Choice of CAD Model Adaptation Process for Virtual Reality using Classification Techniques

Florence Danglade[1] and Christophe Guillet[2]

[1]Arts et Metiers ParisTech, florence.danglade@ensam.eu
[2]Universite de Bourgogne, christophe.guillet@u-bourgogne.fr

Corresponding author: Florence Danglade, florence.danglade@ensam.eu

Abstract. Virtual reality and augmented reality (V/AR) are powerful techniques for training, assistance, or supporting activities in the industry. However, the deployment of V/AR techniques in the industry is held back by various factors. The difficulty in adapting an original CAD model to a 3D model for V/AR is one of these factors. Currently, the adaptation process is very time consuming, and its result is unsatisfactory. The adaptation result is often of poor quality or it is poorly adapted to objective of the V/AR activity. A formalization of the specific needs of each V/AR activity will allow improving the level of satisfaction. To ensure a result of the adaptation that meets these specifications, it is necessary to know the most appropriate adaptation process. We, therefore, propose an approach using classification methods to predict the best adaptation process from cases of CAD model preparation for specific V/AR activities. Our approach allows obtaining a 3D model for V/AR without compromise between the quality of the adaptation and its duration.The developer of V/AR application could produce 3D content faster and better. This should facilitate the deployment of V/AR techniques in the industry. The proposed approach is illustrated and validated for two different objectives of industrial V/AR activities.

Keywords: CAD model, virtual reality, CAD-VR adaptation, classification, machine learning
DOI: https://doi.org/10.14733/cadaps.2022.494-509

1 INTRODUCTION

The techniques of virtual and augmented reality (V/AR) help the digitalization for the Industrie 4.0 [21]. As shown by [12, 19, 18, 15], these techniques are already in common use in all product life cycle phases. The V/AR techniques are used in industry for training, during a project review, or for technical assistance during activities of design, manufacturing, use, or maintenance. They use 3D contents that result from Computer-Aided Design (CAD) models. These CAD models can be used directly in V/AR devices without adaptation, for example for design project review, provided that the CAD software allows this. Some tools offer this function, such as the software 3D Experience [4]. Some authors [13] go further, with the direct and intuitive interaction of models in the virtual environment. Other, more recent studies address the subject of the direct use and interactive modifications of CAD model in V/AR devices [23]. For example, [24] provide end users direct modifications of CAD objects in the immersive application, using a shape-based 3D interaction technique. To modify the CAD models in the virtual environment, [14] propose the synchronization of the model description between the CAD and V/AR applications. In all of these studies, the assumption is that the quality of the CAD model in virtual environment is perfect. This is not always the case (bad quality of rendering, degraded geometry, low latency, no smooth viewing, and so on). The non-quality of the CAD model in virtual environment is due to several reasons, CAD and V/AR formats are not compatible; CAD models are too large for V/AR applications; the adaptation process does not meet the need for a specific V/AR activity. [25] proposed a hybrid method for the integration of a CAD system and a virtual sketching system. The author noted the difficulties of conversion between the CAD and V/AR systems, and the requirement to perform the integration of operations manually. These latest findings are still relevant, some operations like metadata preservation are still manual.

In the end, the V/AR application is often disappointing [20, 28]. This slows down the deployment of V/AR techniques in the industry. It is therefore often necessary to adapt upstream the CAD model. For this purpose, [22] propose an independent CAD and virtual system workflow. Among all of the adaptation operations, the main operations are the model simplification by details and polygons numbers reducing. Many tools offer a variety of adaptation functions (components removing, details removing, local simplification, and global simplification). There are many commercial tools, some of which are described in sec. 2.2. These tools are steadily improving, in particular thanks to recent studies. Therefore, for example, [29] propose a framework integrating a pre-processing algorithm for an automatic generation of level of detail for massive models. [26] were interested in the problem of the bad quality of the rendering. They developed a simplification algorithm that improves the rendering. All of these methods of CAD model adaptation requires manual operations and deep knowledge particularly during the choice of control parameters. These operations are usually performed by the V/AR application developer. Ideally, many iterations would be necessary to obtain the optimal adapted model that perfectly meets the needs of the final application. The adaptation operations are very time-consuming. Thus, when the V/AR application developer has obtained a result that works, he implements it even if the quality is not excellent and even if the result does not perfectly meet the need of the end-user.

The intention in this paper is not to propose new methods of adaptation or improve them, but to guide the developer in the choice of methods, tools, and their control parameters. We propose to use machine learning techniques to predict a CAD model adaptation process that fully satisfies the requirements of quality and duration. To satisfy the quality criteria, it will be necessary to formalize the requirements and take into account the specific need of the final application. To ensure an acceptable duration of operations, the result of the adaptation must meet the quality requirements from the first iteration. In previous work [17, 16], it was proposed a method to evaluate an adaptation process of a CAD model by using machine learning techniques in a different context. In this paper, we propose a new approach to predict the best adaptation process of CAD models for a specific V/AR application using techniques of classification. One challenge was to model a specific adaptation process of CAD data for each objective of V/AR application. For this purpose, it will be necessary to begin by formalizing the need for the final V/AR application, then to formalize the processes adaptation and their performance. A second challenge was to identify variables that influence the choice of the adaptation process. This will involve extracting the characteristics of the CAD models that are correlated with the variables characterizing the adaptation processes and their performance.

The prediction of the adaptations operations should, eventually, reduce the duration of the development of the V/AR application and improve the quality of the final V/AR application. To reach these objectives, section 2.1 analyses the needs for 3D models in V/AR applications. Section 2.2 gives tools and methods to adapt a CAD model. Knowing the requirements and the operations of CAD model adaptation, we propose, in section 3.1 an overall method to choose an adaptation process using machine learning techniques. Each step of this overall approach will be developed in the following sections 3.2 to 3.6. In section 4, the proposed approach will be illustrated and validated on examples of adaptation for various original CAD models and industrial V/AR applications.

2 CAD MODEL ADAPTATION FOR V/AR APPLICATIONS

2.1 Addressing the Needs Throughout the Product Life Cycle

V/AR industrial applications are used throughout the product life cycle. The CAD model is specific to each phase of the product life cycle and each V/AR objective (Fig. 1). It requires adapting the CAD model to each phase and each V/AR objective. As with many products and services, V/AR applications are expected to have a reduced time to market, a low development cost, and a high quality. In order to satisfy the needs of time to market and development cost, tools are required to easily and quickly adapt an original CAD model for a V/AR objective. These tools are described in the following section. About high quality, the V/AR application should satisfy a set of criteria. The requirement level of these criteria depends on the objective of the V/AR application. The adaptation CAD model has an impact on some criteria. Table 2 lists these criteria and their requirements for the extreme levels.

Visualization quality criteria. This criterion gives an indicator of disorders due to latency or discomfort during visualization of static content and animations. A model with a minimal preparation includes a large number of objects and polygons. This slows down the fluidity of the application and consequently degrades the quality of the viewing. If the V/AR objective requires a high level of visualization requirement, it will be necessary to reduce as much as possible this number of objects and polygons.

Shapes and dimensions precision criteria. This criterion is met when the geometry of the adapted 3D model is identical to the original CAD model. If a high level of requirement is expected for this criterion, the CAD model adaptation process should preserve the geometry of the model within an acceptable tolerance. If a high visualization quality is also expected, it will be necessary to compromise.

*Level of details and realism criteria.*This criterion is met when the rendering of the 3D model for V/AR is similar to those of the physical product. The adaptation process must then integrate functions, which allow all the details and realism to be transcribed.

Preservation of physics criteria. This criterion is met when the behavior of the 3D model is the same as the physical product. The adaptation process should preserve laws of physics, mechanics mechanical properties, and simulation models.

Facility of changes criteria. This criterion is met when changes on the original model (shape, dimensions, simulation parameters, metadata) can be transferred to the V/AR application. The adaptation process should enable easy and rapid changes, and if possible real-time changes.

Possible collaborative work criteria. This criterion is met when the adapted model allows onsite or distance collaborative work.

Fig. 1 gives expected high levels of requirements for some examples of adapted CAD models. This figure shows that requirements and CAD adaptation are specific to the V/AR objective.

2.2 Operations and Tools for CAD Adaptation

The main CAD adaptation methods are simplification, remodeling, or idealization.

The operations of simplification are multiples [27]: components removing, details removing and global simplification. Detail removing or defeaturing consists in removing details of the parts like holes, pockets, pads, fillets, chamfers or complexes faces. The purpose of global simplication is to reduce the number of faces and polygons of the overall part. Methods of global simplication are the creation of convex hull, decimation or faces clustering.

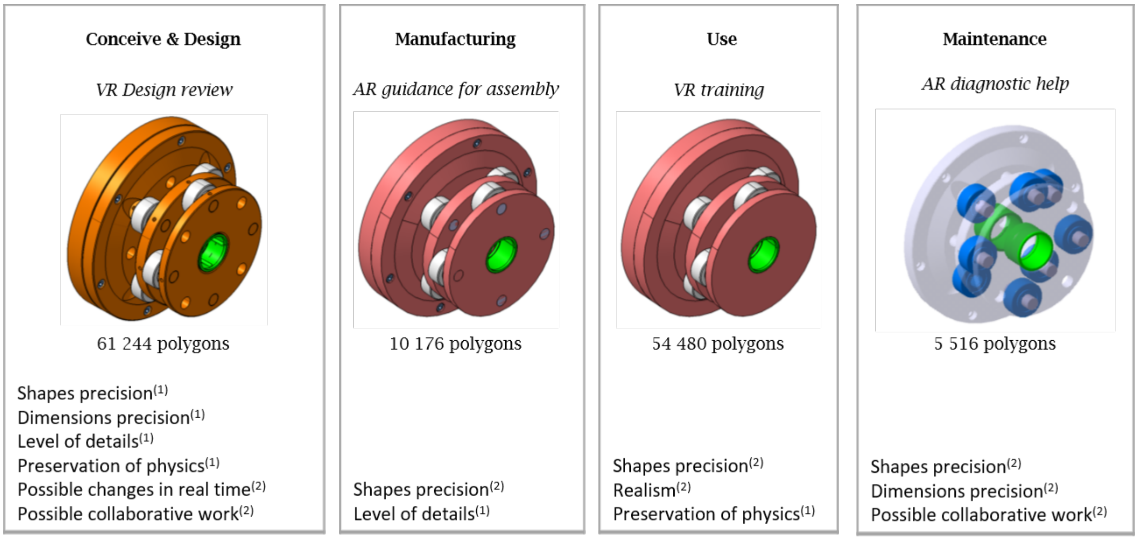


Figure 1: Examples of adapted models and requirements of V/AR applications in industry for different V/AR objectives. (1): Very high level of requirement, (2): high level of requirements

The operation of remodeling consists in creating a new simplified model without using the original CAD model. This operation is used when the simplification operations seem too heavy to implement.

The operation of idealization consists in reducing the dimension of the model in order to obtain a wire frame model, a 2D surface model, or a 3D surface model.

These adaptation operations can be realized by three main families of adaptation tools: CAD software, adaptation software, and computer graphic software. The choice of an adaptation tool is based on the quality criteria of the previous section, the adaptation time, and the cost of software.

The CAD software like *CATIA* [4], *NX Siemens* [7], Inventor [6], or CREO [5] allows to preserve all features of the original CAD model (shapes, dimensions, details, physic) and enables changes in real-time. The limits of adaption with CAD software are the high cost, the lack of performance of global simplification, and the poor quality of the rendering.

The adaptation software are specific tools for adaptation (*PIXYZ Studio* [8], **TechSoft3D HOOPS** [11], *3D Juump* [1]) or tools with effective adaptation features like *Rhino* [10]. They quickly simplify the CAD models with a high quality of rendering. The limits of these tools are the difficulty of achievement of details removing, and the lack of parameters for the simplification operations.

The computer graphic software (*Blender* [3], *3DSMAX* [2]) are widely used to generate 3D polygonal models for V/AR applications. The developers of the V/AR application tend to use them also for CAD adaptation. These tools offer a large number of features and parameters with a very high quality of rendering. Their limits are the adaptation duration and the need for mastering polygonal modeling. They are not easily accessible to SMEs. Furthermore, their file formats (polygonal model) differ from file formats of the original CAD model (surfaces B-Rep). This makes it difficult to change the adapted model when the original CAD model is modified.

The use of a single tool is generally not satisfactory. If the CAD software is used alone, the quality of the adapted model is usually poor, the number of polygons is too large for the V/AR devices, and the quality of the rendering is poor. Using adaptation software alone gives a good rendering, but the number of details is too large. That can slow the V/AR visualization or make it impossible. Using computer graphic software alone

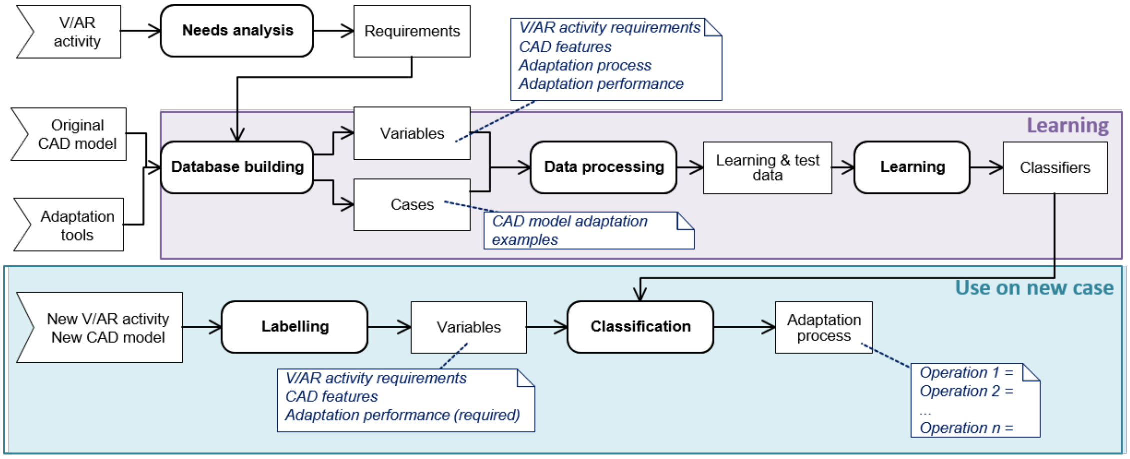


Figure 2: Framework to choose a CAD model adaptation process for V/AR using classification techniques

is very time-consuming. The combination of these tools allows to benefit from the interests of all tools. It is often necessary to use several adaptation operations and tools simultaneously. A CAD adaptation process can therefore be modeled by a combination of operations and tools. We end up with a large number of possible processes. The developer of V/AR application applies the first workable process that he finds, although the process is not optimized. Figure 3a gives some examples of not-optimized adaptation processes. The following section aims to propose a method for helping the developer of V/AR application to adapt the CAD model while respecting all the criteria of quality, time, and cost.

3 METHOD TO CHOOSE A CAD MODEL ADAPTATION PROCESS FOR V/AR USING CLASSIFICATION TECHNIQUES

3.1 Overall Approach

The overall approach includes two main stages. First, machine learning techniques are used on labeled data to configure classifiers that can predict the adaption process. At a later stage, the configured classifiers propose a set of adaptation operations for a new case of CAD model adaptation (new CAD model or new V/AR activity) that respect all requirements on quality, cost, and time. The learning method is based on four main steps (Fig. 2). The first step consists in formalizing the requirements related to the V/AR activities. Then, a learning database is built by describing the requirements, the original CAD models, the adaptation processes, and the adaptation performance. Learning data are labeled and compiled in a matrix (Tab. 1). Each row of the matrix represents a case that describes a known case of component CAD model adaptation for a specific V/AR activity. Columns of the matrix represent vectors of variables that describe requirements (objective of V/AR activities, required quality criteria), original CAD models, adaptation operations and their performance (levels of satisfaction, adaption time). In a third step, a set of tools for data processing is applied (e.g. normalization, reduction). This processing will allow adapting the data to the learning algorithms. This will also reduce the database to the variables that most influence the choice of the adaptation process. The next learning step consists in configuring classifiers for the choice of adaptation operations. These steps are described in detail in the following sections.

Variables:	V/AR Objectives	Quality Criteria	Satisfaction Levels	CAD Features	Adaptation Operations	Adaption Time
Values:	Qualitative	Numeric	Numeric	Numeric	Qualitative	Numeric
Known case 1:	$Xvar(1)$	$Xreq,1(1)$: $Xreq,6(1)$	$Xq,1(1)$: $Xq,8(1)$, $Xsq(1)$	$Xcad,i(1)$	$Yop,0(1)$: $Yop,5(1)$	$Ytim(1)$, $Xst(1)$
Known case 2:	$Xvar(2)$	$Xreq,1(2)$: $Xreq,6(2)$	$Xq,1(2)$: $Xq,8(2)$, $Xsq(2)$	$Xcad,i(2)$	$Yop,0(2)$: $Yop,5(2)$	$Ytim(2)$, $Xst(2)$
New case a:	$Xvar(a)$	$Xreq,1(a)$: $Xreq,6(a)$	$Xq,1(a)=1$: $Xq,8(a)=1$, $Xsq(a)=1$	$Xcad,i(a)$	$Yop,0(a)=?$: $Yop,5(a)=?$	$Ytim(a)=?$, $Xst(a)=1$

Table 1: matrix for learning (known cases) and prediction (new cases) database

3.2 Need Analysis and Requirement Data

In order to meet the needs of the V/AR application user, the 3D model must be specifically adapted to the purpose of the V/AR activity. For each model, it will be necessary to start by analyzing the objectives of V/AR and its need. Then, the quality of the adapted models can be evaluated. All this information is compiled in the learning database, using a set of variables related to requirements (Tab. 1): $Xvar$, $Xreq,i$, Xq,i, and Xsq.

$Xvar$ is a qualitative variable that describes the objective by specifying: i) the type of application (AR or VR), ii) the product life phase (design, manufacturing, maintenance, or service), iii) the type of activity (visualization, review, assistance, or training).

$Xreq,i$ is a vector of six variables that represents the expected level of quality criteria in connection with the CAD model adaptation. The quality criteria of an adapted model are described in Sec. 2.1 and Tab. 2. The levels of requirements are : low ($Xreq,i=0$), medium ($Xreq,i=0.25$), high ($Xreq,i=0.75$), and very high ($Xreq,i=1$). The meanings of low and very high level of requirements are detailed in Tab. 2.

Xq,i is a vector of six variables that gives the satisfaction level of the adapted 3D model for each criterion $Xreq,i$. The variable Xq,i is 0 if the result doesn't meet the criterion; $Xq,$ is 0.5 if the result partially meets the criterion; Xq,i is 1 if the result fully meets the criterion; Xq,i is 1.5 in case of over-quality. The global level of satisfaction Xsq is evaluated from the weighted average by factors wi (Tab. 2).

Tab. 7 gives examples of values for these requirement criteria $Xreq,i$, Tab. 8 gives their respective level of satisfaction Xq,i. For the example "part 1", a same preparation for two different objectives of V/AR application leads to an over-quality for one objective (AR guidance) and an under-quality for the other (VR training). This shows the necessity of taking into account the need for the application of V/AR when preparing the CAD model.

3.3 Database Building: Adaptation Processes

The operations and tools used for the adaptation of CAD model for V/AR applications were presented in Sec. 2.2. An adaptation process will be described by a sequence from one to several operations. The processes adaptation are described in the learning database using a vector of six variables Yop,n for the description of the operations and two variables of duration $Ytim$ and Xst . The qualitative variable $Yop,0$ specifies the main adaptation method according to three classes : $Yop,0=1$ for model simplification method, $Yop,0=2$

Requirements:	Weight	Low or no requirements (Xreq,i=0)	Very high requirements (Xreq,i=1)
$Xreq,1:$ visualizations quality	$w1 = 1$	No visualization requirements	No latency or discomfort during visualization
$Xreq,2:$ shapes, dimensions precision	$w2 = 0.8$	The adapted and original CAD model may differ	The adapted model is completely identical to the original CAD model
$Xreq,3:$ level of details and realism	$w3 = 0.8$	A schematic representation is sufficient	The adapted model has the same rendering as the physical product
$Xreq,4:$ physics preservation	$w4 = 0.6$	No physics requirements	The adapted model behavior is the same as the physical product
$Xreq,5:$ changes facility	$w5 = 0.5$	No change is required	Real-time changes on adapted model are possible
$Xreq,6:$ possible collaborative work	$w6 = 0.5$	No collaborative work is required	All collaborative works is possible

Table 2: Criteria of quality requirements of the 3D model for a V/AR activity

for idealization method, $Yop,0 = 3$ for remodeling method. The five following variables Yop,n describe operations by specifying the used tool and the adaptation function. These qualitative variables are written as two characters $Tx.Px$ (tab. 3). The first character Tx specifies the used tool and potentially the used function. The second character Px specifies the parameters of the adaptation function.

The quantitative variable $Ytim$ is the duration (number of hours) of the adaptation. The variable Xst gives the acceptability of the adaptation duration, considering the complexity of the CAD model: $Xst = 1$ if the duration of adaptation is very fast or fully acceptable, $Xst = 0.75$ for a fast adaptation, $Xst = 0.25$ for a slow adaptation, and $Xst = 0$ for a very slow or unacceptable adaptation.

Tab. 9 gives examples of values for variables Yop,n, $Ytim$, and Xst that characterize adaptation processes.

Today, choosing an adaptation process is often an arbitrary decision. The performance of the adaptation is therefore unsatisfactory. The objective of this work is to predict the output variables Yop,n with levels of satisfaction on quality Xsq and duration Xst closed to 1.

3.4 Database Building: Original CAD Model for use in V/AR Application

When the designer of V/AR application prepares a CAD model, he uses subjective criteria to choose his adaptation operations. These criteria are related to the size and shape of each component, and the overall product. To achieve this it is necessary to formalize these subjective criteria into variables that can be used by machine learning tools. Each component of the original CAD model that is a candidate for adaptation is described from a set of features: size features, shape features, and product features.

Size features provide information on the size of the component, this will allow comparing the size of the candidate for adaptation with the other components and with the overall model. The variables that characterize the size are area, volume, and lengths. These features inform if the adaptation candidate is small or not.

	Tx	Px
$Yop, 1$ components removing	$T1 = CADsoft$ $T2 = Adaptsoft$ $T3 = CGsoft$	$P1 =$ hidden components are deleted $P2 =$ hidden and small components are removed $P3 =$ only the main components are kept
$Yop, 2$ details removing and local simplification	$T11 = CADsoft$ (feature removing) $T12 = CADsoft$ (surface reconstruction) $T2 = Adaptsoft$ $T3 = CGsoft$	$P1 =$ hidden details are deleted $P2 =$ hidden and small details are removed $P3 =$ all details are deleted
$Yop, 3$ global simplification	$T1 = CADsoft$ $T2 = Adaptsoft$ $T3 = CGsoft$	$R =$ ratio of polygons numbers between adapted and original model $P1 = R < 15\%$ $P2 = 15\% < R < 40\%$ $P3 = 4\% < R < 65\%$ $P4 = 65\% < R < 90\%$ $P5 = R > 90\%$
$Yop, 4$ idealization	$T11 = CADsoft$ (geometry retrieval) $T12 = CADsoft$ (remodeling) $T21 = Adaptsoft$ (geometry retrieval) $T22 = Adaptsoft$ (remodeling) $T3 = Cgsoft$ (remodeling)	$P1 =$ wire frame idealization $P2 =$ 2D surface idealization $P3 =$ 3D surface idealization
$Yop, 5$ remodeling	$T1 = CADsoft$ $T2 = Adaptsoft$ $T3 = CGsoft$	$P1 =$ remodeling with conservation of shapes and dimensions (distances between original and remodeled model $<$ 5% of model length) $P2 =$ remodeling with conservation of shapes $P3 =$ approximate remodeling

Table 3: Variables of adaptation operation for learning Database ($CADSoft =$ CAD software, $Adaptsoft =$ adaptation software, $CGsoft =$ Computer graphic software)

Product features provide information on the component compared to the other components (e.g. visibility of component, number of similar components in the product, links with other components). Size and product features thus help the designer decide on the removal or the preservation of the component.

Shape features provide information on the shape and the complexity of the component. These characteristics are determined from physical quantities such as compactness, curvatures, number of faces, number of details, or the ratio between these physical quantities. The more complex a model is, the more difficult and time-consuming it is to adapt. Knowing the complexity of the model should help estimate the quality and the duration of the adaptation operations.

Each feature is labeled to be a potential variable for learning and classification. Thus, the database initially contains a set of 34 $XCAD, j$ variables, j is the index of the variable. Initially, these variables were chosen to best characterize a CAD model, ensuring that two CAD models with even a small difference do not have the same values on one or more variables. At this stage, we do not know which variables will influence the choice of process adaptation. This point is discussed in the next section.

3.5 With F1 Data Processing and Learning

Data processing first consists in transforming all qualitative data in quantitative data. Then operations of normalization and repair of missing or aberrant data are applied. The main purpose of data processing is the selection of variables that influence the choice of the adaptation process. Principal Component Analysis gives projections of variables on factorial plans. These plans and correlation matrix make it possible to identify the correlated variables with each other and their correlation coefficient. In practical terms, the weakly correlated variables (correlation coefficient between -0.3 and $+0.3$) with the variables relating to the adaptation process (Yop, n, Xsq, Xst, and $Ytim$) are deleted. Then if two variables are strongly correlated with each other (correlation coefficient greater than $+0.6$), the variable the least correlated with the variables relating to the adaptation process is deleted. Thus, these methods allow identifying among the 34 $XCAD, j$ variables, the most influential variables on the Yop, n, Xsq, Xst, and $Ytim$. This will improve the performance of the classification and facilitate future data setting.

The learning step consists in selecting and configuring classifiers to predict the best operation sequence for a new CAD model or a new V/AR objective. These classifiers will have to predict the classes of the six variables which describe the process adaptations ($Yop, 0$ to $Yop, 5$) as well as the duration of the operations $Ytim$. Data are partitioned into a group for learning (80% of cases) and into a group for tests (20% of cases). The total number of cases is not very high. The k-fold cross-validation method (with $k = 10$) improves the classification performance. Various classifiers are tested and then optimized: Decision Tree, Artificial Neural Network, and Support Vector Machines. Classifiers are evaluated with the group of cases for tests using criteria of prediction errors and F1 scores. F1 score (Eq. (1),Eq. (2),Eq. (3)) is calculated for each class of variables to be estimated from the numbers of true positives (TP), true negatives (FN) and false negatives (FN) for a class "x". The classification better if the F1 score is closed to 1.

$$F1Score = \frac{2 * Precision * Recall}{Precision + Recall} \tag{1}$$

$$Precision(class = x) = \frac{TP(class = x)}{TP(class = x) + FP(class = x)} \tag{2}$$

$$Recall(class = x) = \frac{TP(class = x)}{TP(class = x) + FN(class = x)} \tag{3}$$

Among the prediction errors, we will distinguish the results for which the performance of the adaptation is degraded and those that lead to an over-quality. A classifier whose errors lead to a degradation of quality will not be retained. The best classifier will be used to predict the adaptation process on new cases.

3.6 Classification for a New Case

For a new CAD model or a new V/AR activity, the CAD model is first divided into several components (single part or sub-assemblies). Each component is a new case for the prediction of the adaptation process. For each component, known variables ($Xvar$, $Xreq$ and $Xcad$) are labeled. The satisfaction levels of quality and time (Xq, Xsq, Xst) are set to 1. The configured classifiers first predict the $Yop,0$ variable giving the overall process of adaptation: $Yop,0 = 1$ for simplification, $Yop,0 = 2$ for idealization, and $Yop,0 = 3$ for remodeling.

Then according to the previous result, the variables $Yop,1$ to $Yop,5$ and $Ytim,1$ to $Ytim,5$ are predicted or forced to the value of 0 when the operation is not used (tab. 9). This gives the complete adaptation process and its duration for each component. By using this method for all the components, the overall adaptation process and its duration are known for the entire CAD model. The proposed adaptation operations are optimal without compromise. Therefore, the developer of the V/AR application can follow the proposed process.

4 RESULTS

4.1 Uses Cases

We evaluated the proposed method on two V/AR applications and on four different CAD models. Application supports belong to the field of manufacturing (part of machine tool, 3D printing machine, robot, part of special machine). The first V/AR application was an AR application for the guidance of the operator during the assembly of a mechanical device. The second V/AR application was a VR application for training during manufacturing. The first three supports were used to create the learning database. The three CAD models were divided into 75 components (single parts and sub-assemblies). Each component has been adapted for the two V/AR objectives with different methods or tools of adaptation. In the end, the learning database contains 600 cases of adapted CAD models. The last support (indexer system of Fig. 1 and Fig. 3) was used for the tests of classification on new cases and the general validation of the method. Tools for adaptation are CATIAV5 [4] (CAD software), Pixyz [8] (adaptation software), and 3DSMax [2] (computer graphic software).

4.2 Influencing Variables Selection

Principal component analysis and correlation matrix were obtained using the software *R* [9] and its packages *FactoMineR*, *FactoExtra*, and *Hmisc*Hmisc. Principal component analysis and correlation matrix allowed the reduction of the $Xcad$ variables number from 34 to 6 variables: faces number, box volume, ratio of volumes between component and product, ratio of areas, compacity, and ratio between number of triangles and area. Tab. 4 provides the meaning of these six variables and their coefficients of correlation with the variables that characterize the adaptation process ($Xvar$, $Yop,0$, Yst, and Ysl). All selected variables are correlated with at least one of the characteristic variables (correlation coefficient: $r < -0.6$ or $r > +0.6$). These variables are not correlated with each other.

4.3 Classification and Use on New Cases

Classifiers have been configured and tested with the packages *caret*, *nnet*, *rpart*, and *e1071* of the *R* software. The best classifier is a Support Vector Machines algorithm with a sigmoid kernel. Tab. 5 and Tab. 6 show acceptable prediction errors and high F1 scores for this classifier. The F1 score of the $Yop,4$ variable remains insufficient. This is explained by the low number of cases of adaptation that implement the operation of idealization. The addition of new cases in the database should improve these scores.

Fig. 3 gives examples of the use of our method for two parts and two V/AR activities. For each part, a first process is proposed by the developer without the prediction tool. A second process is predicted with our method

Xcad selected variables:	Correlation coefficients: $Xvar$	$Yop,0$	Xst	Xsq
Faces Number = number of faces of the component	**0.85**	0.13	0.52	**0.76**
Box Volume = volume of the bounding box of the component	-0.22	0.12	0.51	**0.66**
Volumes Ratio = $\frac{Volume(component)}{Volume(product)}$	-0.25	0.02	-0.26	**-0.61**
Areas Ratio = $\frac{Area(component)}{Area(bounding.box)}$	-0.72	0.13	**0.61**	0.44
Compacity = $\frac{Volume(component)^2}{Area(component)^3}$	**-0.61**	**-0.83**	-0.36	-0.58
Triangles Area Ratio = $\frac{Triangle.Number(component)}{Area(component)}$	**0.73**	**-0.65**	-0.21	0.25

Table 4: selected variables describing the size and shape features of CAD models and correlation coefficients with others variables

F1 scores mini − maxi :	$Yop,0$	$Yop,1$	$Yop,2$	$Yop,3$	$Yop,4$	$Yop,5$
Neural network (nnet package):	0.46−0.95	0.32−0.95	0.36−0.95	0.41−0.95	0.33−0.85	0.42−0.92
Decision tree (rpart package):	0.79−1	0.62−1	0.73−1	0.75−1	0.47−0.9	0.52−0.9
SVM (e1071 package):	0.92−1	0.79−1	0.86−1	0.90−1	0.5−1	0.72−1

Table 5: minimum and maximum F1 scores for tested classifiers

Prediction errors :	$Yop,0$	$Yop,1$	$Yop,2$	$Yop,3$	$Yop,4$	$Yop,5$
Total:	3.20%	16.60%	9.10%	7.50%	35%	42%
Giving an over quality:	3.20%	5.80%	3.30%	4.20%	31%	23%
Reducing the quality:	0%	10.80%	5.80%	3.30%	4%	19%

Table 6: Predictions errors of SVM classifier

taking into account the purpose of the application. Tab. 7 gives the values of variables that characterize the need for each application purpose. The Fig. 3 gives the used adaptation process ($Yop, 0$ variable), the quality level of the adaptation (Xsq variable), and the duration in number of hours of the process ($Ytim$ variable). Tab. 8 gives the levels of quality Xq, i and Xsq, which correspond to proposed model by the developer without predictions (with predictions these values are equal to 1). The predicted operations of adaptation are detailed in table 9. Regarding the part 1 without prediction, the designer of V/AR application re-models the part, using computer graphic software and keeping all the details as a precaution. This leads to an over quality and a waste of time. The predicted adaptation process for the objective of AR guidance, consists in transforming the CAD model into a 2D surface containing all the details. Lighter, the model is no longer over-quality. For the objective of VR training, the predicted adaptation process consists in removing all details. The result is completely satisfactory for the intended objective and the time saving is significant. Regarding the part 2, the designer of the V/AR application simplifies the sub-assembly by first removing small details and then reducing the number of polygons. The result is unsatisfactory because the requirements are not taken into account (conservation of details like screws for AR guidance and precision of shapes for VR training). On the other hand, these requirements are well respected for models with predicted adaptation processes. In summary, for these examples, the prediction of the adaptation process provides an adaptation with a level of quality that perfectly meets the need. Our method can also save time by identifying more precisely the details to be simplified.

	$Xvar$	$Xreq,1$	$Xreq,2$	$Xreq,3$	$Xreq,4$	$Xreq,5$	$Xreq,6$
Part 1 AR guidance	AR	0.25	0.75	1	0	0	0
Part 1 VR training	VR	0.25	0.75	0.75	1	0	0.25
Part 2 AR guidance	AR	0.25	0.75	1	0	0	0
Part 2 VR training	VR	0.25	0.75	0.75	1	0	0.25

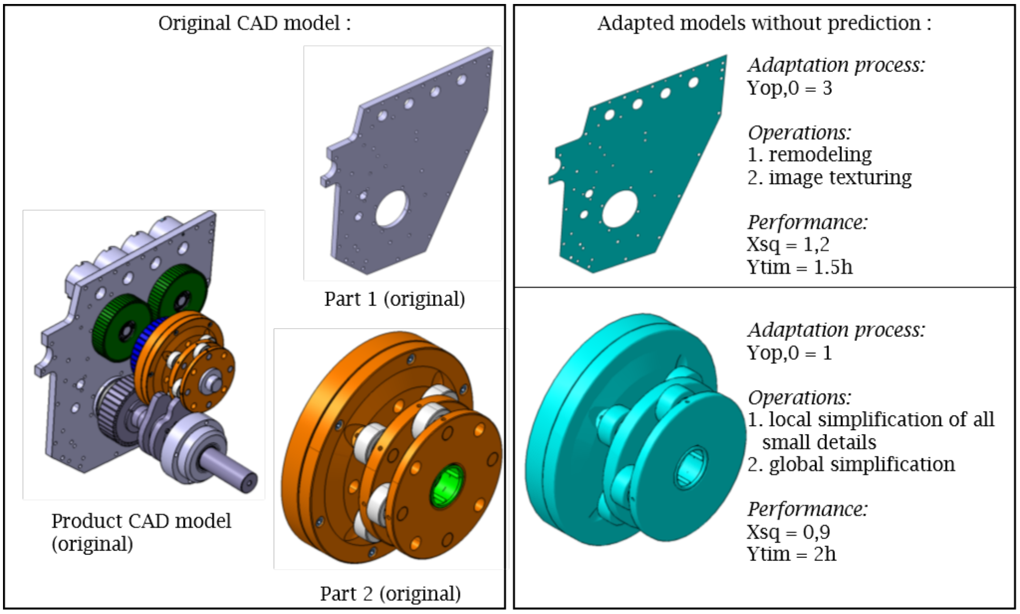
Table 7: Examples of vectors of requirements variables ($Xreq, i$) (Part 1 and Part 2 of Fig.3)

	$Xq,1$	$Xq,2$	$Xq,3$	$Xq,4$	$Xq,5$	$Xq,6$	Xsq
Part 1 AR guidance	1.5	1.5	1	1	1	1	1.2
Part 1 VR training	0	0.5	1	0.5	1	1	0.6
Part 2 AR guidance	0.5	1	1	1	1	1	0.9
Part 2 VR training	1	1	1	0.5	1	1	0.9

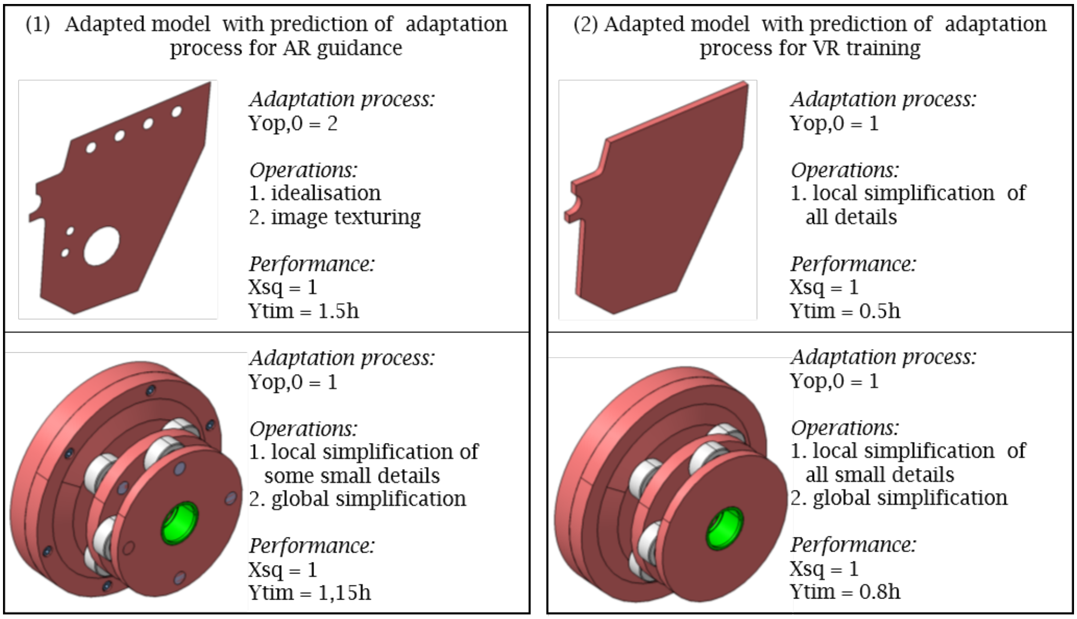
Table 8: Examples of vectors of levels of quality (Xq, i and Xsq) for a without prediction adaptation (Part 1 and Part 2 of Fig.3)

5 CONCLUSIONS

In this paper, a classification method for the choice of a CAD model adaptation process for virtual reality had been developed. Our objective is to assist the developers of VR applications in choosing a process for adapting a CAD model taking into account the specific need of the VR application. The commercial tools are very powerful, but the user must be guided in the choice of parameters (elements to remove, elements to simplify, level of simplification, and so on). The idea is to use machine learning techniques first to select the variables



(a) Original and adapted model without prediction



(b) adapted model with prediction of adaptation processe

Figure 3: Examples of use on new case

that influence the choice of the adaptation process among all variables that describe a CAD model. While the designer relies on subjective criteria to choose the adaptation operations, our method allowed to identify the correlations between the characteristics of the CAD model, the type of process adaptation, its quality,

	$Yop,0$	$Yop,1$	$Yop,$	$Yop,3$	$Yop,4$	$Yop,5$	$Ytim$	Xst
Part 1 (0)	3	0	0	0	0	Yop,1	1.5h	0.25
Part 1 (1)	2	0	0	0	T11-P2	0	1.5h	0.25
Part 1 (2)	1	0	T11-P3	0	0	0	0,5h	1
Part 2 (0)	1	0	T3-P2	T3-P3	0	0	2h	0.25
Part 2 (1)	1	T1-P1	T11-P1	T2-P3	0	0	1.15h	0.75
Part 2 (2)	1	T1-P2	T11-P2	T2-P3	0	0	0.8h	1

Table 9: Examples of vectors of variables describing the adaptation operations, (0) = without prediction and all V/AR objectives, (1) = with prediction for AR guidance, (2) = with prediction for VR training (Part 1 and Part 2 of Fig.3)

and its duration. Then machine learning techniques are used to configure a set of classifiers that can predict the overall adaptation process, each adaptation operation and their durations. The results of classification obtained on new cases are promising. The first classifier predicts with very good accuracy the overall process of adaptation. The accuracy of the classification that predicts the different adaptation operation depends on the number of cases for each operation in the learning database. In the future, new cases will fuel this database, which will make it possible to have a greater number of cases and thus improve the precision of the classifications. One challenge was to propose a specific adaptation process by taking into account the requirements of the V/AR activity. In addition to taking as input the variables that describe the CAD model, the classifiers take into account the requirements specific to the intended V/AR application. Our results show that the predicted adaptation processes are well different depending on the activity and this process meets the needs of the user.

The adaptation operations essentially consist in simplifying the CAD model globally or on the details of the model. By maintaining the right level of necessary detail for the final application of V/AR, the risks of having a degraded model (e.g. inverted normals, deformed surfaces, formation of holes, or too many polygons) are limited. In addition to ensuring a good quality of the adapted model, the proposed method makes it possible to know a priori the adaptation process without having to test it beforehand in the final application of V/AR. This avoids long iterations between CAD software, adaptation tools, and V/AR application creation tools. Therefore, this method helps the developer to adapt the CAD model at the best cost and with an ideal level of satisfaction for the final user. In the end, this should facilitate the deployment of V/AR techniques in the industry. With our method, the process of operations is predicted before operations are carried out. In future work, we could predict the $n+1$ operation in real-time by taking into account the actual result of the n operation.

ORCID

Florence Danglade, http://orcid.org/0000-0002-8281-1004
Christophe Guillet, http://orcid.org/0000-0001-8104-4600

REFERENCES

[1] 3D Juump. https://www.akka-technologies.com/digital-mock-up/.
[2] 3DS MAX. https://www.autodesk.fr/products/3ds-max/overview.
[3] Blender. https://www.blender.org.

[4] CATIA. http://www.3ds.com/products-services/catia/.

[5] CREO. https://www.ptc.com/en/products/creo.

[6] Inventor. https://www.autodesk.com/products/inventor/overview.

[7] NX. https://www.plm.automation.siemens.com/global/fr/products/nx/.

[8] Pixyz Studio. https://www.pixyz-software.com.

[9] R. https://www.r-project.org/.

[10] Rhino. https://www.rhino3d.com.

[11] TechSoft3D HOOPS. https://www.techsoft3d.com/markets/ar-vr/.

[12] Alcacer, V.; Cruz-Machado, V.: Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems. Engineering Science and Technology, an International Journal, 22(3), 899–919, 2019. http://doi.org/10.1016/j.jestch.2019.01.006.

[13] Bourdot, P.; Convard, T.; Picon, F.; Ammi, M.; Touraine, D.; Vezien, J.M.: VR-CAD integration: Multimodal immersive interaction and advanced haptic paradigms for implicit edition of CAD models. CAD Computer Aided Design, 42(5), 445–461, 2010. http://doi.org/10.1016/j.cad.2008.10.014.

[14] Chotrov, D.; Maleshkov, S.: Simultaneous bidirectional geometric model synchronization between CAD and VR applications. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 8034 LNCS(PART 2), 288–297, 2013. http://doi.org/10.1007/978-3-642-41939-3_28.

[15] Damiani, L.; Demartini, M.; Guizzi, G.; Revetria, R.; Tonelli, F.: Augmented and virtual reality applications in industrial systems: A qualitative review towards the industry 4.0 era. vol. 51, 624–630, 2018. http://doi.org/10.1016/j.ifacol.2018.08.388.

[16] Danglade, F.; Pernot, J.P.; Veron, P.; Fine, L.: A priori evaluation of simulation models preparation processes using artificial intelligence techniques. Computers in Industry, 91, 45 – 61, 2017. http://doi.org/https://doi.org/10.1016/j.compind.2017.06.001.

[17] Danglade, F.; Veron, P.; Pernot, J.P.; Fine, L.: Estimation of CAD model simplification impact on CFD analysis using machine learning techniques. 1–5, 2015.

[18] Dini, G.; Mura, M.D.: Application of Augmented Reality Techniques in Through-life Engineering Services. vol. 38, 14–23, 2015. http://doi.org/10.1016/j.procir.2015.07.044.

[19] Fraga-Lamas, P.; Fernandez-Carames, T.M.; Blanco-Novoa, O.; Vilar-Montesinos, M.A.: A Review on Industrial Augmented Reality Systems for the Industry 4.0 Shipyard. vol. 6, 13358–13375, 2018. http://doi.org/10.1109/ACCESS.2018.2808326.

[20] Horejsi, P.: Augmented Reality System for Virtual Training of Parts Assembly. vol. 100, 699–706, 2015. http://doi.org/10.1016/j.proeng.2015.01.422.

[21] Kerin, M.; Pham, D.T.: A review of emerging industry 4.0 technologies in remanufacturing. Journal of Cleaner Production, 237, 117805, 2019. http://doi.org/10.1016/j.jclepro.2019.117805.

[22] Lorenz, M.; Spranger, M.; Riedel, T.; Purzel, F.; Wittstock, V.; Klimant, P.: Cad to vr-a methodology for the automated conversion of kinematic cad models to virtual reality. In Procedia CIRP, vol. 41, 358–363, 2016. http://doi.org/10.1016/j.procir.2015.12.115.

[23] Martin, P.; Masfrand, S.; Okuya, Y.; Bourdot, P.: A vr-cad data model for immersive design the crea-vr proof of concept. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 10324 LNCS, 222–241, 2017. http://doi.org/10.1007/978-3-319-60922-5_17.

[24] Okuya, Y.; Ladeveze, N.; Fleury, C.; Bourdot, P.: ShapeGuide: Shape-Based 3D Interaction for Parameter

Modification of Native CAD Data. Frontiers in Robotics and AI, 5, 118, 2018. http://doi.org/10.3389/frobt.2018.00118.

[25] Stark, R.; Israel, J.H.; Wohler, T.: Towards hybrid modelling environments merging desktop cad and virtual reality-technologies. vol. 59, 179 – 182, 2010. http://doi.org/http://dx.doi.org/10.1016/j.cirp.2010.03.102.

[26] Tang, Y.; Xu, Y.; Yuan, L.L.: Geometry modeling for virtual reality based on cad data. Open Cybernetics and Systemics Journal, 9, 2339–2343, 2015.

[27] Thakur, A.; Banerjee, A.G.; Gupta, S.K.: A survey of cad model simplification techniques for physics-based simulation applications. Computer-Aided Design, 41(2), 65–80, 2009. http://doi.org/http://dx.doi.org/10.1016/j.cad.2008.11.009.

[28] Wolfartsberger, J.: Analyzing the potential of Virtual Reality for engineering design review. Automation in Construction, 104, 27–37, 2019. http://doi.org/10.1016/j.autcon.2019.03.018.

[29] Xue, J.; Zhao, G.: Interactive rendering and modification of massive aircraft cad models in immersive environment. Computer-Aided Design and Applications, 12(4), 393–402, 2015. http://doi.org/10.1080/16864360.2014.997635.