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INFLUENCE OF CURVES AND SURFACE OPTIONS ON PARAMETERS OF MODELLING AND ANALYSIS FOR NON FUNCTIONAL PARTS IN REVERSE ENGINEERING APPLICATIONS

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Abstract
In Reverse engineering applications, a physical object is scanned using CMM and cloud points are obtained. Section curves, guide curves, surfaces, closed surfaces and solids are developed from the cloud points. Selection of appropriate curve and surface options influence physical parameters viz., curve length surface area and volume. In this work a specific curve combination is considered and the physical parameters are numerically evaluated for lofted and coons surface options. The number of sections is either two or three. The applicability of these surface options for non-functional parts such as sauce dispenser etc., are studied. The variation and error percentage are obtained for comparing surface area, volume and section curve. Also the models are analyzed for deflection and vonmises stress. The percentage error in deflection, minimum stress and maximum stress corresponding to different curves and surface options are determined for illustration.
Keywords: section curves, guide curves, lofted surface, coons surface, physical parameter.

Nomenclature

$(SS)_L$	Lofted surface area in single section (mm^2)
$(MS)_L$	Lofted surface area in multi section (mm^2)
$abs(\varepsilon)_L$	Absolute variation in lofted surface between single and multi-section (mm)
$(\%\varepsilon)_L$	Percentage error in lofted surface between single and multi-section
$(SS)_C$	Coons surface area in single section (mm^2)
$(MS)_C$	Coons surface area in multi section (mm^2)
$abs(\varepsilon)_C$	Absolute variation in coons surface between single and multi-section (mm)
$(\%\varepsilon)_C$	Percentage error in coons surface between single and multi-section
ASCL	Actual section curve length (mm)
ELSCL	Extracted lofted surface curve length (mm)
$abs(\varepsilon Si)_L$	Absolute variation in lofted surface between ASCL and ELSCL (mm)
$(\%\varepsilon Si)_L$	Percentage error in lofted surface between ASCL and ELSCL
ECSCL	Extracted coons surface curve length (mm)
$abs(\varepsilon Si)_C$	Absolute variation in coons surface between ASCL and ECSCL (mm)
$(\%\varepsilon Si)_C$	Percentage error in coons surface between ASCL and ECSCL
$abs(\varepsilon)_{LC}$	Absolute variation in lofted and coons surface (mm)
$(\%\varepsilon)_{LC}$	Percentage error in lofted and coons surface
$abs(\varepsilon Si)_{LC}$	Absolute variation in lofted and coons surface between ELSCL and ECSCL (mm)
$(\%\varepsilon Si)_{LC}$	Percentage error in lofted and coons surface between ELSCL and ECSCL
L	Lofted surface
C	Coons surface

LC	Lofted and Coons surface

Introduction

Reverse engineering (RE) is used to develop the CAD model from an existing component. Rapid prototyping (RP) is used to manufacture the component from the CAD model by material adding process. Non-functional components such as containers having complex three dimensional structures for petroleum transit can be modeled using RE. Also complex shapes used in domestic container are easily developed using RE so as to provide aesthetic appeal. However Physical parameters namely volume of component is to be maintained within limits stringently so as to contain the required quantity of filling material. Similarly the surface area needs to be minimized as it determines the volume of raw material (especially for hollow components with uniform and smaller thickness) required for manufacturing the component by RP. Similarly the variations in section curve length can make the part design ergonomically poor for manual handling of domestic container and hence gross variations in section curve length needs to be avoided.

CMM is used to scan such component and obtain the point cloud data set. Section curves, guide curves, surfaces, closed surfaces and solid are fitted over the cloud data set after noise filtering. Lofted (Ruled) surface and Coons surface options are used to obtain the solid from the section curves and guide curves. The curves and surface options influence the above mentioned physical parameter significantly.

Coons surface is developed by four boundary curves Suhas Subramanya describe that four positional vectors eight tangent vector and four twist vectors are required to create coons surface. Richard Southern and Neil A. Dodgson Used a two-step method in which, smooth vertex patches are initially defined by extrapolating and then blending a univariate or bivariate surface representation.

In medical applications a copy of the fracture or a deformity in a bone with complex geometry can be accurately and rapidly manufactured by integrating (RE) and RP [1]. As it difficult to use correct surface option in developing the solids from the CMM could point data an alternative method (Stereo Lithography Apparatus) is widely used where in a component is manufactured directly from could point data.

Reconstruction of biological surfaces such as the surface of skull is carried out in RE using triangular mesh or polygonal mesh [2]. In contrast surfaces in engineering components are modeled in RE by fitting various surfaces such as lofted and coons surfaces. Korosec et al [3] attempted the optimization of accuracy in surface fitting by minimizing the standard deviation of error. They reported that accuracy of the scanned surface varies with surface angle. Li and Gu [4] made an extensive review on free form surface inspection techniques by considering the comparison between the measurement surface and the design model constructed using NURBS surfaces. Zhongwei [5] highlighted the following properties of NURBS or B-spline curves and surfaces that make it widely used for modeling of free form surfaces.

1. Strong convex hull properties i.e., the curve lies within the convex hull of control points.
2. Local approximation i.e., if a control point is moved it affects only the portion of the curve in the specified interval.

Varady [6] discussed the various issues including segmentation and surface fitting in RE of geometric modeling. An assumption made that the surface of an object can be natural broken down in to various component surfaces which meet along sharp or smooth edges. Segmentation describes the process of logical dividing original point set into subsets one for each natural surface so that each subset contain just those points sampled from a particular natural surface. Each surface is properly jointed to its neighbor by a boundary curve lying in each surface. Also they discuss four important approaches for free form segmentation as follows.

1. Global approximating surfaces
2. Curve network based surfaces

3. Arbitrary topology surfaces
4. Functional decomposed surfaces
5. The second approach is based on a curve network which divides up the surface by means of a series of characteristics curves, which my to be sharp edges of the boundary, lines of external curvature, lines of symmetry etc.

Nanya et al [7] used shape-from-silhouette method for reconstructing a voxel based 3d model from the silhouette of 2D images. Ishida et al [8] developed a new dive that utilizes electrical discharge machine to manufacture holes with various cross sections considering the obstacles in design of such holes in industrial product. Abe et al [9] proposed a new method of machine error compensation, wherein a 3D surface data of the machined part is modified according to the machine error measured by CMM. Tamaki et al [10] developed a method of replicating a snow crystal using a UV light-curing resin. Mizogughi et al [11] proposed an algorithm for detecting a common class of symmetries in engineering from scanned meshes of a verity of objects. [12] Analyzed an adequate number of design solution for medium – size pocked bearing.

Replication of object matching level is usually achieved by trial and error method. It takes a number of iteration steps to achieve an acceptable level of matching. In RE, the matching accuracy is usually evaluated qualitatively by superimposing the scanned data and CAD model.

Research on RE applied to widely varying industrial problems are reported in literature. Three dimensional measurements of the feet using laser based measuring head is reported by Novak and Babnik [12]. Semantic interoperability for product models created using Boolean operation on geometric features is discussed by Gupta and Gurumoorthy [13]. Application of RE using neutron tomography for the reconstruction of gas turbine parts is discussed by Roos and Quin [14]. Recovery of worn parts using reverse engineering is demonstrated with case studies on damaged cam and damaged turbine blade are reported by Bagci et al [15]. Three dimensional reconstructions of biological parts that have under gone complex fracture, for medical application is reported by Bagariaa and Deshpande [16]. RP of free formed components by modern forming using surface layered manufacturing is discussed in Yongnian and Shengjie [17]. Use of B-spline surfaces in integrating RE and RP techniques is discussed by Zhongwei et al [18]. A review of various free form surface technique including measurement data accusation method, surface description method, localization technique, inspection planning technique etc. are discussed by Li et al [19].

In RE qualitative and quantitative analysis of physical parameter are discussed in literature [15, 20-21].

In RE qualitative evaluation of matching accuracy between the scan data and CAD model is investigated through error map to study the repair volume of turbine blades [15].

Although various issues in reverse engineering applications are discussed in literature, results for comparison by the numerical evaluation of the mismatch level in physical parameters are not available in the literature. Such numerical evaluations will be useful to determine the matching accuracy in modeling non-functional parts such as sauce dispenser.

In this work the matching accuracy of the model is analyzed qualitatively and quantitatively in order to reduce the number of iterations. The physical parameters of the model such as length of section curve, surface area of surfaces and volume of solids are analyzed for matching accuracy.

Methodology

The qualitative analysis of matching accuracy is discussed in literature. The deviation of the RP manufactured component from that of the physical part is investigated in literature [20].To study the versatility of the manufacturing process. The influences of the deviation in the RP components on their structural performance as evaluated through stress analysis using finite element software is available in literature [21]. The cross-section distortion obtained from comparison of a CAD model and a scanned model of its used worn out blade are also in literature [15]. The distortion measured in mm unit and the extracted repair batch geometry along with its repair volume interns of error color maps are also presented in literature [22].

Considering the above studies a methodology is proposed in this paper to investigate the influence of selecting various surface options and number of sections on the fundamental physical parameters such as area and volume. In RE application the matching level is often evaluated by the designer through qualitative visual interpretation and hence there exists an ambiguity. In order to overcome this ambiguity a quantitative numerical evaluation of the matching accuracy in various physical parameters is proposed in this work. The physical parameters such as surface area, volume and section curve lengths are used for the quantitative evaluation. Components having circular section curve, having symmetry about Centre plane are Consider. The axis of the component is assumed to be a straight line passing through the centers of the circular section curves. The comparisons are carried out as follows for the quantitative numerical evaluation.

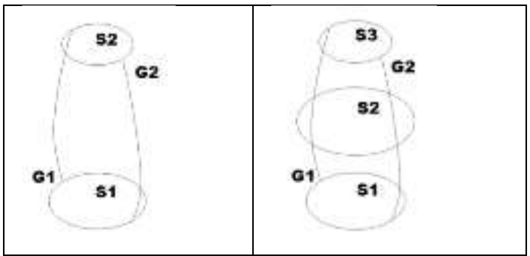
1. Comparison of surface area between that of single section and multi section models
2. Comparison of volume between that of single section and multi section models
3. Comparison of curve length between that of actual section curve and extracted section curve. (Actual curves are also termed as reference curves)

In this study, single section having two section curves with lengths S1, S2 and multi section having three section curves with lengths S1, S2 and S3 are considered as shown in Fig. 1. The three section curves are equally spaced along the axis/center plane. Similarly, two guide curves with lengths G1 and G2 are considered.

The details of the length of the curves for different combinations are given below.

Curve combination (CC): Length of section curve are different (S1≠S2≠S3) and guide curve are equal (G1=G2).

The curve lengths are randomly chosen in order to demonstrate the methodology. For instance the section curve length S1=185.045mm, S2=220.339mm and S3=135.841mm of CC are obtained as half the circumference of the circles having radii of 29.439mm, 35.054mm and 21.611mm respectively. Guide curve length are measured using measured tool in CATIAv5 as G1=G2=119.635mm. These values shown in Table 1 are used as reference to evaluate the mismatch between different surface options.



(a) (b)

Fig. 1. Curve Combination: (a) Single section; (b) Multi-section.

Table 1. Reference curve lengths and typical objects

Curve combinations	Section curve length and guide curve length	Applications	Typical object
CC	S1=185.045mm S2=220.339mm S3=135.841mm G1= G2= 119.635mm	Sauce dispenser	

2.1Procedure for modeling

The scanned cloud point's data in dxf format are imported to AUTOCAD software. The guide curve is drawn using two circles connected using tangency conditions each circle passing through three points that are randomly selected from the cloud point data. The co-ordinates of the Center and radius ofeach circle are measured using measure tool.

Parametric modeling of guide curve is carried out in CATIAv5. Using the co-ordinates of Center and radius the circles are drawn and connected using tangency condition. Two horizontal lines 116.668mm apart are drawn to intersect the circles. The circular arc that lies in between these two lines is retained and the remaining portion of circles is trimmed out using trim tool. Mirror command is used to obtain another curve which is exactly symmetrical (about y-axis) to the original guide curve.

Evaluation methodology of matching accuracy

The procedure is explained in Fig. 2. The procedure is formulated to overcome the ambiguity often encountered by the designers. The evaluation methodology proposed is demonstrated in CATIAv5 which is widely used software for free form surfaces or synthetic surfaces.

Initially the two surfaces lofted and coons are fitted over the curve combinations using tangency continuity. The surfaces obtained are compared for matching accuracy. Solids are created by closing the surfaces obtained. The Solids created will be the 3D-CAD model. Again the solids are compared for matching accuracy. The objective of such comparisons is to study the influence of the number of sections on surfaces and solids. Later, from the solid, extracted surfaces and extracted curves are obtained for the comparison of curve length. In case of curves the section curve length and guide curve length of the actual curve are compared with that of the extracted curves. The objective of this comparison is to study the marginal changes in curve length due to surface fitting using various surface options available.

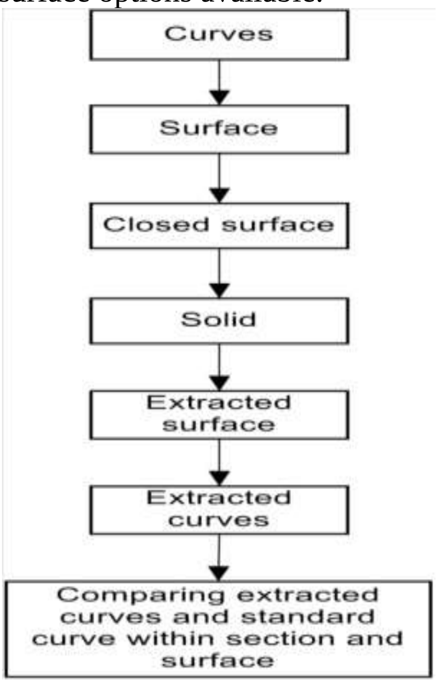


Fig.2. Evaluation Method

3.1Qualitative Evaluation Method of Matching Accuracy

Designers usually rely on qualitative procedure for the evaluation of matching accuracy. The designers in industries usually adopt the following procedure for qualitative evaluation of mismatch between scan data mesh model and the developed CAD model in RE applications. Ambiguity is often encountered by the designers in determining the mismatch. Initially scan data is used to

develop curves from which surfaces, closed surfaces and solids are developed subsequently one after another. The surface area of the surface and the volume of the solid are obtain as measured using the measure tool in software. These parameters measured from single section are compared is compared with the corresponding parameters in multi section.
Such a typical procedure is extended and described below in detail. The qualitative comparisons are carryout various procedures without any such comparison that lead to ambiguity.

- By superimposing the surface fitted using single section and multi section
- By superimposing the solid created from closed surface fitted over single section and multi section
- By superimposing the extracted curves corresponding to single and multi-sections

The above steps are described below for lofted and coons surfaces.

3.1.1 Lofted surface single and multi-section comparison

Lofted surfaces are fitted for the curve combination using single section and multi section the matching level corresponding to the three comparisons are shown in Fig. 3. The superimposition shows the matching level between the corresponding surfaces, solids and extracted curves (section curves and guide curves).

3.1.2 Coons surface single and multi-section comparison

For the Coons-surface the mismatching of corresponding surfaces, solids, and extracted curves for the curve combination are shown in Fig. 4.
The qualitative analysis discussed above explains the possible mismatching in surfaces, solids, and curves due to single section and multi section while using certain surface options and curve combination. Also the qualitative analysis does not indicate the degree of mismatching leading to ambiguity. In order to overcome this ambiguity a quantitative numerical analysis is proposed below which can provide certain thumb rule for the designers to use.

3.2 Quantitative numerical evaluation method

The objective of the comparison is to study the influence of the number of sections on surface area and the volume. Later, from the solid, extracted surfaces and extracted curves are obtained for the comparison of curve length. In case of curves the section curve length and guide curve length of the actual curve are compared with that of the extracted curves. The objective of the comparison is to study the marginal changes in curve length due to surface fitting using various surface options available. Designers use various procedures without any such comparison that lead to ambiguity. Hence the numerical comparison of the physical parameters is important in determining the suitability of utilizing various surface options available, especially in nonfunctional parts.
Reference numerical values of the physical parameters are compared as described in the methodology. In numerical evaluation, surface area, volume, and curves length are measured using 'measure tool bar' in CATIAv5. Measure tool bar contains Measure between, Measure item and Measure inertia icons.
The variation (ε) between the corresponding physical parameter and the respective percentage error (%ε) are obtained.

Influences on modeling parameters

4.1 Single and multi-section comparison

4.1.1 Lofted surface

In numerical evaluation of lofted surface the %ε are either zero or negligibly small when rounded off to two decimal as shown in Table 2.

Table 2. Lofted surface Comparison - Single and Multi-Section

Variation (ε) and Percentage error (%ε)		**Surface Area (SA)**			**Volume (V)**		
$(SS)_L$		24269.660 **mm^2**			26452.809 **mm^3**		
$(MS)_L$		24270.261 **mm^2**			26453.104 **mm^3**		
$abs(\varepsilon)_L = (SS)_L – (MS)_L$		0.601 **mm^2**			0.295 **mm^3**		
$(\%\varepsilon)_L = ((SS)_L – (MS)_L) / (SS)_L$		0.00			0.00		
Comparison of ASCL and ELSCL		**Single Section (SS)**			**Multi Section (MS)**		
		S1	**S2**	**S3**	**S1**	**S2**	**S3**
ASCL	**mm**	185.045	220.339	135.841	185.045	220.339	135.841
ELSCL	**mm**	185.045	220.339	135.841	185.045	220.339	135.841
$abs(\varepsilon Si)_L$ = (ASCL) – (ELSCL)	**mm**	0.000	0.000	0.000	0.000	0.000	0.000
$(\%\varepsilon Si)_L$ = ((ASCL) – (ELSCL)) / (ASCL)		0.00	0.00	0.00	0.00	0.00	0.00

4.1.2 Coons surface

In coons surface the %ε in the parameters SA and V are significant while comparing single and multi- sections as shown in Table 3. For coons surface the %ε in SA while comparing single section and multi section is 5.15. Similarly for volume V the %ε is 4.72. Also the %ε while comparing ASCL with ESSCCL is 6.56 and while comparing ASCL with EMSCCL is 0.04.

4.2 Comparison of surface options

Unlike lofted surface, in the coons surface %ε in SA, and V are significantly high. Hence coons surface parameters are compared against lofted surface parameters separately for single section as well as for multi section as expressed.

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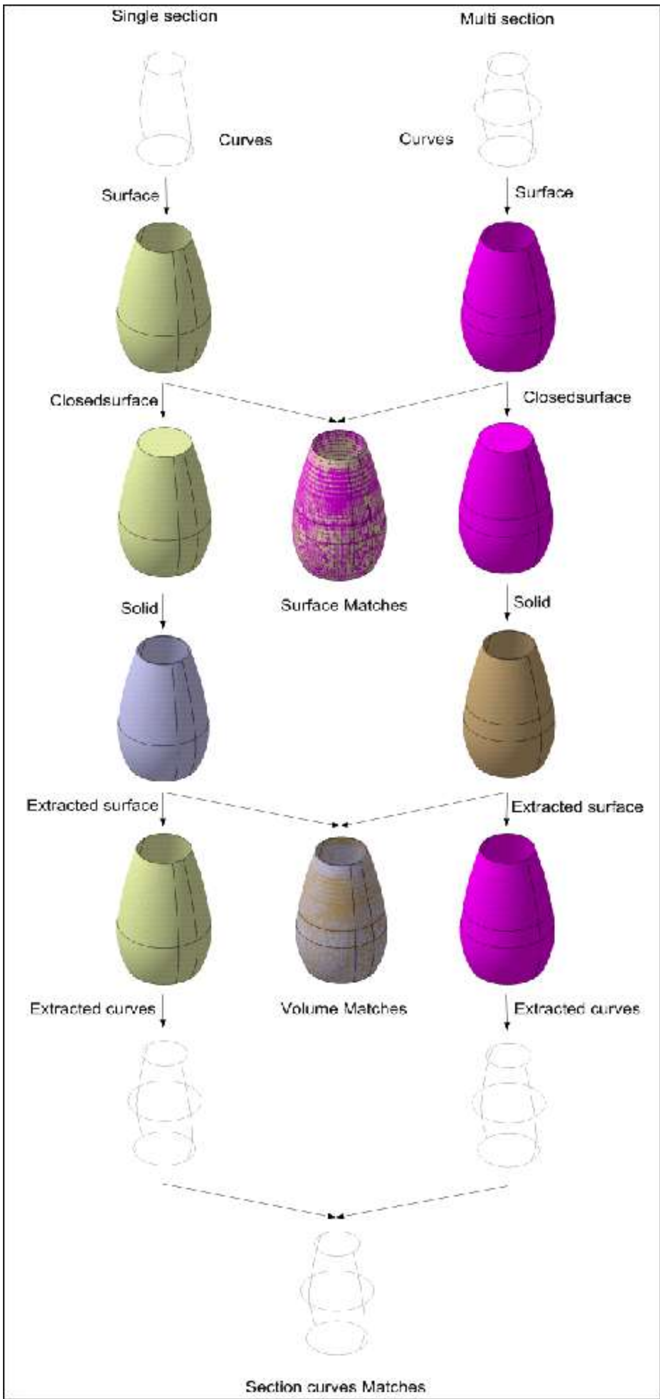

Fig. 3. Lofted surface single and multi-section comparison

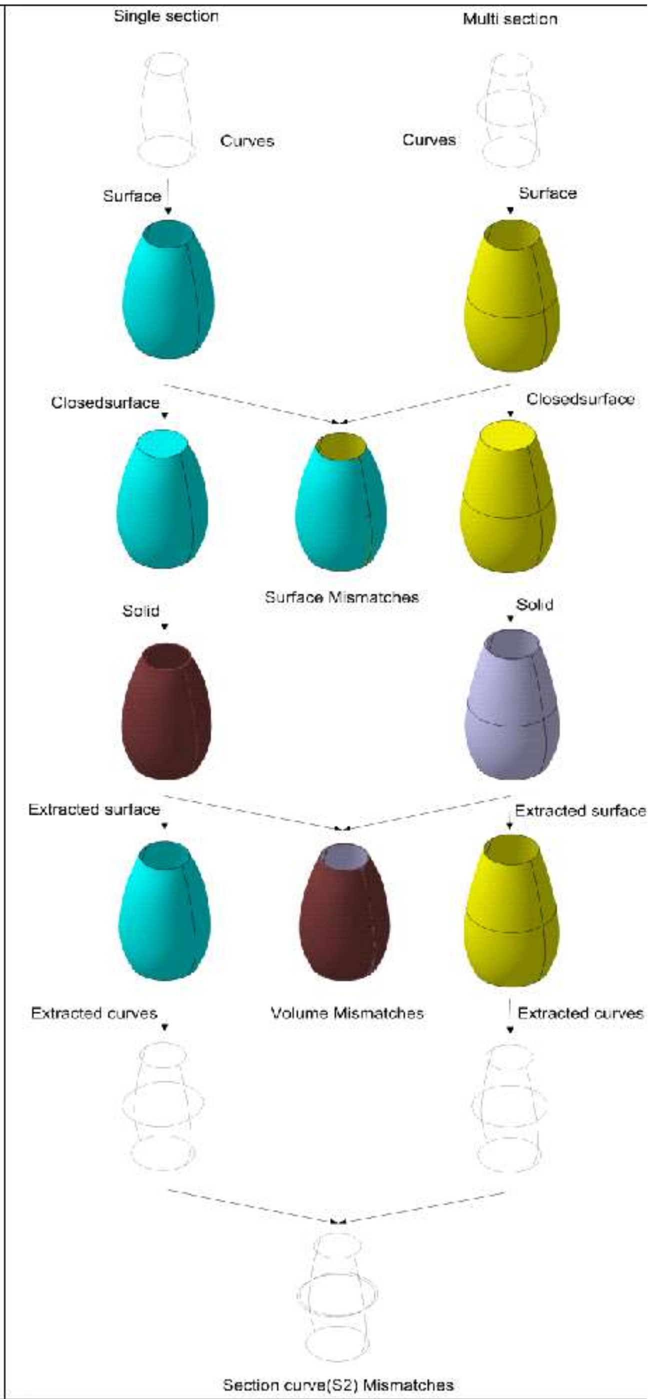

Fig. 4. Coons surface single and multi-section comparison

Table 3. Coons surface Comparison - Single and Multi-Section

Variation (ε) and Percentage error (%ε)		Surface Area (SA)			Volume (V)		
$(SS)_C$		25529.764 **mm²**			27706.727 **mm³**		
$(MS)_C$		24214.019 **mm²**			26397.885 **mm³**		
$abs(\varepsilon)_C = (SS)_C - (MS)_C$		1315.745 **mm²**			1308.842 **mm³**		
$(\%\varepsilon)_C = ((SS)_C - (MS)_C) / (SS)_C$		5.15			4.72		
Comparison of ASCL and ECSCL		**Single Section (SS)**			**Multi Section (MS)**		
		S1	**S2**	**S3**	**S1**	**S2**	**S3**
ASCL	**mm**	185.045	220.339	135.841	185.045	220.339	135.841
ECSCL	**mm**	185.045	234.783	135.841	185.045	220.252	135.841
$abs(\varepsilon Si)_C$ = (ASCL) – (ECSCL)	**mm**	0.000	14.444	0.000	0.000	0.087	0.000
$(\%\varepsilon Si)_C$ = ((ASCL) – (ECSCL)) / (ASCL)		0.00	6.56	0.00	0.00	0.04	0.00

The calculated values are presented in Table 4. It shows that for SA the %ε between lofted surface and coons surface corresponding to single section is 5.19 and that of multi section is 0.23. Similarly for volume V the %ε between lofted surface and coons surface corresponding to single section is 4.74 and that of multi section is 0.21. Also for SCL the %ε between lofted surface and coons surface corresponding to single section is 6.56 and that of multi section is 0.04. Thus the %ε between lofted surface and coons surface for single section is high as compared to multi section for all the physical parameter considered. The %ε is expected to decrease with increasing number of section curves. The quantitative evaluation helps to numerically evaluate %ε in various physical parameters of a CAD model so as to eliminate the ambiguity that exists in qualitative evaluation.

Table 4. Lofted and Coons Comparison - Single and Multi-Section

Variation (ε) and Percentage error (%ε)			**Surface Area (SA)**			**Volume (V)**		
SS	$(SS)_L$		24269.66 **mm²**			26452.809 **mm³**		
	$(SS)_C$		25529.764 **mm²**			27706.727 **mm³**		
	$abs(\varepsilon)_{LC} = (SS)_L - (SS)_C$		1260.104 **mm²**			1253.918 **mm³**		
	$(\%\varepsilon)_{LC} = ((SS)_L - (SS)_C) / (SS)_L$		5.19			4.74		
MS	$(MS)_L$		24270.261 **mm²**			26453.104 **mm³**		
	$(MS)_C$		24214.019 **mm²**			26397.885 **mm³**		
	$abs(\varepsilon)_{LC} = (MS)_L - (MS)_C$		56.242 **mm²**			55.219 **mm³**		
	$(\%\varepsilon)_{LC} = ((MS)_L - (MS)_C) / (MS)_L$		0.23			0.21		
Comparison of ELSCL and ECSCL			**Single Section (SS)**			**Multi Section (MS)**		
			S1	**S2**	**S3**	**S1**	**S2**	**S3**
ELSCL		**mm**	185.045	220.339	135.841	185.045	220.339	135.841
ECSCL		**mm**	185.045	234.783	135.841	185.045	220.252	135.841
$abs(\varepsilon Si)_{LC}$ = (ELSCL) – (ECSCL) **mm**			0.000	14.444	0.000	0.000	0.087	0.000
$(\%\varepsilon Si)_{LC}$ = ((ELSCL) – (ECSCL)) / (ELSCL)			0.00	6.56	0.00	0.00	0.04	0.00

Influences on analysis parameters

The influence on deflection u is similar to the influence on any of the modeling parameters. However the influence on vonmises stress is not monotonous un like the influence on modeling parameters. More specifically the minimum stress decreases initial and increase whereas the maximum stress increase initial and then decrease. In either case the error decrease as the result converge with larger number of section curves.

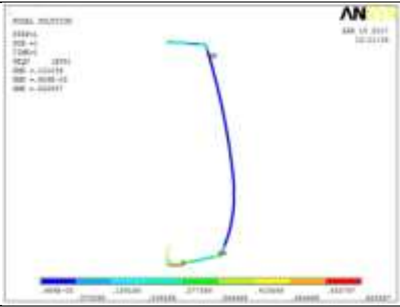

Fig 5. Analysis for lofted surface single section in vonmises stress

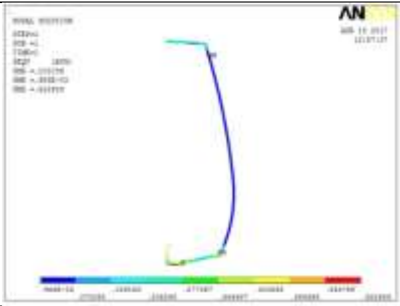

Fig 6. Analysis for lofted surface multi section in vonmises stress

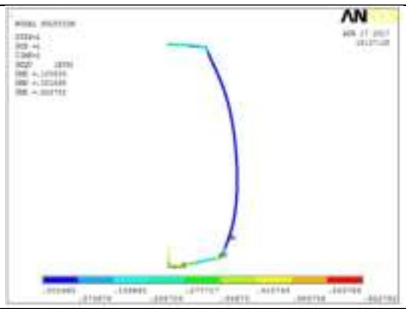

Fig 7. Analysis for coons surface single section in vonmises stress

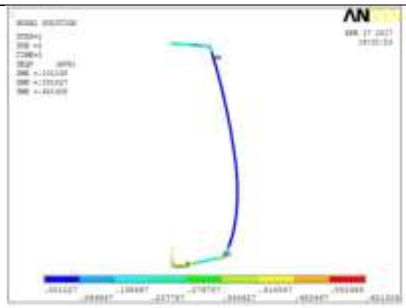

Fig 8. Analysis for coons surface multi section in vonmises stress

Table 5. Comparison of Analysis Result of Lofted Single and Multi-Section

Parameters	**$(SS)_L$**	**$(MS)_L$**	**$abs(\varepsilon)_L = (SS)_L – (MS)_L$**	**$(\%\varepsilon)_L = ((SS)_L – (MS)_L) / (SS)_L$**
u	0.101036	0.101036	0.000000	0.00
σ_{min}	0.000989	0.000985	0.000004	0.40
σ_{max}	0.622887	0.622889	0.000002	0.00

Table 6. Comparison of Analysis Result of Coons Single and Multi-Section

Parameters	**$(SS)_C$**	**$(MS)_C$**	**$abs(\varepsilon)_C = (SS)_C – (MS)_C$**	**$(\%\varepsilon)_C = ((SS)_C – (MS)_C) / (SS)_C$**
u	0.100829	0.101153	0.000324	0.32
σ_{min}	0.001665	0.001027	0.000638	38.32
σ_{max}	0.622782	0.621308	0.001474	0.24

Table 7. Comparison of Analysis Result of Lofted and Coons Single section

Parameters	**$(SS)_L$**	**$(SS)_C$**	**$abs(\varepsilon)_{LC} = (SS)_L – (SS)_C$**	**$(\%\varepsilon)_{LC} = ((SS)_L – (SS)_C) / (SS)_L$**
u	0.101036	0.100829	0.000207	0.20
σ_{min}	0.000989	0.001665	0.000676	68.35
σ_{max}	0.622887	0.622782	0.000105	0.02

Table 8. Comparison of Analysis Result of Lofted and Coons Multi section

Parameters	$(MS)_L$	$(MS)_C$	$abs(\varepsilon)_{LC} = (MS)_L - (MS)_C$	$(\%\varepsilon)_{LC} = ((MS)_L - (MS)_C) / (MS)_L$
u	0.101036	0.101153	0.000117	0.12
σ_{min}	0.000985	0.001027	0.000042	4.26
σ_{max}	0.622889	0.621308	0.001581	0.25

Conclusions

In Reverse engineering applications, selection of appropriate curve and surface options influence physical parameters viz., curve length, surface area and volume. Ambiguity is often encountered by the designers in determining through qualitative evaluation the mismatch between scan data mesh model and the developed CAD model in RE applications.

Hence the numerical comparison of the physical parameters is proposed in this work for non-functional parts while determining the suitability of utilizing various surface options available in CAD packages.

In numerical evaluation of lofted surface the %ε are either zero or negligibly small. In coons surface the %ε in the parameters SA and V are significant while comparing single and multi-sections.

The %ε in SA is 5.15 and %ε in V is 4.72. Also the %ε while comparing ASCL with ESSCCL is 6.56 and while comparing ASCL with EMSCCL is 0.04.

While comparing lofted surface and coons surface %ε is high for single section and less for multi section for all the physical parameter considered. The quantitative evaluation helps to numerically evaluate %ε in various physical parameters of a CAD model so as to eliminate the ambiguity that exists in qualitative evaluation.

The %ε in lofted section is negligible small for both deflection and vonmises stress. Hence the designer is recommended used lofted surface where ever possible. The %ε decreases with lager number of sections for both deflection and vonmises stress. Hence the designer is recommended to use sufficiently lager number of section curves.

If the designer is particular in using coons surface then the recommendation is to use sufficiently large number of section curves. Alternatively if the designer particular in using single section then the recommendation is to select lofted surface option. The above recommendations are common for both the modeling parameters and analysis parameters.

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