattern (extrusion) – trajectory – line segment
- rotation pattern (revolution) – trajectory – circle or its part,
- general pattern – trajectory – random curve.

Objects built by pattern are mostly used as construction elements in CSG representation or are transformed to B-Rep model.

a) b)

Fig. 8 *Patterns: a) pattern with trajectory b) result model*

1.3 Current approaches to analysis of 3D model reconstruction from technical drawing

Reconstruction methods developed by many researchers can be classified according to representation of the result solid into two main branches:

- Boundary representation of solids (Boundary representation - B-Rep),
- Constructive Solid Geometry (CSG).

Older approaches are based on boundary representation of 3D solids (B-Rep). 2D point and lines of perpendicular projections are transformed to 3D points and lines. The lines have to be verified and classified according to various criteria so that the duplicity and errors are eliminated. A wire-frame is built which is subsequently processed. The surfaces are built of line segments and then the volume 3D model in b-Rep is built.

Newer approaches are based on addition and material take off, therefore they are close to various technological procedures of part production. To construct a 3D volume model they use CSG representation. The binary tree is built in which the nodes represent Boolean operations (addition, subtraction and intersection) and leaves represent primitive objects. Some methods begin with a boundary prism and gradually take off redundant material. More sophisticated methods search for partial projections of primitive elements and the target 3D solid is built by adding and subtracting basic or complex volume elements.

Most of the methods described come out of three perpendicular projections. They process only geometric and topological information closely related to individual basic views and other data of the drawing are ignored.

This chapter provides a look back to the history where I briefly describe and analyze how some of the authors dealt with the issue. I used only information from sources that were available to me. A detail overview with some additional sources and some missing can be found in [8], [18] and [25].

1.3.1 Foreign research

1.3.1.1 Boundary representation of solids (B-Rep)

Idesawa and his paper [27] from 1973 is considered to be a pioneer in automated reconstruction of 3D objects form 2D perpendicular projections. His method is based on the boundary representation and on the bottom-up approach:

- generating 3D peaks and edges,
- constructing of wire-frame,
- removing invalid edges,
- generating surfaces,
- removing invalid surfaces,
- building 3D volume solid via B-Rep.

This first solution was limited only to reconstruction of angular solids with perpendicular surfaces. In the course of years, other authors improved his method and enhanced the set of 3D objects which could be reconstructed via boundary representation. Oblique surfaces, curvatures, cylindrical and conical surfaces were added.

Sakurai and Gossard in paper [46] dealt for the first time with the possibility of generating curved surfaces built by circle arches. They note that the tangents of edges located on the transit between curved and straight areas should be implemented, since they are not displayed in perpendicular projections. The peaks, as well as edges, were classified, for example, as standard, tangential, silhouette. This classification in the process of pre-processing of views has significantly simplified subsequent operations.

Dutta and Srivinas [14] developed the method for curved solids reconstruction by using only two polygonal perpendicular projections. First they generated all possible third views corresponding with two views given. Subsequently, these new views were analyzed and there were line segments distinguished which could be replaced by a circle arch. Finally, all curved solids corresponding to the couple of input projections were generated.

In paper [28], by authors Itoh and Suzuki, the method to eliminate pathological peaks, edges and surfaces originating in building the surface model was described. It works on the principle of Boolean evaluation of limit criteria.

You and Yang developed the method for B-Rep model reconstruction comprising plane as well as curved surfaces [74]. Similar to others using boundary representation, it came out of wire-frame and had to solve the elimination of pathological edges and surfaces. It did not generate all possible combinations of lines and surfaces, but only those reasonable for building a manifold.

Masuda and Numao introduced an efficient method based on cell principle [37]. From projections only one wire-frame of non-manifold was made which was the basis for looking for various candidates for result volume model. In this wire-frame, the cells bounded by various combinations of surfaces were distinguished and it was tested if after their removal the resulting solid projections corresponded to the input projections. It also dealt with man-made errors in the process of drawing the projections. Their method could correct and complement the missing projections of edges as well as the misused line type (continuous instead of dashed line).

Shin and Shin in their contribution [49] developed Sakurai´s method and introduced 3D volume solid reconstruction by using geometric properties and topology of geometric primitives.

Watanabe in paper [71] introduced the method working on B-Rep principle via which he could process inconsistent data as well. It distinguished redundant line segments, unsuitable line type (visible/hidden) and missing line segments. This method is usable in the processing of drawings contained by the vectorization of scanned paper model.

Liu et al. developed the method [34] for solids reconstruction comprising surfaces built by conic sections whose axes can be oblique regarding the axes of coordinate system and therefore they projected as deformed.

1.3.1.2 Constructive solid geometry (CSG)

Constructive solid geometry was first used ten years after Idesawa in a paper translated by Aldefeld [1]. His method allowed using only basic volume primitives as construction elements. Axes of cylindrical surfaces had to be parallel to some of the axes of coordinate system – this was practically the basic criterion of all further methods.

Since then CSG representation was preferred by more researchers, especially for its speed and simplicity with which it was possible to describe 3D volume model. New methods originated, they are also known as top-down methods.

CSG method used by You and Yang in [73] had the boundary prism as the basic solid. Individual construction elements are distinguished one by one, reconstructed by using the profile drawing and subsequently taken off until final 3D volume solid was not achieved. First there was the possibility to process auxiliary and partial views also. They also dealt with the extraction of dimensions and tolerances.

Geng et al. introduced the method [21] which tried to involve the approach of man to the description of technical drawings. He used three projections and built a 3D prism divided into volume cells. 3D object decomposed into 3D cells groups, where each of the cells was generated by using auxiliary algorithms for wire-frames. The reconstruction process began at the bottom and went on layer by layer up to the peak of the cell prism. In each layer of cells the most suitable operation was used as well as the direction for the reconstruction of given element/elements within. The result volume solid was then constructed only by merging of objects built in individual layers.

An interesting method was brought by Cicek and Gulesin in paper [7]. First they reconstructed construction elements by using drawing operations or profile rotation which were in three perpendicular views recognized as internal entities. Then, from external profiles of projections, three basic volume solids were drawn. All internal construction elements were then subtracted. Final volume model was constructed via intersection of all these three solids.

Lee and Han dealt with reconstruction of rotation solids in [31]. They proposed a method by which they could build even the most complex rotation parts such as shafts with many take offs. They used the efficiency of CSG solid representation.

Liu and Ye in their paper [33] presented the method based on semantic analysis and comprehension of technical drawings. Graphical information was extracted from projections, then the semantic methods were used to recognize the primitives and components and their relations. Each component was reconstructed individually by using the most suitable algorithm. Finally, all primitive objects and components were set into a larger volume solid by using Boolean operations and CSG representation. Each new type of a reconstructed component was stored as a sample for improving the efficiency of further tasks processing. In another paper [32] Liu et al. enhanced their method and developed the module for processing technical drawings in AutoCAD.

Another method coming out from restricting prism was developed by Cayiroglu et al. in paper [5]. This method began with a prism which was big enough so that all the result solid could be in. In processing they proceeded layer by layer from top to bottom and redundant volume was taken off. In each layer horizontal empty surface regions were recognized as well as related free volume below them. The bottom boundary was built by surfaces divided into horizontal, oblique and curved. Subtracted volume was reconstructed between these top and bottom surfaces. The resulting 3D solid was constructed only by gradual take off of partial volumes.

Wang and Latif elaborated a method [70] which utilized fuzzy logic to recognize construction elements as well as the choice how to proceed in their reconstruction. The basic principle was to decide whether to use the operation of profile drawing or its rotation. 3D volume model was then constructed by Boolean volume operations.

The latest contribution to the field was the method introduced by Xie et al. in paper [72]. Like many other authors, he used CSG representation of solids and focused on recognition of hatched sections and on intersections of cylindrical hollow solids.

1.3.1.3 Other methods and analysis

The utilization of graphs was elaborated in detail by Flasinski in his contribution [19]. He described and analyzed the application possibilities of graphics grammar for recording all solid properties defined by B-Rep or CSG method.

Dori and Tombre in their paper [10] analyzed if we were already able to automate the whole process of 3D solid reconstruction from paper drawing to 3D digital model. They analyzed known approaches from scanning and cleaning the raster drawing, through vectorization and text and lines recognition, semantic analysis to pre-processing of vector format and generating 3D solid.

In another contribution [11], Dori and Weiss investigated the possibility of processing real drawings which could comprise incorrect lines with dimensions. They elaborated a graph of limiting criteria considering recognized dimensions for each of the views. They prepared a network, recording all geometric, structure and topological relations of individual entities. They reconstructed 3D object on the basis of these graphs. It is practically the only method considering the dimensions of processed projections as well.

Golovin and Veselov [23] pointed out that almost all methods developed so far were only in their theoretical and testing phases. They implemented the applications processing input projections and constructing 3D model, however, they frequently missed connection with real CAD/CAM system. The authors therefore implemented several modules which besides 3D model reconstruction could process DXF files and export the result model into the file format of engineering standards such as IGES and STEP.

Suh and McCasland created a program for teaching correct description of perpendicular projections thus supporting 3D imagination of students [54]. In isometric view, students construct 3D solid interactively via boundary representation elements.

Bhushan and Gurumoorthy introduced the method based on volume representation of solids for the reconstruction of more 3D solids from a technical drawing set [3].

Similar issue was dealt by Tanaka et al. [58], they introduced the method for converting 2D drawing set into 3D models of construction parts. They used B-Rep approach.

Besides reconstructing the models of parts, there is also an effort to reconstruct 3D models of buildings from architectonic drawings [35].

1.3.1.4 Patents

Besides articles published in various journals or conference proceedings, there are several patents related to the topic.

Fujita registered the patent [20] for conversion of 2D CAD drawings into 3D CAD drawings. It is the method utilizing CSG approach for constructing the solid from volume elements made by drawing the profile.

In their patent [29] Kondo et al. utilized B-Rep for volume solid description. Projections were transformed to 3D and investigated the section planes where it came to the change of profile. Regarding this information they calculated the position of edges and surfaces to construct 3D model.

Numao et al. in patent [40] came out of three main perpendicular projections to construct a wire-frame of a non-manifold. The model was further processed, from various combinations of internal surfaces volume cells were built. By material take off form these cells a target solid was attempted. The patent is based on the method published in [37].

1.3.2 Domestic research

Several students with the Departments of Applied Informatics and Automation, STU MTF UIAM in Trnava shared by their Master theses in the research of the topic as well. I can mention the most interesting ones.

Chovan [26] dealt with generating 3D wire-frame of an angular part. He developed functions for pre-processing input data such as alignment and elimination of incorrect lines. He had to investigate also the issue of pathological edges mentioned by authors utilizing boundary representation of 3D solids. His solution was implemented in language C++ and represented the module into AutoCAD using ObjectARX program interface application.

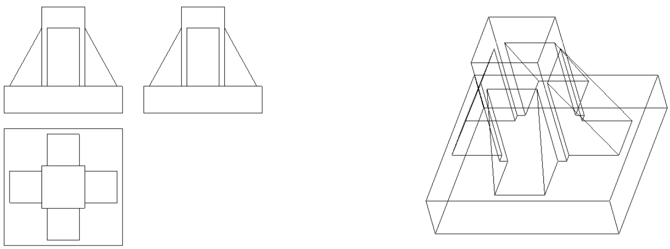


Fig. 9 *Three projections and result wire-frame*

Pavelek elaborated an individual application in v C++ processing DXF files and reconstructed the solid surface model. In his Master thesis [42] he precisely analyzed the rules of perpendicular projections origin and proposed and implemented a reverse approach. It could process also unambiguous and unclear inputs. For visualization via Open GL he implemented a simple triangular algorithm.

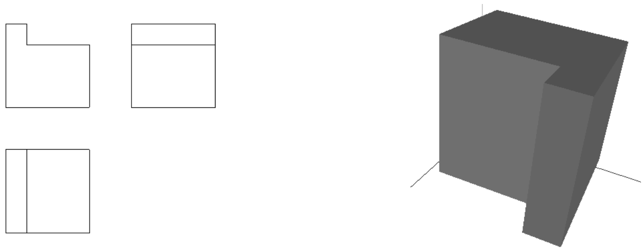


Fig. 10 *Three projections and result surface model*

Benkovský dealt with the reconstruction of simple rotation parts from one projection [2]. He used 3D Studio MAX and its script language as the testing and development environment. To read the input data, he utilized DXF file.

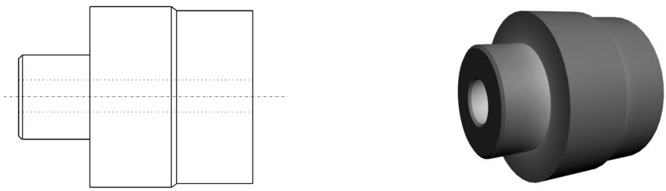


Fig. 11 *One projection and result volume model*

Besides generating 3D models from projections also complementary fields related to reading and visualization of DXF data files and data structures for solids representations were investigated [51], [59].

1.3.3 Summary

Regarding the aforementioned overview of 3D solid reconstruction methods from its perpendicular projections, I put together criteria for comparison of their main properties. In criteria selection I considered the overviews already mentioned in [8], [18], [25] and complemented them by some other ones which were missing.

List of investigated criteria and their possible values:

- type of surface: plane, cylindrical;
- rotation solids: yes, no;
- interaction with user: yes, no;
- representation of solid: B-Rep, CSG;
- correction of input projection errors: yes, no;
- processing of dimensions: yes, no;
- number of views: 1, 2, 3, more;
- processing of sections: yes, no;
- processing of partial views: yes, no;
- more than one solution: yes, no.

Data summarized in Table 3 show that transformation process is generally well managed. Nevertheless, there are still some elements which are not taken into consideration and which should be included in the future. They are sections and cross-sections, partial and auxiliary views, or even more than three basic views. It will be necessary to process dimensions and correct the projection lines dimensions according to them. To be able to process vectorized drawings and not only original vector drawings, the corrections of input projections lines should be improved.

OVERVIEW OF 3D SOLIDS RECONSTRUCTION METHODS

Table 3

Year	Authors	Reference	Surfaces		Rotation solids	Interaction	Representation		Errors correction	Dimensions	No. of views	Sections	Partial views	More than 1 solution
			Plane	Cylindrical			B-Rep	CSG						
1973	Idesawa	[27]	x				x				3			
1983	Aldefeld	[1]	x	x				x			3			
	Sakurai	[46]	x	x		x	x				3			x
1992	Dutta	[14]	x	x			x				2			x
	Kondo	[29]	x				x				3			
1994	Numao	[40]	x	x			x				3			
1996	Dori	[11]	x	x			x	x		x	3			
	Itoh	[28]	x	x			x				3			
	You	[74]	x	x			x	x		x	3			
1997	Masuda	[37]	x	x			x		x		3			x
1998	Shin	[49]	x	x			x				3			
	Watanabe	[71]	x	x			x		x		3			
	You	[73]	x	x				x		x	2+		x	
2001	Fujita	[20]	x	x				x			3			
	Liu	[34]	x	x			x				3			
2002	Geng	[21]	x	x		x		x			3			
2004	Cicek	[7]	x	x				x			3			
	Chovan	[26]	x				x		x		3			
	Tanaka	[58]	x	x			x				3			
2005	Lee	[31]	x	x	x			x			2-3			
	Liu	[33]	x	x	x			x			3	x	x	
2006	Benkovský	[2]	x		x			x	x		1			
	Bhushan	[3]	x	x	x			x			3			
	Pavelek	[42]	x				x		x		3			
2007	Cayiroglu	[5]	x	x				x			3			
	Golovin	[23]	x	x			x	x			3			
	Wang	[70]	x	x	x			x			2-3	x		
2009	Suh	[54]	x			x	x				3			
	Xie	[72]	x	x				x			3	x		

2. SELECTED METHODS AND OWN SOLUTION PROCEDURE

The procedure of 3D model of rotation part reconstruction from 2D vector record can be divided into the following steps:

- Stating input conditions and limit criteria.
- Selection of algorithm implementation for verification of proposed solution.
- Reading input data from vector technical drawing of a part.
- Processing of individual projections.
- Construction of 3D part model.
- Visualization of reconstructed 3D part model.

The processing of vector data is preceded by stating input conditions and limiting criteria which have to be considered in algorithm development and which have to be met by the drawing given. In the beginning phase, these limits allow concentrating on typical features of rotation parts. In following phases of the project, other construction elements are added, thus enhancing the processing by categories of more complex parts.

2.1 Selection of input and output format and way of implementation

In selection of input and output vector format record, the following possibilities were considered:

- publicly available standard formats (DXF, STEP, IGES),
- proprietary formats of selected CAD/CAM systems (mostly unknown and protected by patents),
- utilization of API host CAD/CAM system.

Since 3D part model is reconstructed to be processed further in some of CAD/CAM systems, it is more suitable to utilize its application programming interface [61]. This approach allows using services of a related system, either by reading input vector data or by constructing a 3D solid. Another advantage – we can work with its native file format or with some standard format for technical documentation exchange and do not have to deal with the implementation of file inputs and outputs. By suitable application proposal, we can this way build input-output modules into some CAD/CAM systems (points 1 and 6) and execute the whole process of vector data processing unto 3D model reconstruction in one common module (points 2 to 5). Or we can complement this module later by our own input-output interface for reading and recording of standard formats.

Selecting from more CAD and complex CAD/CAM systems, we chose the simpler of them, i.e. AutoCAD by AutoDesk Company which was and still is the most used CAD system for building standard drawing documentation of parts. There are many original vector drawings made in some of the older versions of AutoCAD. My experience in modules programming via various API of the system was another reason. In this monograph ObjectARX interface and Visual C++ development environment are used. Specific way of proposed solution implementation is documented in Chapter 3.

2.2 Definition of input limit criteria

Algorithm presented here can process technical drawings meeting the following limits related to drawing elements, used lines and geometric elements, scale of projection as well as to number and kinds of views [62].

2.2.1 Elements of technical drawing

Technical drawing of a part can comprise three basic views – plan, front and side views. All views have to be placed on one level in which no other drawing elements, such as dimensions, individual sections and cross-section, hatching, text information, etc., are located. Supported line types are shown in the following table.

SUPPORTED TYPES OF LINE Table 4

Line	Type	Display
visible edges	thick continuous	————————
hidden edges	thin dashed interrupted	– – – – – – – – – –
axes	thin dash-dot interrupted	—·—·—·—·—

All these elements have to be placed on the first level of the drawing. There is the future possibility of allowing the user to set their own level for each of the line types given.

2.2.2 Geometric elements

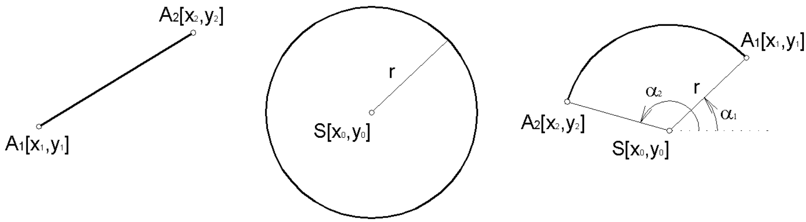
Edges and axes displayed in perpendicular projections can comprise only the following element types: line segments, circles, circle arcs.

Only intersections of line segment with another line segment, circle or circle arc are looked for. Other conic sections and technical curves were eliminated to simplify the algorithm design.

Geometric shapes which can be decomposed into the elements aforementioned are after reading of vector data from the drawing automatically replaced. This relates especially to rectangles and lines given as polyline.

Geometric elements are represented by their vector shape describing their basic geometric properties.

- **Line segment** is defined by coordinates of start and end points (Fig. 12a).
- **Circle** is defined by coordinates of centre and radius (Fig. 12b). In processing, it is automatically replaced by circle arc with start angle 0 and end angle 2π.
- **Circle arc** is defined by coordinates of centre, radius and start and end angles (Fig. 12c). Angles have to be defined in the positive anticlockwise orientation. To simplify the processing, the end points coordinates are automatically calculated as well.



a) b) c)

Fig. 12 *Properties of geometric elements*

2.2.3 Dimensions and projecting scale

Dimensions are eliminated from the processing; they will be included later on, since without their data it is not possible to transform some of the drawings to 3D automatically. Therefore, they should be considered in further phases of the investigation.

Projecting scale of part projections display in the drawing is closely related to dimensions. All dimensions are processed in the same way as they have been drawn in the drawing, i.e. in scale 1:1. This makes it possible to solve by setting up the scale by the user or after dimensions reading and processing.

2.2.4 Projections

As mentioned before, three basic projections are recognized automatically – front, side and plan views. If the drawing comprises only a front view, the rotation part is made by the operation of profile rotation around the main rotation axis. Without processing at least one other projection, it is not possible to reconstruct properly other than symmetric rotation part. Only by including the other projection is it possible to properly recognize asymmetric elements of the rotation part. We can consider this by automatic recognition of solid types. If the drawing comprises more than one view, there is high probability that the rotation part is not reconstruct-able only by profile rotation as it comprises either elements arranged symmetrically (e.g. holes), or elements of asymmetry (cut-offs, slots).

If there is only a front view and the spaced circle within, they are elements symmetrically arranged along the part circumference (e.g. flange with holes for screws). Processing of such a drawing requires the recognition of dimensions or interaction with the user.

Projections should not be connected by any line or axis. Their connection would prevent automatic recognition of projection based on the position of line groups.

2.3 Proposal of automation algorithm of 3D model design

Proposed algorithm for generating 3D module by reconstruction from 2D vector record can be divided into following basic steps:

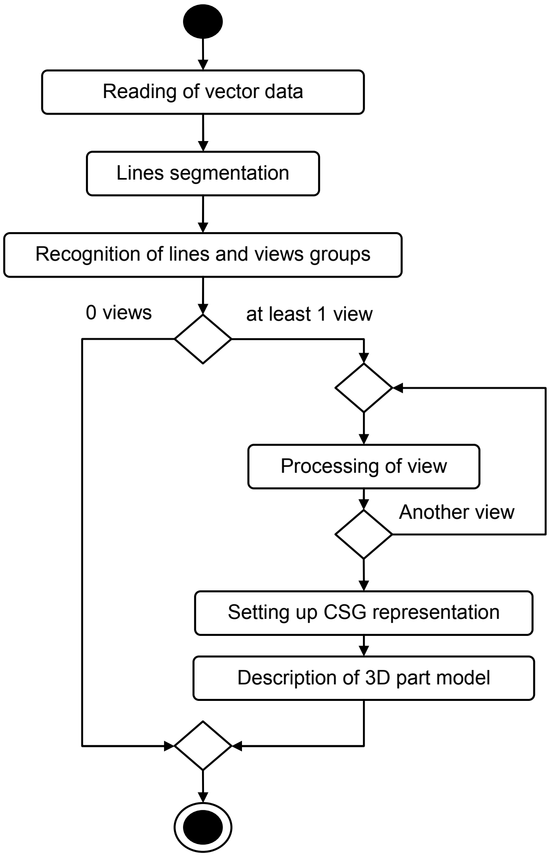


Fig. 13 *Basic algorithm of 3D model reconstruction*

2.3.1 Reading of vector data

Vector drawing read in CAD system is searched by the module communicating via API of the graphic system given. Supported geometric elements are looked for (line segment, circle and circle arc). Circle is replaced by circle arc with start angle 0 and end angle 2π (Fig. 14). Rectangles and other line sequences (polyline) given only by a polyline are decomposed into individual line segments (Fig. 15).

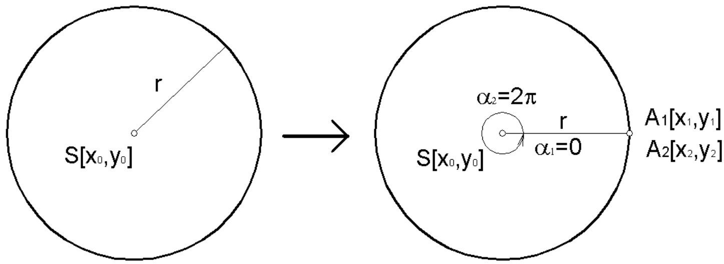


Fig. 14 *Circle replaced by circle arc*

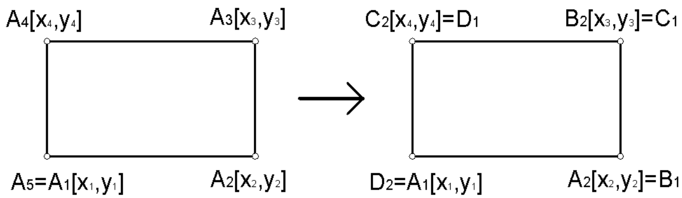


Fig. 15 *Polyline replaced by individual lines*

Geometric information on each element as well as complementary information on type, thickness and colour of the line and related level in which it is located are preserved. All these data are stored into related data structure representing the entry of module processing.

2.3.2 Segmentation of lines

All read lines are subject to segmentation to areas among the points of intersection. The relations and rules mentioned in the beginning of the monograph can be used. In the course of segmentation, the long lines are replaced by their segments which occur among points of intersection and other lines. By segmentation, first, the position of all existing points of intersection is recorded to the records of intersecting lines. Subsequently, all lines are searched and regarding these intersections the segments are distributed.

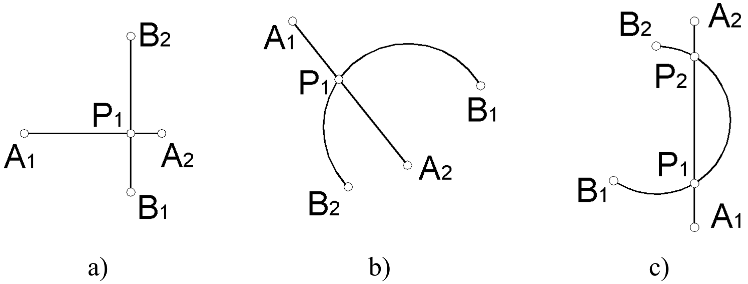


Fig. 16 *Segmentation of lines:*
a) two line segments, b) c) line segment and arc

Circle arcs are moreover segmented in places where they intersect the axes of the main coordinate system of the drawing (Fig. 17), as it is necessary to verify if the point from one projection corresponds with the peak of the given arc in the other projection.

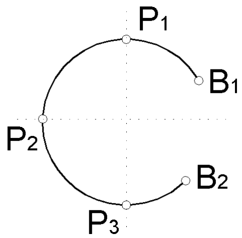


Fig. 17 *Segmentation of arcs in points of intersection with axes*

2.3.3 Recognition of line groups and projections

This process serves for recognition of line groups building individual projections. To process the list of line groups, the method called preorder for searching the tree nodes is utilized [9], [16], [39], [47], [48].

Searching is carried out recursively. It begins with a random line and the following line connected to the first one by some point is looked for (Fig. 18b). Then, another subsequent line is searched until their end is found. By return, further possible connections of lines on the related level as well as other branches are tested. Each of graph lines found is indicated by a serial number (number of line group) as well as by a serial number of branch level. If after surveying all connected lines there are any lines left without tree indication, there is another tree, i.e. another lines group (Fig. 18a) to be surveyed similarly.

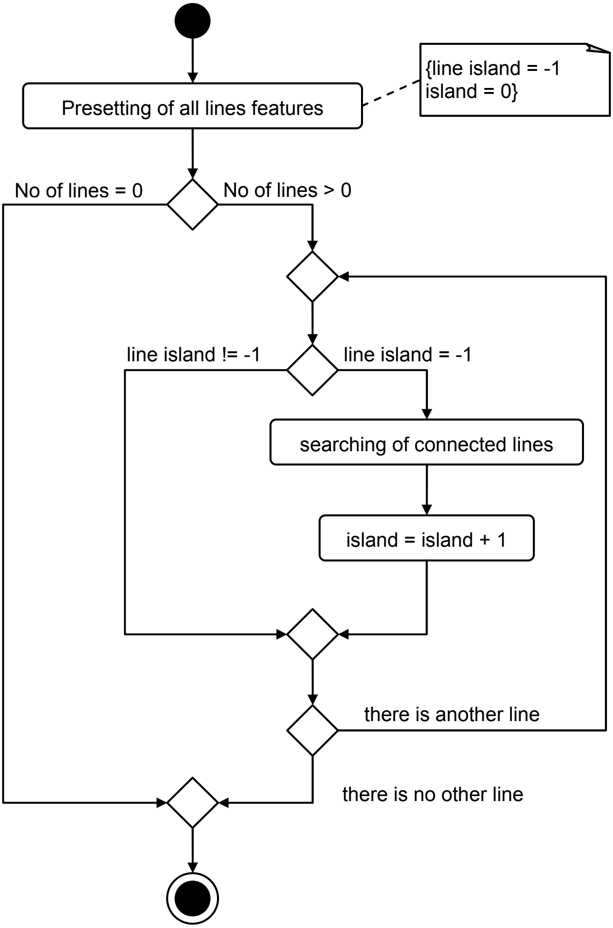


Fig. 18a *Algorithm of searching groups of lines*

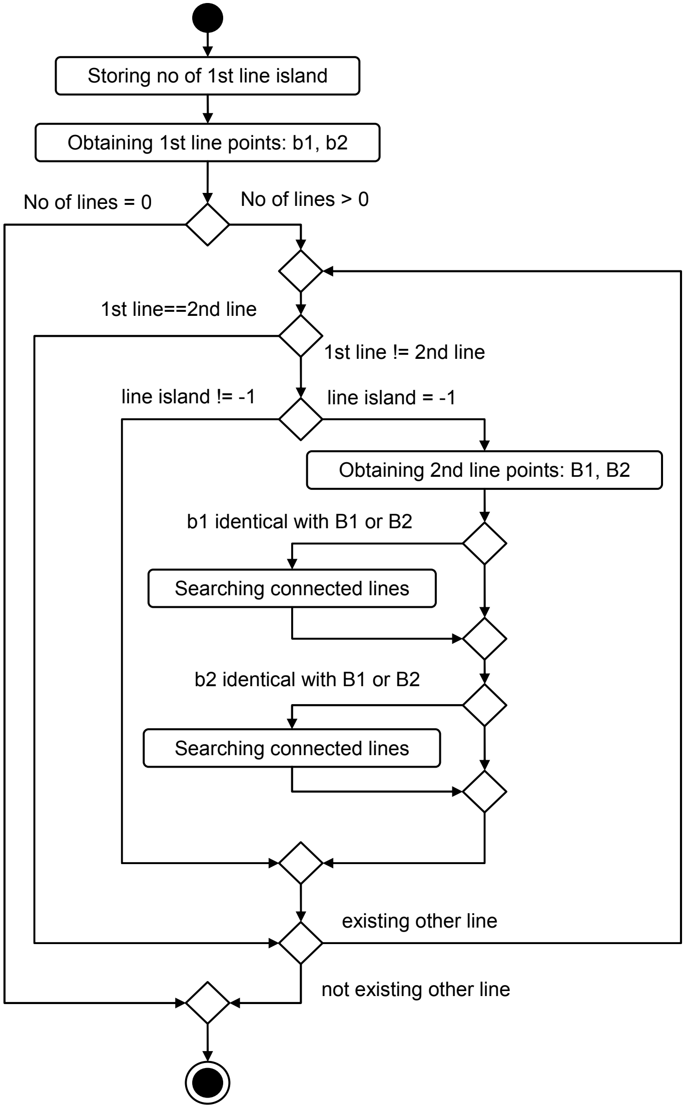


Fig. 18b *Algorithm of searching groups of lines*

After recognition of all groups of lines, these groups are investigated for mutual positions and size. This way the lines of front view – left up, of side view – right up and plan view – left bottom are recognized. Obviously such a simple classification would not be successful in the case of more views (Fig. 19).

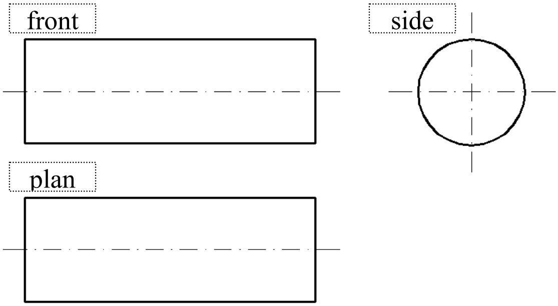


Fig. 19 *Positions of recognized projections*

If there is a group of lines whose restricting rectangle passes in one of the projections, then it is included with the projection. Such a group of lines is a construction element which in given view represents the projection of edges of volume added or taken off regarding the projection of the closest bigger outline (Fig. 20).

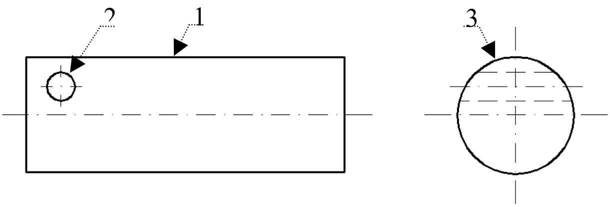


Fig. 20 *Islands of line segments*

2.3.4 Front view processing

For processing of the rotation part front view, it is important to recognize properly the main axis of rotation and to find the external outline. Next, the axis-symmetrical and axis-asymmetrical internal construction elements are processed.

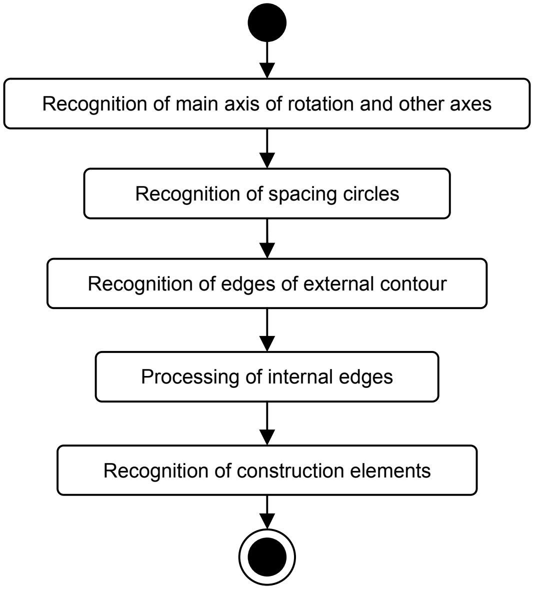


Fig. 21 *Processing of individual views*

2.3.4.1 Recognition of main axis of rotation and other axes

According to rules of technical drawings, each symmetry axis shall protrude over the edges of the related symmetric part. Since all lines including axes are segmented, in looking for axes we process all segments not connected by two points to another segment. This first segment shall be oriented from the first point to the other point, where the former has the smallest coordinates x and y. If it is not true, the points are changed. Further segments of axes are searched as tangents to the current segment while they have to be connected to its second point by its first point. If the line segment is a tangent but connects with its second point, its points exchange. It proceeds like this until there exists a following segment.

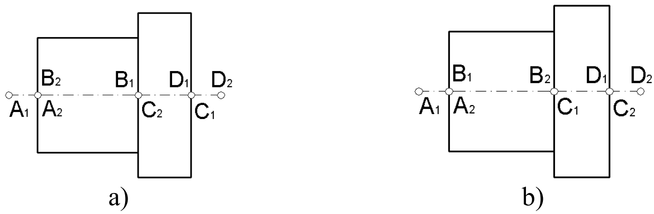


Fig. 22 *Segments of axes:*
a) before arrangement b) after arrangement

Each axis is built by the aforementioned way and stored as an independent list of oriented segments. The list of axes is then searched and the longest axis, which is considered to be the main rotation axis, is looked for. The axis selection is confirmed by its symmetrical placement in the centre of the projection. For the purposes of simplified further processing, a copy in the form of a long line with one segment is made.

By this way, the main axis of rotation is recognized in any incline, particularly as horizontal or vertical axes. In case of horizontal orientation of the main axis in the front view, the circle segments of edges should be placed in the side view. In case of vertical orientation of the main axis, the circle segments should be placed in the plan view.

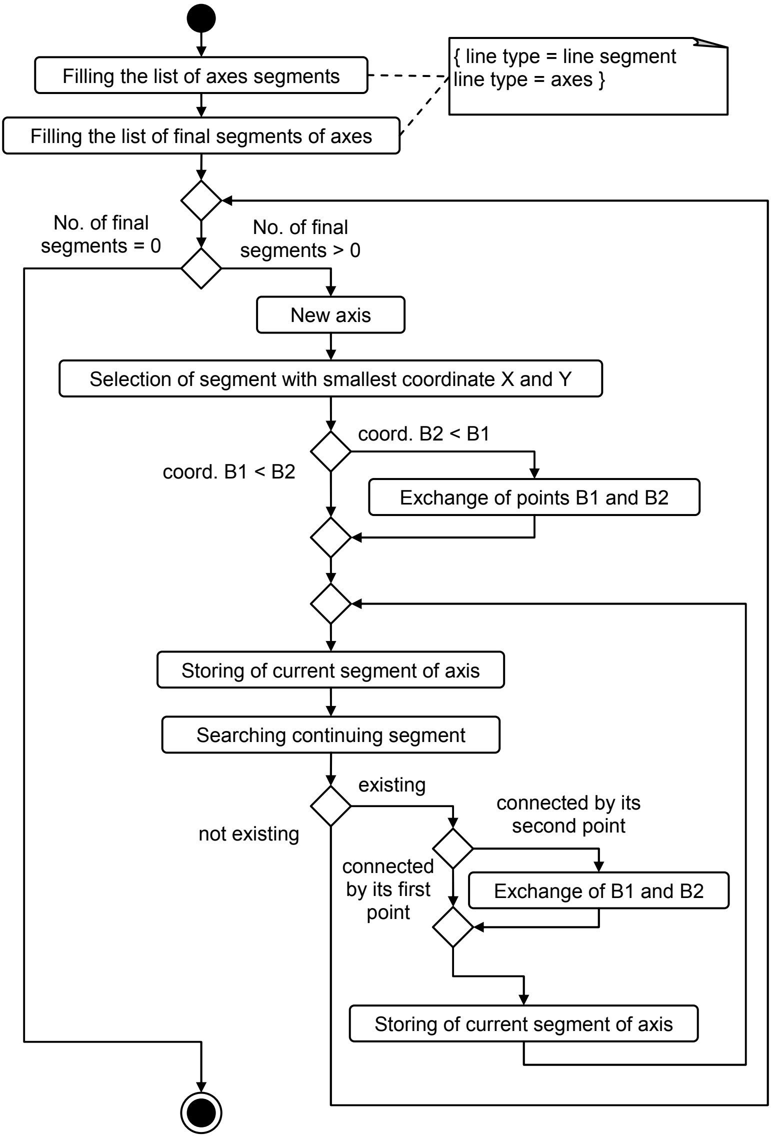
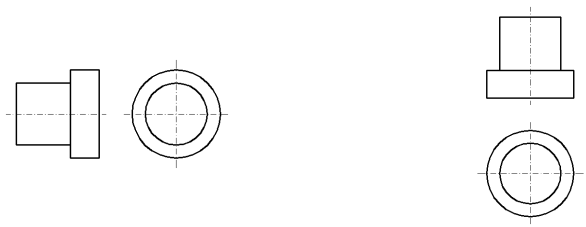


Fig. 23 *Algorithm of searching axes*



a) b)

Fig. 24 *Main axis of rotation: a) horizontal b) vertical*

2.3.4.2 Recognition of spaced circles

Besides axes composed of line segments, in the drawing there can be spaced circles or their parts, i.e. in our case dot-and-dashed circle arcs. These arc sequences are searched similarly as line segments of straight axes.

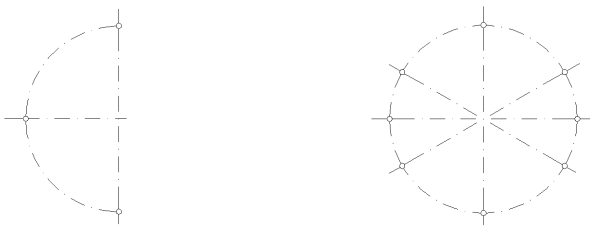


Fig. 25 *Segments of spaced circle*

We begin first by arcs which do not have both end points connected to another arc. Individual arcs in the sequence should have a common centre, identical radius and the end angle of one should be the start angle of the other arc. If after searching all interrupted spaced circles there are dot-and-dashed circle segments, they are searched as well, and any of the unprocessed segment is chosen as an initial one. The process repeats until all circle arcs with dot-and-dashed line are processed. Each sequence of oriented segments of spaced circles is stored into an independent list.

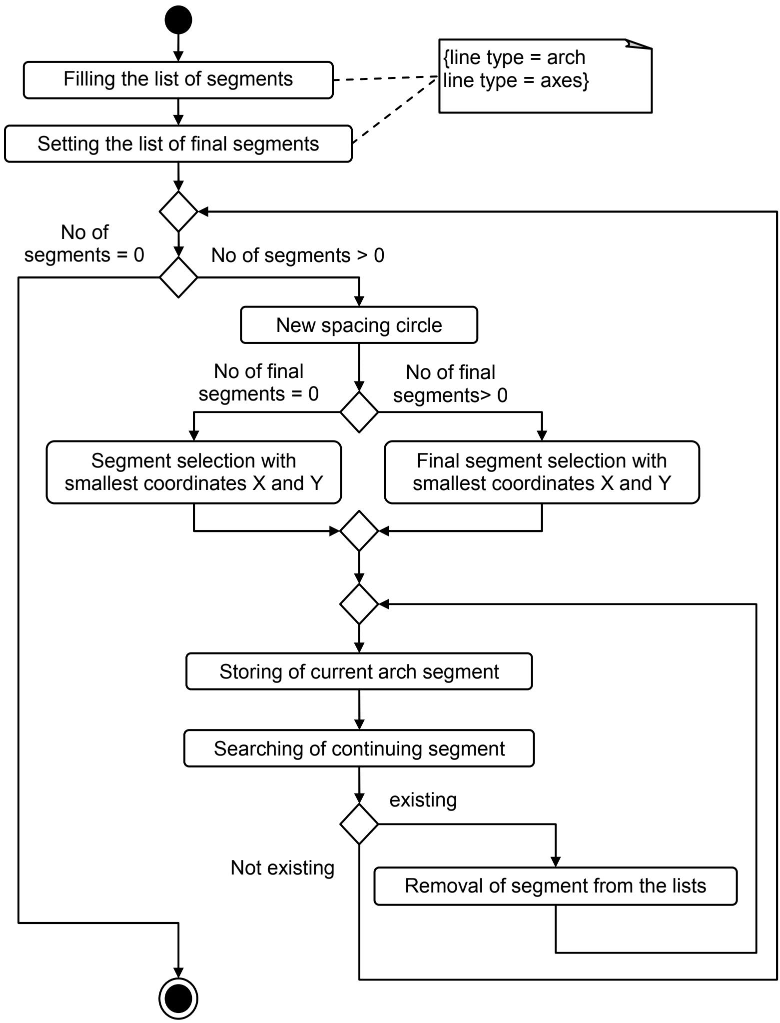


***Fig. 26** Algorithm of searching spacing circles*

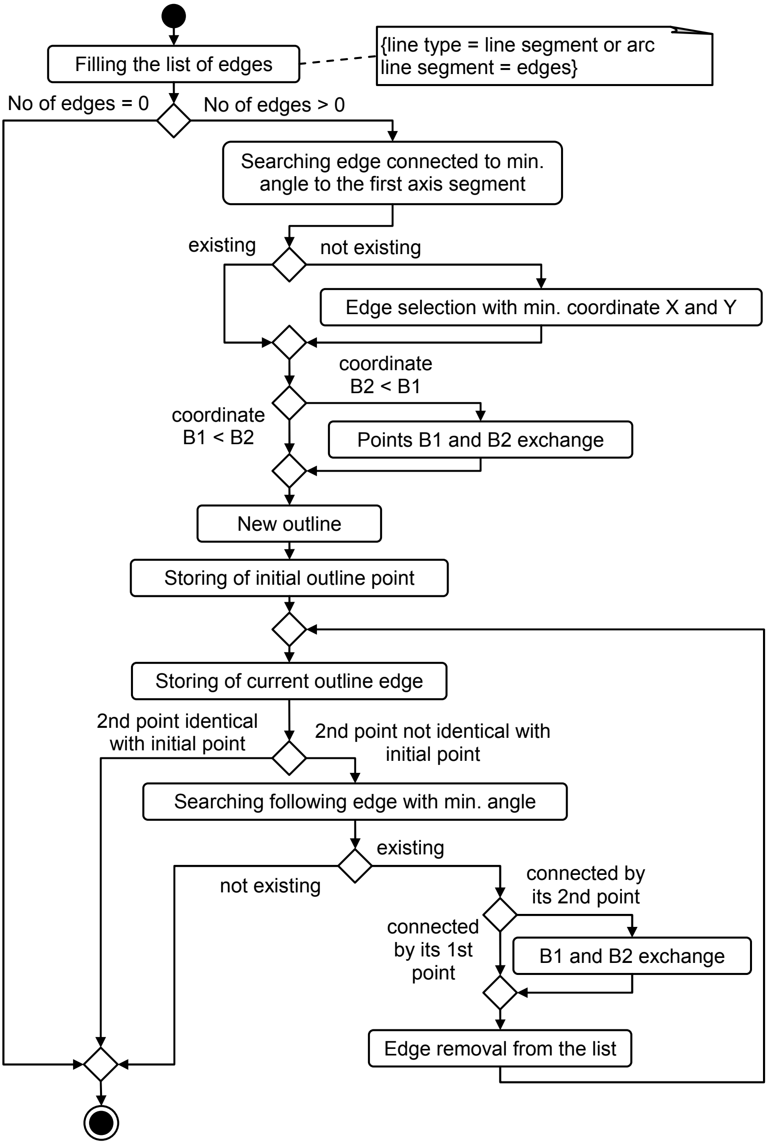
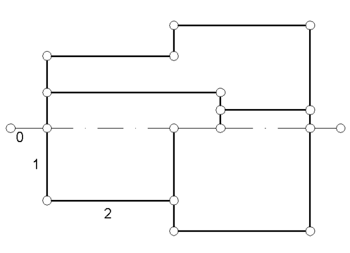


Fig. 27 *Algorithm of searching external outline*

2.3.4.3 Recognition of external outline edges

Looking for an external outline starts with finding the first segment of the main axis of rotation connected to some of the edges (Fig. 27).

This edge should have the smallest union towards the axis segment given, which ensures that we will not begin with another outline edge. Next, the related orientation of this first outline edge should be ensured, i.e. its first point should connect to the other point of axis segment given. If not, the points of the first outline line exchange. Then we proceed similarly: we look for the edge connected to the other point of current edge with the smallest angle towards it. Incorrect orientation is solved by the exchange of start and end points of the line points. This procedure repeats until we come back to the start point of the outline.



a) b)

Fig. 28 *Searching of external outline: a) source, b) result*

Individual segments are stored in an independent list of oriented lines; the other half of the outline is separated while transferring the main axis of rotation. The outlines are then complemented and closed by segments of axis of rotation and the lines orientation of each of the outline halves is preserved (Fig. 29).

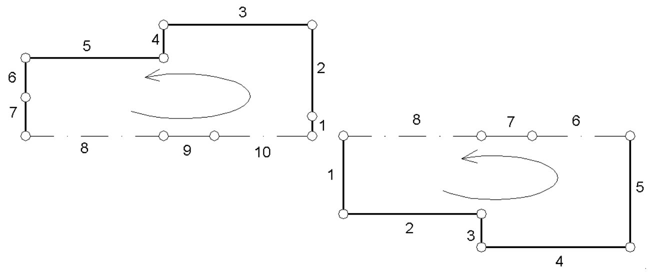


Fig. 29 *Upper and bottom halves of external outline closed by axis*

This method is called the **method of minimum angle** since into the area boundary only lines with minimum angle towards current segment are included (Fig. 30). By this way of projection lines transfer the areas represented by the oriented graph, where the internal area surface is located on the left from the direction of its boundary bypass, can be obtained.

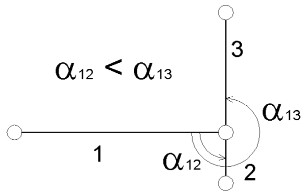
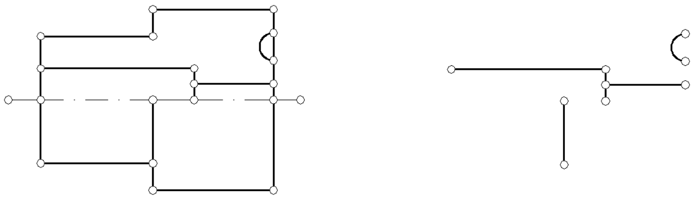


Fig. 30 *Principle of minimum angle method*

2.3.4.4 Processing of internal edges

All lines comprised in the outline are copied into an independent list. The list is searched similarly, by searching the line groups of the whole drawing (Chapter 2.3.3, Fig. 18). I named the lines building independent groups of edges *islands*. Internal islands, independent from each of the projection halves, are then analyzed to find how they have been built.



a) b)

Fig. 31 *Searching of internal edges: a) source, b) result*

Algorithm can differentiate the following types of internal islands. For clarity of individual elements placement, the axes (dot-and-dashed line) and simplified outlines (dotted line) are drawn in the examples.

2.3.4.4.1 *<u>Types of internal islands</u>*

A – Continuous hole in axis of rotation

One end point is on the perpendicular going through the end point of axis of rotation; the other end point is on the perpendicular going through the other end point of axis of rotation. Holes are along the whole part length.

Fig. 32 *Continuous hole in axis of rotation with/without stepping*

B – Blind hole in axis of rotation

One end point is on the perpendicular going through the end point of axis of rotation; the other end point is on the axis of rotation. This is a typical example of drilled holes in the part or a drive for a pen.

Fig. 33 *Blind hole in axis of rotation*

C – Surface take off on edge beyond axis

Two end points of various lines are on the perpendicular going through the same end point of axis of rotation. It can be an intercircle of a given profile or blind holes on a spaced circle. Axes of symmetry can be located in this area as well.

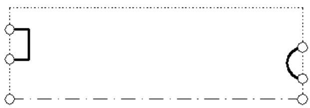


Fig. 34 *Surface take off on edge*

D – Surface take off on other part

Two end points of various lines are on the perpendicular going through the same random point of axis of rotation, e.g. intercircle of the given profile or symmetrically placed holes along the part´s circumference. The axes of symmetry can be placed in this area as well.

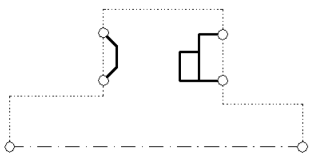


Fig. 35 *Surface take off on other part than edge*

E – Continuous line beyond axis of rotation

Two end points are on two outline edges perpendicular to axis (a). This line is mostly combined with a similar parallel line (b) and together they represent a continuous hole beyond axis of rotation. The continuous hole, symmetrically arranged on the spaced circle, is the most typical element with such a projection in the section. In this case the axis of symmetry will be placed between the lines.

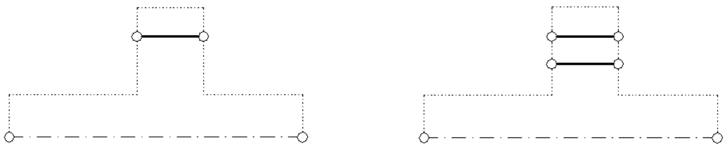


Fig. 36 *Continuous line beyond axis of rotation*

F – Continuous hole beyond axis of rotation

Two end points of various lines are on the perpendicular going through the same random point of the axis of rotation; and two other end points of various lines are on the perpendicular going through the random point of the same random point of the axis of rotation. They can be the holes placed symmetrically on the spaced circle. The axis of symmetry should pass through the area as well.

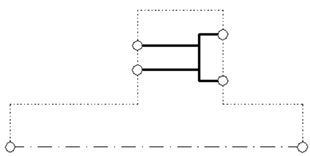


Fig. 37 *Continuous hole beyond axis of rotation*

G – Internal island on axis

Two end points are on the axis of rotation and no point is on the outline. A slot for a pen or continuous hole are typical examples.

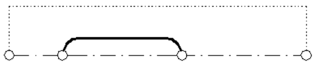


Fig. 38 *Internal island on axis of rotation*

H – Internal closed island beyond axis

It is a closed area within the outline. It can be e.g. the projection of a hole going perpendicular to the part´s diameter.

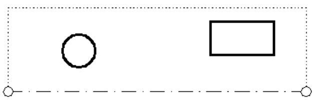


Fig. 39 *Internal closed island beyond axis*

I – Internal island connected with other than perpendicular outline line

At least one point is on the external cover of the solid, the other point can be on the outline perpendicular or on the external cover as well. The external cover means the imaginary outline line not perpendicular to axis. This type is represented by various grooves/drives and take offs on the circumference of the solid.

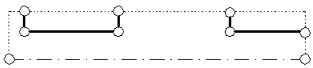


Fig. 40 *Internal island on external outline*

J – Perpendicular line segments connected to outline and axis

Both end points are on common perpendicular to axis, while one point is on the outline, the other point can be (but does not have to be) on the axis (Fig. 41a). Line segments constituting this line should be on this perpendicular. The point not lying on the axis should be connected to it by another part of a given group of lines (Fig. 41b). They represent the projections of the part´s surfaces of rotation. They are not utilized for further processing, therefore they are eliminated.

a) b)

Fig. 41 *Perpendicular line segments connected to outline and axis*

K – Other types of internal lines

Other than aforementioned types of elements, various shape elements or take offs causing asymmetry of upper and bottom outlines are not processed by the algorithm.

After categorization, each island is compared to the lines of islands in the second projection half as well as in other projections, by which their inclusion is confirmed, or modified or specified. The elements not successfully recognized are not used in 3D model reconstruction.

2.3.4.4.2 *Coaxial holes and intercircles*

Elements of A, B, C and D types after their shape and placement in other views verification can be classified into this category. First of all, they have to have the projection in the shape of one or more concentric circles with the centre on main axis.

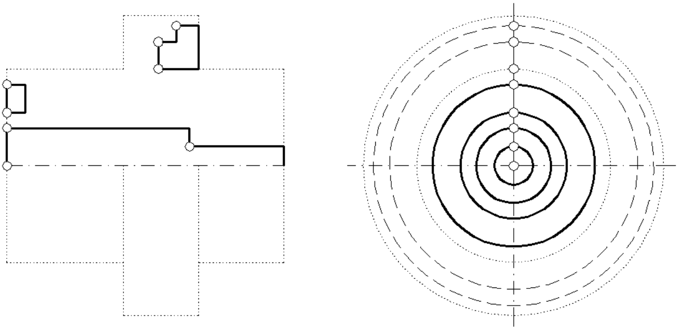


Fig. 42 *Coaxial holes and intercircles*

Islands successfully recognized as parts that can be generated by the rotation around the main axis of rotation are complemented by missing segments, completing the outline of the closed area. Lines of axis and internal areas are used as missing segments. Subsequently, external outlines of these internal areas are searched.

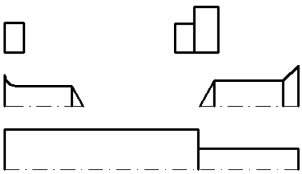


Fig. 43 *Internal islands complemented by missing lines from outline and axis*

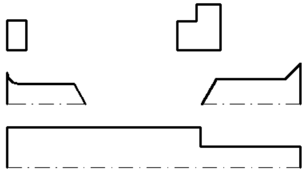


Fig. 44 *Internal islands after finding their outline*

Such prepared internal areas are used as patterns for 3D model building via profile rotation method. Rotation solids and intercircles with related cross-sections are gradually subtracted from the main solid made by the rotation of external part profile.

2.3.4.4.3 Holes and take offs on spaced circle

Such elements as E and F types or C and D types can be classified in this category since they meet the criteria. Islands, whose projections are on the view in the main axis direction on the spaced circle, can be completely processed only if their angle space can be determined, i.e. by the determination of identical projections positions on the spaced circle or by reading the dimensions.

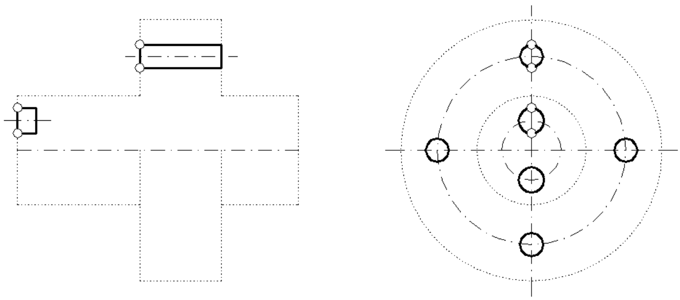


Fig. 45 *Holes and take offs on spaced circle*

If there exists the projection in the shape of a circle or concentric circles with the centre in the axis of verified profile, then we can reconstruct this construction element by the profile rotation found in the front view around its axis. Projections other than circles are not supported.

2.3.4.4.4 *Elements of asymmetry*

Various grooves/drives, take offs or holes not meeting the aforementioned criteria are considered as asymmetric construction elements. Elements of G, H, I, K types can be classified in the category, however, it is necessary to verify the elements of A, B, C, D types as well since they can be built differently than by profile rotation or arrangement on spaced circle.

Construction elements of this category should be considered individually, as they can be made by various ways – profile drawing on the line segment, profile rotation or as some of the basic solids (prism, cylinder, cone).

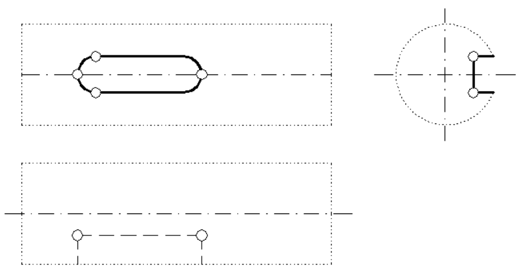


Fig. 46 *Element of asymmetry – drive for pen*

2.3.5 Processing of other views

Side view and plan view are processed only as a complement to the drawing. They serve mainly as a source or decision elements recognized in the front view. They provide information on construction elements dimensions, their placement on circumference, or circumference of a rotation solid. Nevertheless, we cannot avoid their processing by the reconstruction of more complex rotation parts.

The processing of the view whose symmetry axis is parallel to the main symmetry axis of the front view is similar to the processing of the front view.

The processing of the view in the direction of the main symmetry axis is similar to processing of other views, but it requires another approach. It can serve e.g. as a source of profiles for the operation of drawing along the line segment in the direction of the main symmetry axis as well as the angles of construction elements arrangement on the spaced circle.

2.3.6 Setting CSG representation of part

A part is composed of solids made in previous steps via Boolean volume operations. The basic solid is built by the operation of the part´s external half-outline rotation around the main axis of rotation. Subsequently, the volumes originated from internal edges processing are subtracted from it. These solids are placed into the binary tree of CSG representation (Fig. 47).

In CSG tree leaves there are solids built by various methods and in the nodes there is the kind of operation carried out. By the inclusion to the tree stands that on the left there is the basic solid and on the left there is the solid that will be used by a related operation (addition, subtraction, intersection). For instance in the subtraction of volumes, the solid situated in the right branch is subtracted from the solid placed on the left branch. Such a newly constituted solid can be placed to the left or right depending on whether the following operation is executed on it or with it.

The processing is done via **postorder** method for tree processing [9], [39], [47], [48]. It starts with the lowest branch of the entire tree, by coming back to the tree roots, the right or also left nodes are searched. After achieving the root node, the part is completely reconstructed. (Fig. 48).

2.3.7 3D part model projection

Projection of 3D solid model is carried out via API of the related graphic system. The module mediating the communication between it and a module being investigated receives an order to draw the solid while it is given the CSG tree structure completely describing a ready 3D model. The graphic output itself is then executed by CSG tree processing and by gradual building of the result part model via related graphic system functions, in our case in AutoCAD.

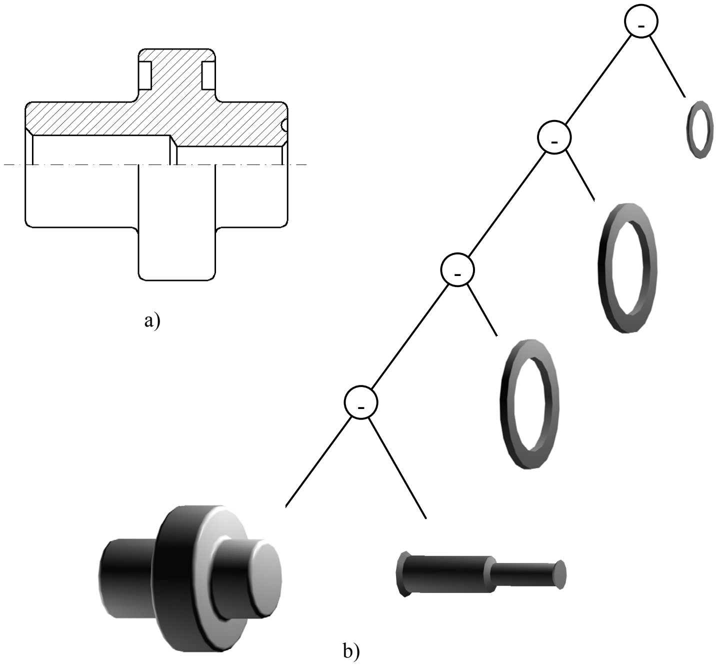


Fig. 47 *CSG part representation:*
a) original projection, b) CSG tree

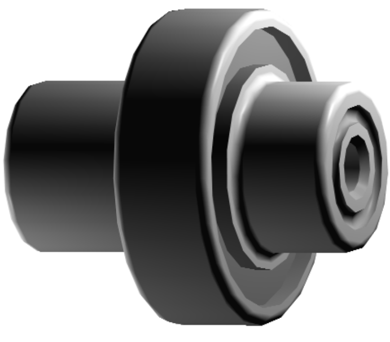


Fig. 48 *Result part*

3. PROGRAM IMPLEMENTATION AND VERIFICATION OF RESULTS

3.1 Implementation of algorithms

Algorithms designed were implemented in Visual C++ 6.0 development environment with using ObjectARX 2000 Libraries, which are the part of application programming interface of CAD system – AutoCAD 2000. Functions of this API are used for essential communication with host graphic system in reading of vector data and drawing the result solid and also for setting off the related functions by the user.

3.1.1 Data structures

The design of a data model representing the static view to the developed application is a significant part of implementation. Its task is to describe all important data properties which it works with as well as specifying the functions which can execute required operations with related data. Application is implemented by OOP approach, and therefore the data model is in the form of classes diagram (Figs. 49 and 50).

Implemented classes:

- cPoint properties of point and auxiliary functions,
- cPoints list of points,
- cLine common properties and functions of line segment and arc,
- cSegment properties of line segment and functions to search mutual position,
- cArc properties of circle arc,
- cLines list of lines and functions for lines segmentation,

- cView lists of lines and functions for view processing,
- cViews list of all views and functions for their processing.

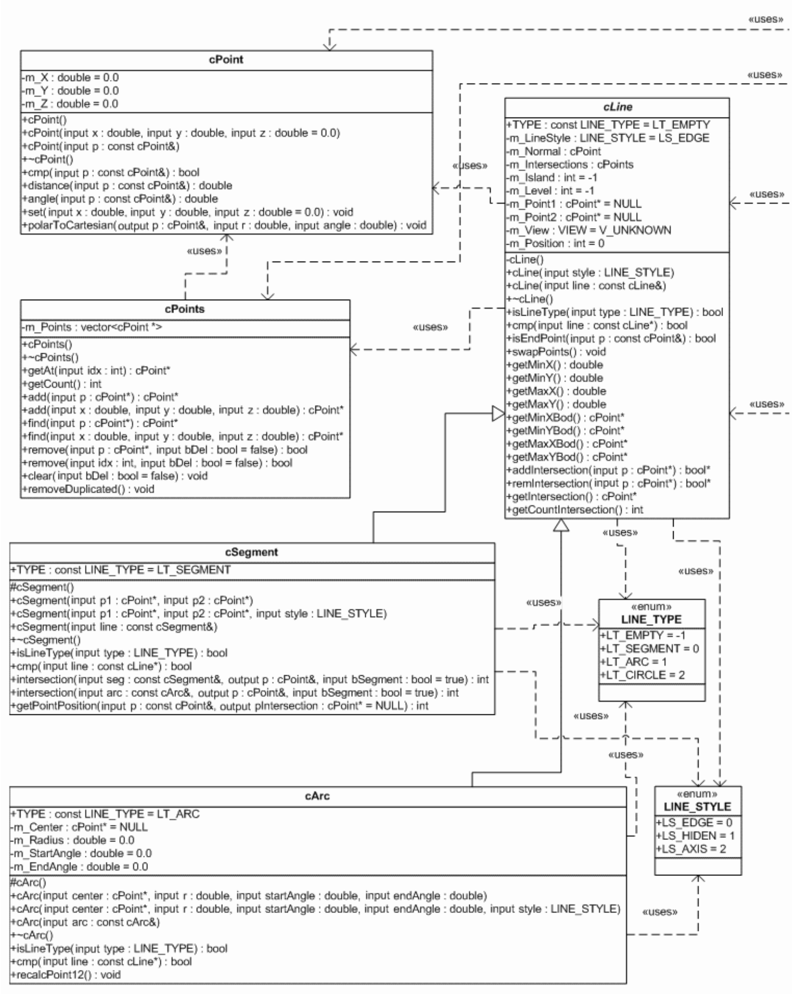


Fig. 49 Diagram of classes, Part 1

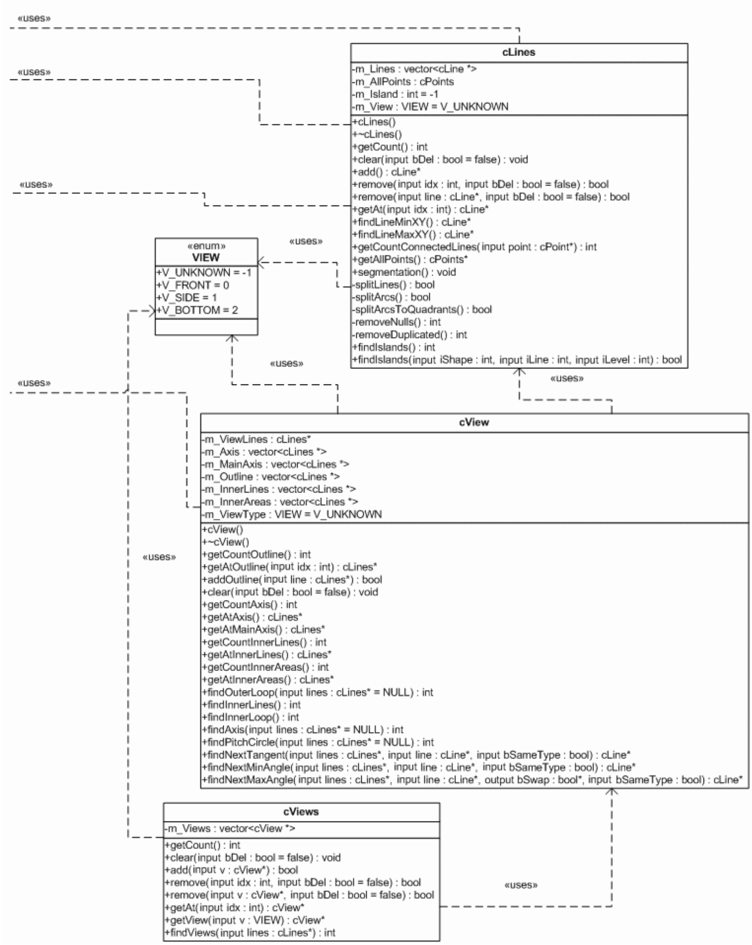


Fig. 50 *Diagram of classes, Part 2*

3.1.2 User interface

To communicate with the user and record information, AutoCAD order line was selected. This simple interface is fully sufficient for testing purposes and verification of designed algorithms' functionality. In the future it will be complemented by a graphic user interface where the user will be able to set up optional input parameters for processing the vector drawing of a part.

Implemented orders that can be activated by user:

- read — reading of lines from drawing and setting of their processing,
- lines — drawing of all lines read from drawing,
- front view — drawing of front view lines,
- side view — drawing of side view lines,
- plan view — drawing of plan view lines,
- axes — drawing of main axis,
- outline — drawing of whole front view outline,
- outline1 — drawing of outline in upper part of a front view,
- outline2 — drawing of outline in bottom part of a front view,
- internal1 — drawing of internal lines in upper part of a front view,
- internal2 — drawing of internal lines in bottom part of a front view,
- areas — drawing of internal closed areas in a front view,
- areas1 — drawing of internal closed areas in upper part of a front view,
- areas2 — drawing of internal closed areas in bottom part of a front view,

- solid1 drawing of result solid,
- solid2 drawing of individual components constituting result solid.

Function **read** passes all through entities of a current drawing and the parameters of those being supported is included into the list of all lines. Subsequently, it calls out the functions for line segmentation and views processing.

All other functions serve for displaying the results of processing, either partial or final ones.

3.1.3 Reading data from vector drawing

Working with a drawing in AutoCAD via ObjectARX requires strict following of specific steps of approaching the individual drawing elements. If I want to work with some object, either an individual element or a list, I have to open it first for reading or recording. Then I can read or modify data from it, and after working with it, I have to close each open object. All drawing elements build a complex hierarchic structure of various types of objects and their lists. On the highest level, there is the drawing itself, the lists of various types follow, e.g space, layers, line types, entities, etc. Each list has its own iterator providing movement in a related list and access to individual elements.

We are interested in entities (line segments, arcs, circles and polyline) which are within the modeling space of drawing block tables. An algorithm to search the lines needed reads as follows:

1. Open table of blocks of active drawing for reading.
2. Open modeling space for reading, close table of blocks.
3. Constitute iterator for movement in modeling space.
4. Until all entities are searches, process the following:
    A. Open entity for reading.
    B. If entity is not from the first level, close it and search next one.
    C. If entity is not type of a line, circle, arc or polyline, close it and search next one.
    D. Identify type, thickness and colour of line according to layer properties.
    E. If it is line segment (AcDbLine)
        a. read initial and end points,
        b. constitute class object cSegment and include into list.
    F. If it is circle (AcDbCircle)
        a. Read centre and radius, initial angle=0, end angle=2π,
        b. Constitute class object cCircle and include into list.
    G. If it is arc (AcDbArc)
        a. read centre, radius, initial angle, end angle,
        b. constitute class object cArc and include it in list.
    H. If it is Polyline (AcDbPolyline)
        a. search all segments and according to their types read the data and constitute class object cSegment or cArc and include in list.
    I. Close entity.
5. Cancel iterator.
6. Close modeling space.

3.1.4 Processing vector data

After reading data from vector drawing, the processing of lines via module implementing the designed method follows:

1. Carry out segmentation of the list of all lines.
2. Search individual projections.
3. Process all views:
   - A. Search axes in the list of view lines.
   - B. Search external outlines in the list of view lines.
   - C. Search internal lines and areas.
   - D. Recognize construction elements of a view.
4. Reconstruct basic solid.
5. Reconstruct construction elements.
6. Constitute CSG model.

If everything goes well, the user can let the result solid drawn by the order **solid1**, or he can have drawn some of the semiresults of processing using related orders.

3.1.5 Setting CSG tree of solid representation

Binary tree CSG structure was replaced by a simple list which is a degenerated tree where each node has only one branch. This simplification was used since the algorithm constitutes the result solid only by subtracting the volume of simple solids from the basic solid. The main part of a part is the first, i.e. basic, solid which was made by the rotation of the external profile around the axis. All other solids in the list represent construction elements subtracted gradually from this first solid. This way, it is possible to replace the simple tree presented in (Fig 47b) by a list.

3.1.6 Constituting final 3D part model

When drawing entities in AutoCAD, it is again necessary to obtain the access to modeling space with the permission to record. The basic solid is constituted and subsequently all other resulting construction parts are modeled and subtracted from the basic solid. To make the solid by the operation of profile drawing along the line segment, it is necessary to constitute first a so-called region. From individual segments building its closed boundary one element originates, which is then used as a pattern.

The function **createRevolution** constituting the rotation solid from the closed polyline and given rotation axis is implemented. It works as follows:

1. Draw gradually the lines from the given list of outline and store references in the area of entities.
2. Constitute region from entities in the area (AcDbRegion).
3. Constitute the volume solid by the region rotation around the given axis by and angle 2π (AcDb3dSolid).
4. Insert the constituted solid in modeling space.

Similarly the function createExtrusion is implemented which builds the solid by closed profile drawing along the normal of given length.

Function createRevolution is used by setting the result solid via CSG representation if the user sets off the order **solid1** or **solid2**:

1. Open table of blocks of active drawing for reading.
2. Open modeling space for record, close table of blocks.
3. Constitute basic solid from the first item on the list by profile rotation.
4. While other profiles are on the list:
   A. constitute solid of construction element by profile rotation,
   B. subtract construction element from basic solid.

5. Close modeling space.

3D visualization of part model is the result. The user can work with this model further directly in host CAD system or store it to the file for later use. The type of output file format depends on the possibilities of CAD system given.

3.2 Verification of results

To verify the truthfulness of designed algorithms, samples were drawn which were subsequently processed by the implemented application. Individual samples are classified by the number of views and types of construction elements comprised. The samples comprise also elements which are not possible to be made by the rotation around the main axis. These elements are recognized, however, they are not processed further since in the application the algorithms for their reconstruction had not been implemented yet.

3.2.1 Naming samples

Sets of samples are named according to the following scheme:

partNN-P-O-K+D.dwg

NN order number of same type sample,

P number of projections,

O orientation of main axis, allowed values are: H = horizontal, V = vertical, S = oblique,

K indication of construction element (A, B, C, D, E, F, G, H); their combinations allowed as well (BC, AE, ...),

D complementary information: nb = front view and side view; np = front view and plan view; section; cross-section.

Figures of projections and result 3D solid are stored in BMP file format with the same name as the sample.

3.2.2 Samples

Samples 01-04 are simple rotation parts displayed only in the front view. They provide verification of basic functions, such as recognition of part outline and main symmetry axis in horizontal and vertical orientations. The outline comprises line segments and circle arcs as well.

Sample 05 is a simple rotation part displayed in various combinations of views and orientations of axis. It has to verify recognition of individual projections in case of one, two or three views by different orientation of the main axis. The ability to work with the oblique symmetry axis of cylindrical surfaces, i.e. with an axis not parallel with coordinate system axes, is verified.

Samples 06-08 are rotation parts with a hole lying in the symmetry axis. The ability to recognize continuous or blind holes displayed in partial or complete sections, either straight or graded, is verified here. The holes are constituted by construction elements taken off the main solid. The parts are again oriented horizontally, vertically and oblique.

Sample 09 comprises an asymmetrical elements – drive for pen where the second view is represented by the section and cross-section. The purpose is to verify whether this second view is correctly recognized. Since the processing of asymmetric elements has not been implemented yet, it is not expected that the groove for pen will be properly reconstructed.

Samples 10-15 represent rotation parts of a flange type with various degree of demand and various combinations of construction elements. The ability to process an amount of external and internal curvatures is verified as well. The samples comprise blind and continuous hole in the axis, shaped take offs beyond the axis. Continuous holes beyond the axis are also included, however, they will be not processed as they have not been implemented yet.

Sample 16 comprises an asymmetric construction element and is displayed in three views in horizontal and vertical orientations. This element will be not processed as well. Implemented application was introduced as a module to AutoCAD, the files of samples were gradually opened and after setting off the order **read** the sample was automatically processed. Subsequently, the semi-results were verified visually and final 3D model via functions mentioned in Chapter 3.1.2.

In all cases, the basic 3D solid model constituted by the part outline was reconstructed. If the sample comprised construction elements such as coaxial hole or intercircle, these were successfully reconstructed and their volumes then subtracted from the basic solid. The processing of other elements has not been completely implemented yet, and therefore not properly reconstructed.

A section of a cylindrical shape was recognized and processed as a side view or a plan view. The cross-section was not recognized since its profile is smaller than the projection on its position. A similar situation would occur in case of the section, which would be carried out in that part of the rotation part behind which no external outline edge could not be projected.

Individual samples as well as result reconstructed 3D models are displayed in Annex.

RESULTS OF TEST SAMPLES PROCESSING Table 5

Name of sample	Recognition				Reconstruction		
	view	main axis	outline	constr. elem.	basic solid	constr. elem.	result model
part01-1-H	N	+	+	no	+	no	+
part02-1-H	N	+	+	no	+	no	+
part02-1-V	N	+	+	no	+	no	+
part03-1-H	N	+	+	no	+	no	+
part04-1-H	N	+	+	no	+	no	+
part05-1-H	N	+	+	no	+	no	+
part05-1-S	N	+	+	no	+	no	+
part05-1-V	N	+	+	no	+	no	+
part05-2-H+nb	N,B	+	+	no	+	no	+
part05-2-V+nb	N,B	+	+	no	+	no	+
part05-2-H+np	N,P	+	+	no	+	no	+
part05-2-V+np	N,P	+	+	no	+	no	+
part05-3-H	N,B,P	+	+	no	+	no	+
part05-3-V	N,B,P	+	+	no	+	no	+
part06-1-H-A	N	+	+	A	+	A	+
part07-1-H-A	N	+	+	A	+	A	+
part07-1-V-A	N	+	+	A	+	A	+
part08-1-V-B	N	+	+	2xB	+	2xB	+
part08-1-S-B	N	+	+	2xB	+	2xB	+
part09-2-H-G+cross-sec	N	+	+	G	+	no	- G
part09-2-H-G+section	N,B	+	+	G	+	no	- G
part10-1-H-B	N	+	+	B	+	B	+
part11-1-H-A	N	+	+	A	+	A	+
part12-1-H-B	N	+	+	B	+	B	+
part13-1-H-BCD	N	+	+	B,C,D	+	B,C,D	+
part14-1-H-AE	N	+	+	A,E	+	A	- E
part15-1-H-AF	N	+	+	A,F	+	A	- F
part16-3-H-H+section	N,B,P	+	+	H	+	no	- H
part16-3-V-H+section	N,B,P	+	+	H	+	no	- H

CONCLUSION

This scientific monograph designs and implements methods which can automatically reconstruct 3D model of the rotation part from its vector record of the technical drawing. The topic is very complex, even after significant elimination of technical drawing elements which have to be considered. The monograph focuses on only the category of rotation parts, which includes a lot of shape elements that have to be taken off the basic solid. Every other construction element increasing asymmetry simultaneously increases the demand of 3D solid reconstruction.

In processing only data related to the basic projections of part edges without dimensions and other drawing elements are used. Vector data are automatically preprocessed by segmentation, and its results are output data for further process of recognizing the projections' elements. After finding the main symmetry axis and external outline, the internal construction elements originated by material take off from the basic rotation part solid are gradually processed as well. Construction elements of a rotation part were classified into basic categories automatically recognized by the algorithm. Elements with identical symmetry axis with basic solid symmetry axis are then automatically reconstructed. There are continuous and blind holes as well as intercircles of various shapes which can be constituted by the profile rotation around the symmetry axis. Partial solids built this way are in the reconstruction gradually subtracted from the basic solid. Part model is described by CSG representation.

Application is now implemented in one enlarging module for AutoCAD graphic system. Application structure allows separating the parts of vector data processing and 3D model reconstruction from input-output operation related to vector data acquisition and drawing of the result model. In the future, this will allow simple implementing of next input-output module for another CAD system.

The main benefits of the monograph can be summarized into the following points:

- Analysis of known approaches to 3D model reconstruction from vector record.
- Brief analysis of possibilities to obtain input vector data and presentation of result model.
- Design of method for preprocessing of vector data.
- Designed methods of pre-processing are suitable also for vector records of non-rotating parts projections.
- Analysis of construction elements most frequent on rotation parts.
- Design of algorithms for automatic generation of 3D model of rotation part comprising only selected construction elements.
- Partial implementation of designed algorithms of automatic generation of 3D rotation part model comprising only selected construction elements.
- Experimental evaluation of provided results.
- Application implementation considering the independence of the processing module on input-output operations of host CAD system.

Designed methods, as well as the application, can be considered as a pilot project to be further enhanced, especially in finishing the implementation of all construction element types processing. Other possibilities to develop the automation of 3D rotation part model reconstruction are as follows:

- Improvement of processing side view and plan view, or other views as well.
- Dimensions processing is one of the most important steps to be investigated. If there are not two or three projections at one's disposal, then some construction elements cannot be properly recognized and reconstructed. They are particularly cylindrical elements whose projection is identical with the projection of a prism.
- Processing of sections and cross-sections not having the position of standard view. It is the localization of sections' place indicated by the section plane (e.g. A-A) and their searching in the drawing.
- Automatic verification of 3D model reconstruction success by generating the projections and their comparing to original vector records.
- Design and implementation of input-output modules for some other CAD/CAM systems, such as Inventor, SolidWorks, ProEngineer.
- Design and implementation of input-output module for independent processing of standard formats such as DXF, STEP, IGES.

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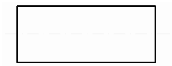
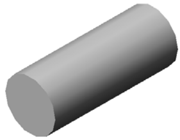
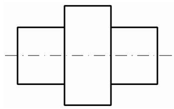
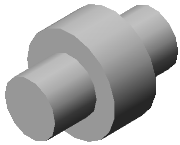
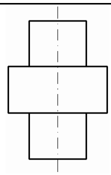
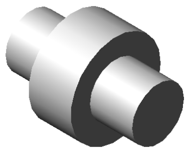
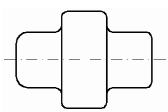
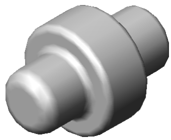
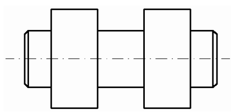
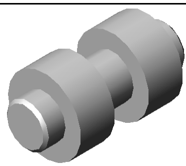
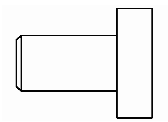
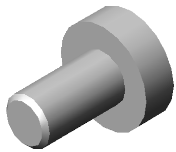
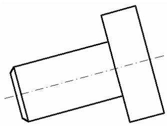
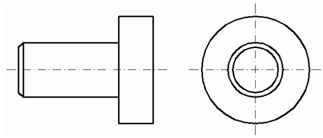
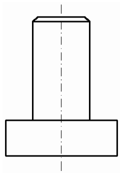
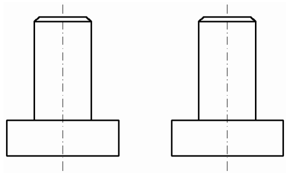
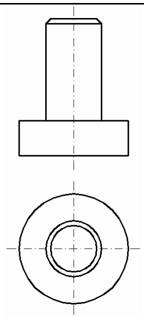
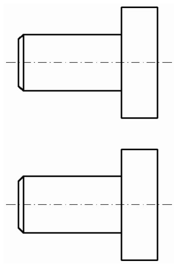
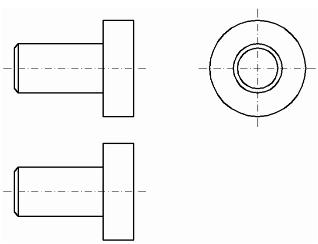
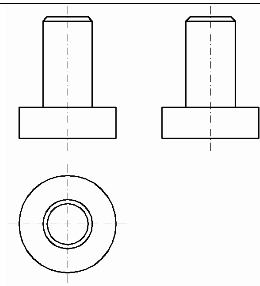
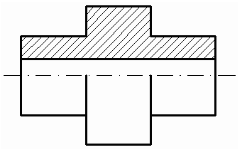
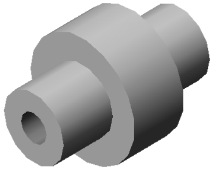
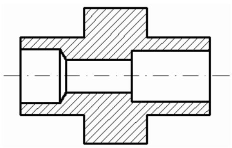
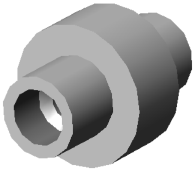
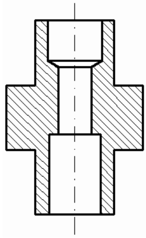
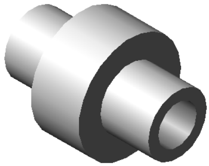
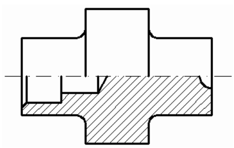
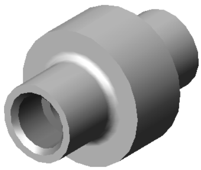
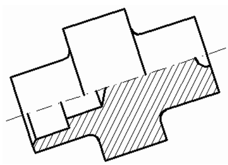
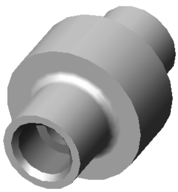
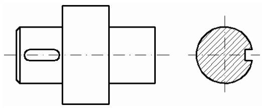
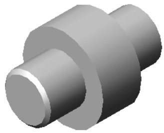
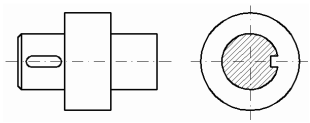
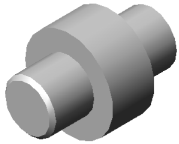
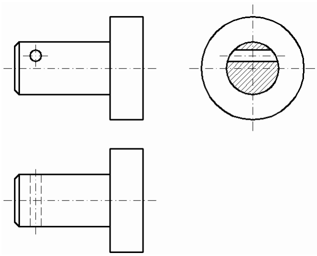
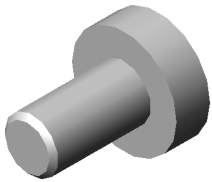
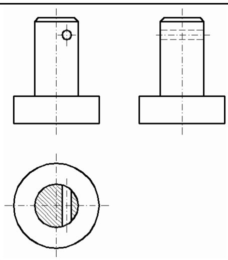
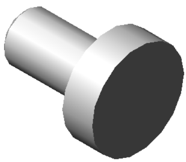
ANNEX – TESTED SAMPLES

S	Projections	3D model
part01-1-H		
part02-1-H		
part02-1-V		
part03-1-H		
part04-1-H		
part05-1-H		

S	Projections	S	Projections
part05-1-S		part05-2-H+nb	
part05-1-V		part05-2-V+nb	
part05-2-V+np		part05-2-H+np	
part05-3-H		part05-3-V	

S	Projections	3D model
part06-1-H-A		
part07-1-H-A		
part07-1-V-A		
part08-1-H-B		
part08-1-S-B		

S	Projections	3D model
part09-1-H-G+prierez		
part09-1-H-G+rez		
part16-3-H-H+rez		
part16-3-V-H+rez		

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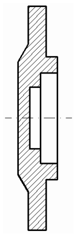
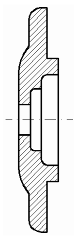
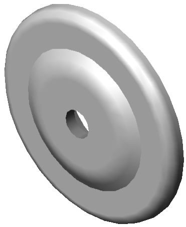
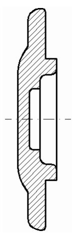
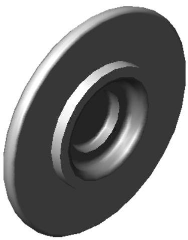
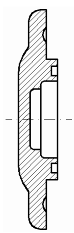
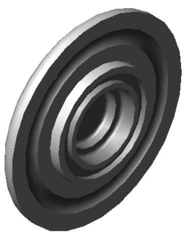
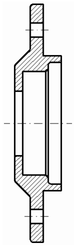
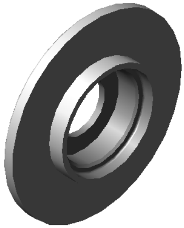
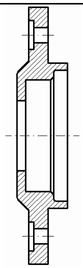
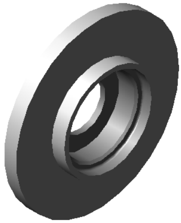
part10-1-H-B		
part11-1-H-A		
part12-1-H-B		
part13-1-H-BCD		

S	Projections	3D model
part14-1-H-AE		
part15-1-H-AF		

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