



Comparison of CAD Modeling Approaches in the Design of Custom Dental Abutments

Iris Huić¹ , Petar Kosec^{1,2} , Tomislav Martinec¹  and Stanko Škec¹ 

¹University of Zagreb Faculty of Mechanical Engineering and Naval Architecture

²Neo Dens Ltd

Corresponding author: Iris Huić, iris.huic@fsb.unizg.hr

Abstract. This study compares three different approaches to CAD modeling custom dental abutments. Custom abutments serve as the critical link between dental implants and prosthetic restorations, requiring both functional accuracy and aesthetic refinement. The increasing integration of digital tools in dental design has led to the adoption of diverse modeling methodologies, each offering distinct advantages in workflow design, customization potential, and manufacturing compatibility. To examine these variations, this study evaluates three distinct approaches: dental CAD modeling, engineering-based modeling, and NURBS-based modeling. These approaches are analyzed through the application of ExoCAD Rijeka 3.1, SolidWorks 2020, and Grasshopper within Rhinoceros 8, respectively. The evaluation criteria for these tools were established through literature review and expert consultations, then categorized into four key criteria: parameter management, abutment geometry modifications, manufacturing readiness, and workflow adaptability. The dental approach utilizes ExoCAD features, structured workflows that streamline standardized designs, but offer limited adaptability for highly customized cases. In contrast, engineering and NURBS-based approaches, utilized by SolidWorks and Rhinoceros, provide advanced customization abilities through parametric and surface modeling but require greater expertise and time investment. The findings underscore the need to select CAD approaches based on specific design requirements, highlighting the role of automation techniques such as parametric modeling in optimizing dental CAD workflows.

Keywords: Dental prosthetics, Engineering CAD approach, Dental CAD approach, NURBS-based modeling approach, Custom dental abutment.

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1 INTRODUCTION

Computer-aided design (CAD) technologies have become indispensable in modern product development across a wide range of engineering and biomedical domains. By enabling the digital representation and manipulation of three-dimensional geometries, CAD tools support reproducible modeling of complex components, facilitating both functional validation and manufacturing

integration. Within biomedical applications, dental prosthetics represent a particularly demanding field, requiring the synthesis of mechanical stability, anatomical accuracy, and aesthetic compatibility. The transition from conventional manual techniques to digital workflows in dental laboratories has led to a growing reliance on CAD tools for the design and customization of patient-specific restorations [1].

In the context of dental prosthetics, prosthodontics refers to the branch of dentistry that specializes in the design and placement of artificial replacements for teeth and related oral structures. Within this field, CAD is primarily used for the design of crowns, bridges, and implant-supported components. Among these, custom dental abutments—intermediate components that connect dental implants to prosthetic restorations—present a unique design challenge. They must be geometrically tailored to the implant connection, support an anatomically appropriate emergence profile, and ensure long-term biomechanical durability. The production of such abutments typically involves the combination of digital design and subtractive or additive manufacturing, collectively referred to as CAD/CAM workflows. Research suggests that custom CAD/CAM abutments offer enhanced clinical outcomes, including improved retention, better angulation control, and reduced risk of screw loosening or micro-movements that may compromise implant longevity [11, 12]. Although CAD tools are built upon similar digital principles, the modeling approaches they implement can differ substantially depending on their underlying geometric representation, modes of user interaction, and target application domains.

This study compares three distinct CAD modeling approaches to digital design of dental abutments: dental, engineering, and NURBS-based modeling. The comparative analysis is guided by criteria identified through a review of relevant literature and considers key aspects such as parameter management, abutment geometry modifications, user expertise, workflow integration, and usability. Existing CAD tools, particularly those tailored to dental applications, are often predefined and “closed”, limiting their potential for broader tool integration. Exploring alternative modeling approaches allows for the evaluation of tools that may offer improved control over geometry generation, better support for customization, and enhanced process automation. By examining these approaches side by side, the study contributes to a better understanding of the advantages and limitations of each approach in the digital design of prosthodontics.

The structure of this paper is as follows: the next section provides background information on the three CAD modeling approaches within the dental context and establishes the basis for defining the evaluation criteria. Section 3 describes the research methodology. Section 4 presents the results, followed by Section 5, which evaluates the approaches against the predefined criteria and discusses their implications and limitations. Finally, Section 6 concludes the study.

2 LITERATURE REVIEW

The literature review provides an overview of the differences between specialized CAD tools and general-purpose CAD tools, as well as the distinctions between surface-based and solid-based modeling approaches. This is important for understanding how these methodologies apply to the dental context, specifically the design of dental abutments. The review then narrows its focus to explore the relevant criteria for comparing CAD approaches, highlighting the specific needs and requirements of dental workflows.

Specialized dental CAD tools such as ExoCAD and 3Shape are developed specifically for dental workflows and include functionalities for designing abutments in alignment with patient anatomy [1, 2]. These tools integrate scan data, enabling clinicians and technicians to design prosthetic components that closely match anatomical and functional requirements [3, 4]. They are frequently highlighted in the literature for their intuitive, predefined workflows aligned with clinical procedures, including the use of libraries for restorations and the integration of scan data [13]. However, this predefined workflow can limit modeling freedom and adaptability, particularly in cases involving complex geometries, unconventional design solutions, or the need for iterative design processes [4].

Traditional dental CAD tools, while efficient for standardized restorations, often lack the adaptability required for designing components that deviate from preset workflows or must integrate with external mechanical tools. As dental needs evolve, the potential of engineering-based CAD modeling approaches to address these challenges is being explored. For instance, in cases involving custom abutments with non-standard geometries or components that interact with implant tools in unconventional ways, the limitations of dental-specific tools became more apparent, prompting further investigation into whether the advanced capabilities of an engineering-based CAD approach can fill this gap.

In response to such challenges, general-purpose engineering CAD tools such as SolidWorks and PTC Creo offer robust parametric modeling capabilities and allow detailed control over parameter relations, geometric constraints, and assemblies [5, 6]. These tools, while not inherently designed for dental applications, are used in contexts where mechanical robustness and structural fidelity are prioritized. Their strength lies in dimension-driven design, allowing users to apply engineering principles to the development of abutments with explicit mechanical properties [5, 14]. For instance, Zhang et al. [11] presented an approach that combines SolidWorks with a dental milling machine to support in-house fabrication of custom abutment components. However, their focus was limited to modeling and manufacturing the base, scan element, abutment, and crown geometry, without addressing the broader integration of clinical considerations, design methodology, and functional requirements that define a comprehensive abutment design process. While these tools offer control and precision, they do not inherently include dental-specific functionalities, which necessitate additional customization and adaptation for use in dental applications. The absence of domain-specific features, combined with the need to develop custom libraries, makes these tools less accessible to dental professionals without an engineering background [5, 15]. Although the ability to support non-dental workflows can be advantageous in certain contexts, it is important to note that this feature may entail a significant learning curve, which could vary depending on the user's background and experience [12]. To be implemented in dental design, engineering-based CAD tools must be adapted to meet the specific requirements of dental applications, which may involve significant modifications [13].

A related approach that addresses some of these design challenges involves the use of NURBS-based CAD tools such as Rhinoceros and Blender, which facilitate curve-driven surface manipulation and are particularly suited to generating organic forms [7]. Their mathematical foundation allows for continuous surface transitions, making them suitable for achieving smooth emergence profiles and aesthetic contours in custom abutment designs, as well as for the broader esthetic and functional modeling of dental restorations [7], [8], [14]. Despite their capabilities in constructing complex surface geometries, these tools typically lack dental-specific modules and require advanced modeling skills, presenting a steeper learning curve for dental technicians and clinicians [14]. Mastering NURBS-based approaches often necessitate advanced technical knowledge, which can limit their widespread use among dental professionals [14]. Nevertheless, their application is closely tied to surface-based and solid-based modeling approaches, which further differentiate these tools. Surface modeling in NURBS-based tools captures complex anatomical forms and supports iterative refinement, making it suitable for aesthetic adjustments [9]. However, it does not verify volumetric integrity, leaving model validity to the user [15]. Solid modeling, common in engineering CAD tools, offers full volumetric representations with parametric consistency, which is useful when mechanical performance is essential [9, 10].

One of the requirements across CAD approaches is parameter management to support individualized dental design. Dental tools like ExoCAD incorporate anatomical input from intraoral scans and CBCT imaging into the modeling process [3], [4]. This anatomical data forms the basis for subsequent design steps, including the customization of digital models according to scanned implant positions and tissue morphology. Scanning abutments are instrumental in virtually transferring implant locations into the CAD environment, thereby facilitating patient-specific modeling. The acquisition of high-resolution rescans is often a prerequisite for this stage. Ahmed [1] stresses the role of intuitive interfaces in enabling users to control key abutment dimensions and alignments, which is crucial for achieving both esthetic and functional requirements. Erofeev and

Kulikov [17] describe adaptive interfaces that respond dynamically to the user's workflow. Micevska and Kandikjan [14] underscore the importance of such parametric workflows for patient-specific modeling, particularly in accommodating distinct anatomic data. This anatomical input forms the foundation for subsequent design steps in dental approaches, where customization is applied based on scanned implant positions and tissue morphology.

As mentioned by Kosec et al. [4], custom dental abutments have three key segments: the implant connection, the transgingival segment, and the prosthesis connection. The ability to modify different abutment segments is a critical aspect of dental design, as it influences the success and longevity of implant-supported prosthetics. The implant connection determines the mechanical compatibility and biological integration of the implant. Studies indicate that variations in connection types, such as conical, internal hex, and external hex, result in different patterns of marginal bone preservation and implant durability. For example, conical connections are often linked to more stable marginal bone levels than flat-to-flat and platform switch designs [18]. The transgingival segment contributes to soft tissue adaptation and peri-implant health. Its shape and material selection can affect both biological response and visual integration within the oral environment [2], [3]. Finally, the prosthetic connection must support proper alignment and retention of the prosthetic crown, ensuring stability and functional load distribution.

For CAD-generated abutments to be clinically viable, they must align with the requirements of computer-aided manufacturing (CAM) technologies. Elkhuizen et al. [19] and Fuster-Torres et al. [20] highlight the importance of STL export functionalities, which enable the transfer of digital models to milling machines such as the Wieland Zenotec Mini. The compatibility between the designed geometry and selected material is a key factor in this transition. Materials like titanium and zirconia are commonly used due to their mechanical strength and biocompatibility, but they also introduce specific design constraints. For instance, the brittleness of zirconia may require increased connector dimensions or limit the inclusion of thin-walled features, while machining titanium may restrict fine details in narrow or sharp geometries. These constraints emphasize the need for design environments that allow users to anticipate and adapt the geometry to material-specific requirements already in the modeling phase. Furthermore, finite element analysis (FEA) is frequently applied before manufacturing to simulate mechanical behavior and assess stress distribution within the abutment structure [21][22]. These simulations help identify geometries that may lead to mechanical failure if not addressed during the design process [23].

The productivity of CAD modeling is also determined by the compatibility between tool workflows and user expertise. The literature differentiates between guided workflows—frequently used in dental tools - and customizable, iterative workflows seen in more advanced approaches [13, 5]. Guided workflows are suitable for repetitive tasks and standardized clinical procedures, such as routine crown designs or straightforward implant placements. In contrast, tools that support iterative modeling offer greater parameter management, which can be especially valuable in complex clinical cases – such as abutments with atypical angulation, limited interocclusal space, or irregular soft-tissue contours – where standard templates may be insufficient [23]. However, this adaptability often necessitates more advanced modeling skills. Guo et al. [24] suggest that experience and proficiency may influence how individuals utilize these tools in design tasks. Son and Lee [25] suggest that repeated and sustained use of CAD tools contributes to progressive improvement in user expertise, particularly in terms of modeling accuracy and time reduction, even among users with limited initial experience. Nonetheless, the NURBS modeling approach remains challenging for many users due to its complex mathematical foundation, which often necessitates specialized training in geometry and surface theory [26]. This complexity has traditionally limited its accessibility, particularly among dental professionals without formal engineering or computational backgrounds. However, recent efforts to integrate NURBS modeling into dental-specific CAD approach—such as the implementation of simplified NURBS-based tools or plugins within systems like ExoCAD or Blender for Dental—have aimed to reduce this barrier [27], [28]. These integrations often include user-friendly interfaces, predefined templates, and context-aware functions tailored to dental restoration workflows, thereby making surface manipulation more intuitive. For example, tools like SimplyNURBS have been developed to support prosthetic modeling by abstracting complex

mathematical foundations and offering guided surface editing, which enhances usability for clinicians and technicians without extensive CAD training [29].

3 METHODOLOGY

The aim of this study is to compare three distinct CAD modeling approaches (dental, engineering, and NURBS-based modeling) by evaluating their advantages and limitations in the context of custom dental abutment design. To achieve this, the study examines one representative CAD tool for each approach: ExoCAD Rijeka 3.1 for dental, SolidWorks 2020 for engineering, and Rhinoceros 8 for NURBS-based modeling.

The rationale behind the selection of each tool is presented first, highlighting its relevance to dental workflows and modeling strategies. Following this, the study defines the evaluation criteria used to guide the comparison. These criteria are derived from literature and reflect the specific functional and contextual demands of custom abutment modeling. The section concludes with an outline of the design task used as a basis for comparison, namely, the modeling of a custom dental abutment—together with an explanation of its segments and modeling requirements.

ExoCAD Rijeka 3.1 was chosen because its dental-specific features, intuitive interface, and high usability. A comparative study by Kosec et al. [4] identified ExoCAD among three different tools as the most effective dental tool in terms of usability and feature set. It supports guided workflows, preconfigured libraries, and automated suggestions, which contribute to consistent outcomes and reduced user errors. SolidWorks 2020 was chosen due to its proven capabilities in parametric modeling [30] and its applicability in dental workflows [27]. It employs a hierarchical modeling structure where changes to one component propagate throughout the model, minimizing errors and streamlining the design process. Additionally, its integration with design tables and equation-based modeling enhances adaptability in parametric adjustments, making it effective for iterative design workflows [10]. SolidWorks also supports surface modeling, a key feature used in this study for dental abutment design due to the transgingival segment involved. In contrast, Rhinoceros 8, enhanced by its integrated visual programming tool Grasshopper, was selected for its capacity to create and control NURBS-based geometries, which are essential for achieving smooth surface transitions and anatomical precision in dental restorations. Grasshopper extends Rhinoceros modeling capabilities by functioning not only as a visual interface but as a fully embedded design environment for building computational logic and automating generative designs. In this context, generative and computational design refer to the ability to programmatically create and refine complex surface geometries, enabling the efficient exploration of customized design solutions that would be challenging to achieve through manual modeling alone. This combination of CAD tools enables a comparative exploration of different modeling approaches, emphasizing their strengths in dental design applications. ExoCAD provided predefined, dental-specific workflows that streamlined the process within its specialized framework. In contrast, SolidWorks and Rhinoceros required significant workflow adjustments to align with the demands of parametric and surface-based modeling. These workflows were carefully harmonized to ensure a fair comparison across the different approaches, allowing for consistent evaluation of their capabilities in the context of custom dental abutment design, as discussed in the results section.

To facilitate a structured comparison of different approaches to dental abutment design, a comparison criteria table was developed. The selection of criteria was informed by the literature review and validated through consultation with an industry expert – an engineer employed in a dental company – who provided additional insights into critical factors relevant to the design of dental abutments. For instance, the height of the transgingival profile must be at least 1.5 to 2 mm below the gingival margin; a concave design in the transgingival segment (shown in Figure 1) is preferred to prevent bacterial buildup; and a square-based design is favored in the prosthesis connection segment to ensure better retention with the restoration. Additionally, the expert contributed by validating the selection of comparison criteria and approving the final designs produced within each modeling approach, ensuring their relevance to practical dental applications. The four criteria, shown in Table 2, encompass: parameter management, abutment geometry

modifications, model usability and manufacturing readiness, and workflow design and user expertise. Each of these criteria provided an evaluation of the advantages and limitations of the selected tools, ensuring assessment of their applicability in dental design.

The criterion of **parameter management (C1)** focuses on how each tool enables the definition, adjustment, and management of design parameters to achieve a final abutment geometry that aligns with functional constraints and clinical requirements. Within this criterion, particular attention is given to how the tools support users in navigating parameter relationships and adjusting design parameters relevant to abutment configuration. Rather than general interface intuitiveness, the evaluation specifically considers the clarity and accessibility of commands and functionalities directly related to parameter manipulation. Furthermore, the accuracy in achieving intended design outcomes – specifically the modeling of abutment segments such as implant connection, transgingival, and prosthesis connection segment – is examined in terms of how well the tools support alignment with anatomical and mechanical constraints. Additionally, the integration of dental-specific features within the tools was considered, as such features directly supported the modeling of clinically relevant geometries and reduced the reliance on external modifications or manual post-processing outside of the CAD tool.

The ability to **modify the geometry of distinct abutment segments (C2)** is assessed as a separate criterion from general parameter management, focusing on context-dependent modifications required for clinical customization. This includes evaluating how each tool supports targeted geometric changes within the implant connection, transgingival segment, and prosthesis connection of the abutment. For the implant connection, the assessment examines the adaptability offered by the tools in adjusting geometric features such as the internal connection type and platform dimensions, while recognizing that in dental-specific CAD approaches, these adjustments are often constrained by pre-configured libraries and fixed parameters. In contrast, engineering and NURBS-based approaches typically offer broader freedom for redefining these features. Modifications to the transgingival segment are analyzed in terms of how the tools enable local contouring to accommodate soft tissue morphology, using context-appropriate methods such as control point editing in surface modeling tools or parameter-driven adjustments in an engineering CAD approach. For the prosthesis connection, the focus is placed on how well the tools accommodate adjustments to angulation, emergence profile, and crown alignment to meet specific restorative requirements.

In addition to abutment geometry modifications, the comparison also considers **model usability and manufacturing readiness (C3)**, both of which are important for enabling a reliable transition from digital design to physical production. Specifically, this includes evaluating the extent of manual preparation required after the modeling phase is completed but before exporting the model for manufacturing. Such manual interventions typically involve tasks like repairing open surfaces, resolving non-manifold edges, and preparing the model for export in formats compatible with dental production workflows. The comparison of CAD tools in this regard focuses on how each tool minimizes these post-modeling interventions through built-in validation and repair functions. Compatibility is assessed in terms of both file format support – such as STL or 3MF, which are accepted in dental milling and 3D printing workflows – and geometric integrity required by dental CAM systems to process abutment models reliably. Industry standards considered in this evaluation include geometric tolerances and surface quality expectations for dental restorations, as well as format specifications recognized by digital dentistry equipment manufacturers.

The design of the **modeling process and the level of user expertise (C4)** required to operate each tool are also addressed in the methodological framework of this study. Specific attention is given to the extent of prior knowledge needed from different professional profiles, including dental technicians familiar with prosthetic workflows, clinicians with an understanding of anatomical constraints, engineers experienced in CAD modeling but without prior exposure to dental applications, and general users with limited experience in either field. The analysis further considers the level of CAD-specific expertise required, focusing on capabilities such as defining and managing parametric models, performing direct surface manipulations, and, where applicable, working with visual programming environments to control geometric relationships and data flows within the tool.

Additionally, while the study examines different approaches to organizing the modeling process – specifically, linear modeling (where users follow a predetermined order of operations) versus iterative modeling (which allows users to revisit and adjust earlier stages of the design) this distinction aids initial understanding of user engagement rather than as a direct evaluative criterion.

Criteria	Description
C1) Parameter management [1][2][7]	Support for controlling design parameters through an interface aligned with dental workflows
C1.1 [1, 2]	Clarity and usability of the tools interface for dental-specific modeling tasks
C1.2 [7]	Availability and integration of dental-specific functionalities
C2) Abutment geometry modifications [8][16][11]	The extent to which different aspects of the abutment design can be customized, including constraints imposed by the tools
C2.1 [16]	Modification ability of the implant connection segment, considering tools-imposed constraints and predefined tool parameters
C2.2 [8]	Modification ability to locally contour the transgingival segment to reflect soft tissue morphology
C2.3 [12, 15]	Modification ability to the prosthesis connection segment, including angulation, emergence profile, and platform alignment, to meet restorative and functional requirements
C3) Model Usability and Manufacturing Readiness [19][20]	Ability to finalize the model for production and assess its adaptability for manufacturing
C3.1 [19]	The level of manual intervention required to prepare the model for manufacturing processes
C3.2 [20]	Compatibility of the generated model with dental production technologies and any additional steps required for optimization
C4) Workflow design and user expertise [1][24][25]	Adaptability of the design process and expertise required for effective use
C4.1 [1]	Level of expertise required to understand the dental context, including dental constraints, patient-specific scans, and gingival conditions
C4.2 [24]	Level of expertise required in CAD modeling, including parametric modeling, direct surface modifications, or scripting
C4.3 [24, 25]	Adaptability of the workflows, distinguishing between linear workflows and iterative workflows

Table 1 List of evaluation criteria for comparing CAD approaches.

In the context of this study, the chosen tool representatives (ExoCAD Rijeka 3.1, SolidWorks 2020, and Rhinoceros 8) were used to design a custom dental abutment for tooth 35, located in the lower left quadrant, following ISO 3950 standards [31]. A dental abutment (Figure 1) serves as the connection between an implant and a visible prosthetic restoration and is composed of three main segments. The implant connection segment forms the interface with the implant, the transgingival segment adapts to the surrounding soft tissues, and the prosthesis connection segment provides support for the prosthetic crown [4].

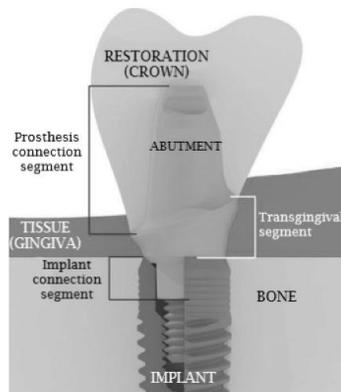


Figure 1: Implant abutment assembly [4].

Designing a custom abutment requires balancing functional and esthetic requirements. Functional requirements focus on a precise fit with the implant and bone, ensuring retention in the implant connection segment. The transgingival segment must accommodate soft tissues to provide comfort and durability, while the prosthesis connection segment supports crown angulation, retention, and alignment, ensuring proper mechanical fit of the restoration. Esthetic requirements relate to the smooth morphological connection between the abutment and the surrounding soft tissues, as well as the alignment of the abutment contours with the final prosthetic restoration to replicate natural tooth emergence profiles. This includes achieving continuous surface transitions, appropriate shaping at the gingival margin, and balanced proportions that support the integration of the soft tissues and maintain visual consistency with neighboring teeth.

4 RESULTS

The results are organized into three subsections, each corresponding to one of the CAD modeling approaches examined in this study: the dental approach (4.1), the engineering approach (4.2), and the NURBS-based modeling approach (4.3). Each is evaluated using the criteria established in the methodology.

4.1 Dental Approach Using ExoCAD

When ExoCAD is launched, the user is prompted to enter case-specific information. This includes patient details such as the patient's name, tooth position, implant system, and platform, and any relevant medical history. Users can also record case-specific notes, which may include laboratory orders, internal communication records, or reference numbers such as case ID. Additionally, users define key parameters such as the type of restoration to be designed, scan modes, implant systems, material selections, and project roles. Project roles include the assigned technician, dental laboratory, or engineer. Upon completing this initial setup, the user advances to the next stage of the process by importing the required digital impressions. Typically, this involves three scans: the working jaw reflecting gingival conditions, the antagonist representing the opposing jaw, and the scan containing the scan-abutment. Once these are loaded, the design interface is launched, as shown in Figure 2. The right side of the figure displays the imported scans, while the left side of the figure shows design functionalities specific to the selected restoration type. The interface is structured to support the adjustment of abutment segments based on anatomical references and clinical requirements. It presents dental-specific functionalities and visual elements that assist in defining dimensions, adjusting angulation, and shaping emergence profiles (C1).

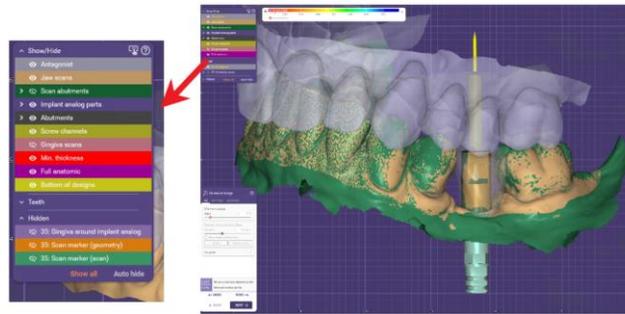


Figure 2: ExoCAD interface with design extension functionalities (left) and abutment scans (right).

The imported scan data serves as the foundation for defining implant positions, understanding the relationship with surrounding soft tissues, and determining the dimensions necessary for the restoration. In ExoCAD, implant positioning is established through a combination of visual guidance and built-in computational functions that align geometric data within the tools implant planning module. These functions assist in positioning by providing automated alignment suggestions based on the scanned geometry, while also allowing the user to manually adjust the implant location interactively during the design process, with immediate visual feedback in the interface. To support accurate design refinement, ExoCAD enables users to isolate or exclude specific portions of the scanned data, allowing focused visibility on critical anatomical features such as the implant site and the surrounding gingival contour. Furthermore, the tool offers control over the orientation of the screw channel, enabling the user to modify the angulation of the channel in relation to anatomical boundaries. This control contributes to appropriate screw access paths and supports structural considerations at the implant site, helping to avoid potential interference with adjacent anatomical features (C1).

The ability to modify different aspects of the abutment design in ExoCAD is subject to tool-imposed constraints specific to the *Wizard Mode*. The implant connection segment is non-modifiable, allowing only for selection from predefined options (such as the implant system, connection type, and platform size). These predefined values, derived from the implant library, establish fixed boundaries for the implant interface geometry, both in terms of width and height for the transgingival and prosthesis connection segments, which are described in the following text, preventing the user from altering these dimensions during design. However, the transgingival segment, which forms the transition between the gingiva and the restoration, offers modification within defined constraints. In *Wizard Mode*, the emergence profile of the transgingival segment is automatically generated based on the imported scan data, but can be manually refined for alignment with the anatomical shape of the gingiva, as shown in Figure 3a. Users can adjust the transition line by moving or adding control points along the emergence transgingival profile. Notably, ExoCAD restricts the vertical positioning of these points to the level of the gingival margin as captured in the scan data; if the user attempts to raise the points beyond this anatomical boundary, the tool automatically returns them to the permissible limit, preventing unrealistic elevations of the emergence transgingival profile. Regarding width, adjustments are allowed within limits imposed by both the fixed implant connection dimensions and the project-defined minimum material thickness. If a user attempts to narrow the transgingival segment below the established material threshold, ExoCAD enforces the limit and prevents further reduction, thereby ensuring sufficient material volume for manufacturing. These refinements contribute to both the functional integration of the abutment and the controlled adaptation to soft tissue contours. ExoCAD enhances this integration by employing color-coded visualizations—blue indicating available space and red signaling tissue compression. While this visual feedback assists users in shaping the transgingival segment to accommodate soft tissues, the adjustments remain bound by the constraints, maintaining continuity between the gingiva profile and the overall abutment design. Additionally, the tool typically generates a concave transgingival

profile by default to promote favorable soft tissue adaptation and reduce bacterial accumulation. Users can manually reshape the contour to flatter or more convex forms by adjusting the control points. The prosthesis connection segment is designed using a structured system of control points arranged along three distinct curves—lower, middle, and upper—as illustrated in Figure 3b. Each curve consists of eight control points for posterior teeth. These points are interconnected, meaning adjustments to one curve dynamically influence the others. Specifically, when the upper curve is modified, corresponding adjustments occur in the middle and lower curves to preserve the overall geometry. The position of these points is constrained by predefined manufacturing parameters. For instance, if a minimum crown thickness has been specified in the project setup, ExoCAD prevents users from reducing the vertical distance between the upper and lower curves below this threshold, thereby maintaining the necessary material volume for fabrication. The control points along these curves define the height, width, and contour of the prosthesis connection segment. Point adjustment is not entirely free form; instead, ExoCAD provides a structured adjustment grid defined by the density and arrangement of control points. Users are limited to repositioning points within a defined spatial envelope, ensuring that modifications remain within manufacturable boundaries and respect material constraints. The lower control points of the prosthesis connection segment can be moved outward within the permitted range, maintaining a minimum angle between adjacent points. This enforced angle supports the geometric formation of the abutment shoulder and prevents excessive narrowing, which could compromise the material integrity required for secure restoration (crown) retention. The upper curve of the prosthesis connection segment and its associated control points define the occlusal contact with the antagonist. Users can adjust the position of control points to refine occlusal contact. However, ExoCAD limits the range of these adjustments to prevent interferences with the antagonist, which the tool identifies based on the imported scan data. Visual indicators within the interface alert the user about potential contacts or collisions. Once all curves have been established, the square base shape of the abutment is finalized, with ExoCAD restricting further modifications that would undermine the geometric limits necessary to prevent rotational displacement of the abutment within the crown **(C2)**.

Once the abutment design is finalized (Figure 3c), ExoCAD moves into the manufacturing preparation phase, offering dedicated steps to ready the model for fabrication. The software allows users to define key actions such as setting the model orientation for milling or printing, selecting the size and type of material block, adjusting offsets to accommodate machining tolerances, and determining sprue placement to ensure proper material flow and structural support during the process. These tasks are carried out in a separate stage following design completion, during which the digital model is prepared for export in formats suitable for manufacturing. ExoCAD includes predefined methods for both subtractive (milling) and additive (3D printing) manufacturing and permits adjustment of essential parameters within each. Users can choose the manufacturing technique, configure support structures, and apply material-specific settings such as shrinkage allowances. However, the software does not handle advanced preparation steps like toolpath generation or component nesting, which are completed using external dental CAM tools. To facilitate this, ExoCAD supports direct export to widely used CAM tools such as HyperDent and WorkNC Dental. These tools manage toolpath creation, component arrangement within material blanks, and post-processing instructions tailored to specific milling machines or 3D printers—extending the preparation process beyond ExoCAD's built-in capabilities and completing the tasks required for fabrication **(C3)**.

ExoCAD supports users with varying levels of experience by providing a structured environment for abutment design, primarily through its *Wizard Mode*. This mode guides users through a defined sequence of operations, including project setup, integration of patient-specific scan data, and generation of the emergence profile. Each stage is organized to reflect standard dental design procedures, such as alignment of anatomical data and application of restoration parameters derived from implant libraries. Within this framework, users are offered predefined selections and visual guidance to support accurate completion of each step. Although *Wizard Mode* structures the process, it still permits controlled design adjustments. If changes to earlier stages become necessary after initial confirmation, users must return to the relevant step to apply modifications.

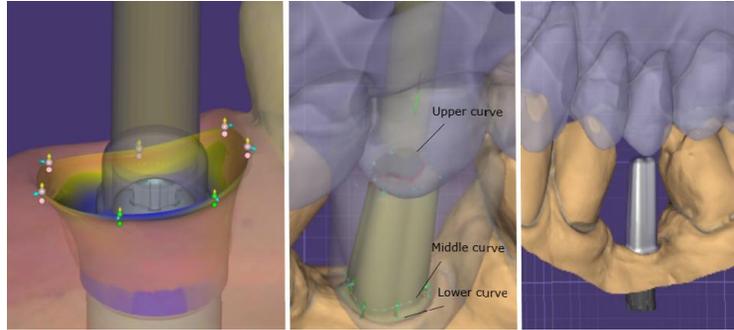


Figure 3: Custom abutment modeling process in ExoCAD Rijeka 3.1., displayed sequentially from left to right. The image illustrates: (a) Transgingival segment, (b) Prosthesis connection segment, and (c) Final abutment design.

For example, adjusting the implant position following its initial definition requires re-execution of subsequent design stages, including the regeneration of the emergence profile and the geometry of the prosthesis connection segment. *Wizard Mode* accommodates these revisions, but they involve manual navigation through the workflow to update dependent design elements. For cases requiring more detailed modifications beyond the capabilities of *Wizard Mode*, ExoCAD includes an *Expert Mode*. This environment enables direct adjustments to geometric features beyond predefined control points, such as fine-tuning the contours of the prosthesis connection or refining the emergence profile. Although these advanced functions allow for detailed control over geometry, they were not applied in this study, as the design of the custom dental abutment remained within the boundaries of standard clinical practice. *Expert Mode* becomes relevant primarily in scenarios involving atypical geometries or highly individualized designs that exceed the limitations of routine workflows. However, it still imposes restrictions: the implant connection geometry is fixed to predefined library elements and cannot be freely modified; the transgingival segment offers only limited curve-based control without additional surface editing; and the prosthesis connection is constrained by a fixed control-point structure that prevents asymmetric or irregular adjustments (C4).

4.2 Engineering Approach in SolidWorks

The process of creating a parametric model of a custom dental abutment in SolidWorks begins with the manual definition of foundational parameters. Since the tool does not offer predefined dental libraries, the user must first establish global variables that determine the principal dimensions and geometric characteristics of the abutment. In this context, a parameter refers to a specific dimension or design feature (e.g., diameter, angle, height), while a variable is the symbolic representation of that parameter within the modeling environment, allowing it to be systematically referenced and modified throughout the design process. These variables include parameters such as the diameter and depth of the implant connection, the height and profile curvature of the transgingival segment (Figure 4b), and the contour and angle of the prosthesis connection segment. These initial parameter values are derived from external patient-specific data, including implant system specifications and anatomical measurements obtained from imported jaw scans, depicted in Figure 4a. Once the variables are established, the hierarchical feature tree in SolidWorks enables the user to systematically construct the model by linking each geometric feature—such as extrusions, revolves, and lofts—to these variables through mathematical equations. This structure ensures that modifications to parameter values automatically propagate throughout the model, maintaining consistent geometric relationships between all segments. The integration of patient jaw scans is performed manually. After importing the scans, the user defines reference planes and axes to position the scans accurately within the SolidWorks interface. Anatomical structures, such as the alveolar ridge and gingival contours, are identified visually within the scan data. Using sketch tools, the user traces critical contours, including the emergence transgingival profile and key outlines for

the transgingival and prosthesis connection segments. Visibility of scan data is managed through the tool's *Hide* and *Show* functions, allowing focused attention on specific aspects of the model during different stages of development. Throughout the modeling process, SolidWorks provides immediate visual feedback within the design environment, reflecting changes in parameter values and their impact on the entire geometry. For example, adjustments to the implant connection diameter dynamically influence the dimensions of the transgingival profile and prosthesis connection, preserving coherence in the overall design. This parametric approach allows for the development of a fully interconnected model in which all segments remain linked, enabling adjustments based on patient-specific inputs and anatomical references. Patient-specific considerations such as bone structure, soft tissue contours, and implant orientation are incorporated by manually correlating features in the scan data with the defined parameters of the model. The accuracy of this correlation depends on the user's ability to interpret scan imagery and translate anatomical details into geometric definitions within the parametric framework (C1).

In SolidWorks, geometric modifications are implemented through a combination of parametric control tables and direct geometric operations, enabling detailed customization of each segment of the abutment model. The implant connection segment is parametrically defined by numerical entries within the parametric control table, as shown in Figure 4c. After the parametric model is created, the user manually inputs values corresponding to the implant system and platform dimensions, such as connection diameter and depth, thereby defining and enabling modification of the implant connection segment. Upon adjusting any value, the parametric dependencies established via global variables and equations automatically update the entire table, propagating changes throughout the connected features of the model. This ensures the implant connection geometry remains consistent with the defined implant specifications. Parameter variation in this environment is continuous within the practical modeling range, allowing users to define numerical values rather than selecting from fixed discrete intervals. For the transgingival segment, modifications are carried out through surface-based modeling rather than solely through the parametric control table. This modeling choice is necessary due to the complex curvature and anatomical adaptation required for this segment, particularly for defining the transgingival emergence profile. Two reference planes were created using four anatomical reference points: mesial, distal, buccal, and lingual. These planes guide the construction of surface features, providing control over the height and contour of the transgingival segment. Specific control points within the surface sketches allow for local adjustments to shape the profile, especially to achieve the clinically preferred concave design. Within SolidWorks, this is achieved by manually adjusting control vertices on the surface, manipulating curvature transitions to produce the desired inward profile. The prosthesis connection segment integrates both the parametric control table and reference points established earlier in the model. Parameter values in the table define macro features such as overall height, diameter, and axial inclination, while reference points guide the precise positioning of sketches used to build the detailed geometry. This combination enables controlled definition of the prosthesis connection's contour, allowing for adaptations to patient-specific anatomy and prosthetic requirements. Ensuring a proper connection with prosthetic restoration involves definition of the mating surfaces within SolidWorks (C2).

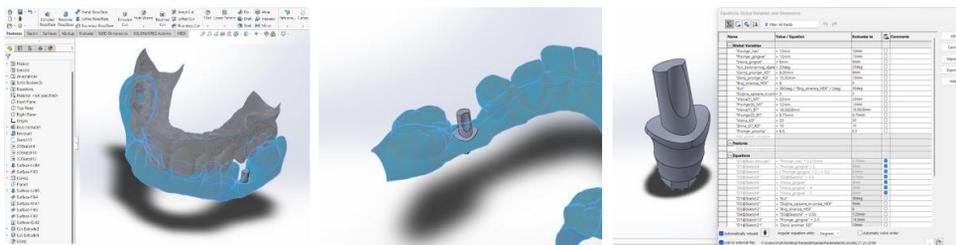


Figure 4: Custom abutment modeling process in SolidWorks 2020, illustrated sequentially from left to right. The figure shows: (a) Setup of design environment and input data preparation, (b)

Geometric alignment of the abutment with patient-specific lower jaw scan, and (c) Parameter abutment and table parameter modification.

After the abutment design is completed, SolidWorks supports the preparation of the model for manufacturing through specific export functionalities and model management features. The tool allows the model to be exported in industry-standard formats such as STL and STEP, which are compatible with dental CAM environments used for additive manufacturing (3D printing) and subtractive manufacturing (CNC milling). While SolidWorks itself does not generate toolpaths or machine instructions, its export capabilities ensure that the parametric model can be transferred to specialized CAM tools for further processing. The parametric structure of the SolidWorks model is maintained beyond the initial design phase, allowing users to perform targeted adjustments without rebuilding the entire geometry. For example, if clinical feedback or production testing identifies the need for modification in implant connection dimensions or transgingival profile, users can revise the relevant parameter values in the control table. Once updated, changes are automatically propagated throughout the dependent features of the model, maintaining the integrity of the design (C3).

The process in SolidWorks requires the user to actively structure the sequence of modeling steps, as the tool does not impose a predefined workflow. Typically, the modeling begins by establishing reference planes and creating base sketches that define the implant connection geometry. From this foundation, additional features are constructed progressively to define the transgingival segment and the prosthesis connection segment. The modeling sequence is logically developed to build upon the initial geometry, ensuring that the fundamental spatial relationships are established before addressing the refinement of detailed features. The hierarchical feature tree within SolidWorks enables clear management of dependencies between model components. Each operation is linked to the foundational sketches and global parameters, which allows users to trace and control how changes in early-stage features affect downstream geometry. This structuring depends entirely on the user's ability to plan and manage the model layout, rather than being automated by the tool. To build the model, the user must have a clear understanding of dental anatomical references, design intentions, and the constraints imposed by the intended manufacturing process. For instance, decisions made during modeling, such as wall thickness, undercut geometry, or surface curvature, must account for the specific requirements of subtractive or additive production technologies. For example, recognizing the correct position of the gingival margin and aligning the implant axis appropriately within the anatomical constraints is essential for accurate feature placement. Integrating reference points derived from patient-specific scan data and applying parametric relationships require familiarity with dental morphology and spatial considerations relevant to implant-supported restorations. Furthermore, expertise in using advanced CAD functionalities within SolidWorks is necessary. This includes defining and managing global variables, constructing surface features for more complex anatomical regions such as the emergence transgingival profile of the transgingival segment and performing adjustments through the parametric control table and direct sketch editing. Such capabilities are essential to maintain the consistency of the model while adapting it to specific clinical scenarios. The workflow developed in SolidWorks is user-determined and can follow either a linear progression, where each design stage is built sequentially, or an iterative path, where users revisit and refine earlier features as needed. The choice between these modeling strategies depends on the user's approach to design development and the complexity of the clinical case (C4).

4.3 NURBS-based Modeling Approach in Rhinoceros

The development of the parametric model for a custom dental abutment in Grasshopper, integrated within the Rhinoceros environment, is shown in Figure 5. This parametric model is manually constructed by the user, who defines relationships between parameters and geometries directly within the Grasshopper script, rather than relying on pre-configured dental modeling tools. The modeling environment includes three integrated elements within the Rhinoceros tool. First, the main Rhinoceros interface provides the visual workspace where the imported jaw scans and the developing

parametric abutment model are displayed. In this viewport, the gray-shaded abutment geometry serves as a visual distinction, helping the user to differentiate the model from the surrounding anatomical scans during its construction. At this stage, the abutment geometry is in development and visualized to support the iterative design process, not as a finalized model. The abutment itself is represented as three connected geometric regions, visible within the Rhinoceros interface: the prosthesis connection segment, the transgingival segment, and the implant connection segment. These segments are progressively formed based on reference points and control parameters defined by the user, rather than being automatically extracted from the scanned data. Second, the Layers panel, which is part of the Rhinoceros interface, is used to organize the imported scans of the upper and lower jaws. Through this panel, users manage the visibility of scans within the viewport to focus on specific areas during modeling. For example, jaw scans can be repositioned directly within the Rhinoceros environment for optimal alignment, while lock functions are applied specifically to prevent accidental repositioning of the scans rather than modifications to their geometry. Third, the Grasshopper visual programming interface provides the environment for controlling the parametric aspects of the abutment model. In this setup, modifiable parameters are visually separated from the full script to simplify the representation of the model-building process. These parameters were manually defined for this case study, based on anatomical references interpreted from the scan data. The script contains 12 adjustable parameters—comprising 11 number sliders and one Graph Mapper—which controls dimensions and geometrical transitions of the abutment segments, including implant connection diameter, transgingival height and contouring, and the inclination and profile of the prosthesis connection segment. Non-adjustable components within the Grasshopper script include foundational geometric constructions such as reference points, circles, and axis definitions that support the generation of surfaces and curves for the abutment. While not exposed as modifiable sliders, these elements are essential to maintain the internal logic and structural coherence of the parametric model. Changes made to the adjustable parameters are reflected dynamically in the Rhinoceros viewport, allowing users to immediately observe the impact of modifications on the abutment geometry. This dynamic update capability facilitates responsive refinement of the model as users adjust proportions and geometries to align with clinical design objectives (C1).

The modeling process in Rhinoceros is organized according to a user-defined sequence, where the order of defining parameters depends on how the user structures the Grasshopper script. In this case study, the process begins with the definition of the implant connection geometry, which is manually parameterized to accommodate various implant systems and platforms. While the tool itself does not provide a predefined database of implant geometries, parameters such as radius, number of polygon sides, and connection height can be adjusted to represent a range of standard implant dimensions. These parameters are controlled through number sliders, which allow continuous value adjustment either by dragging the slider or by entering specific numerical values directly. The curvature profile of the transgingival segment is governed by a combination of adjustable base and top diameters, with the profile further refined using the Graph Mapper component. This tool enables the user to manually shape the transition between the base and top diameters, modifying the curvature of the transgingival profile by adjusting points on the mapping curve. The Graph Mapper requires user input to define the curve shape, providing visual control over the anatomical adaptation to the patient's gingival contour. The final stage of model development focuses on the prosthesis connection segment. Here, the height, diameter, and angulation parameters are manually adjusted to prepare the abutment for integration with prosthetic components such as crowns or bridges (C2).

The parametric modeling method in Rhinoceros allows the user to maintain control over geometric parameters that directly influence the model's suitability for manufacturing processes. By defining dimensions such as screw channel diameter and connection angles within the Grasshopper script, the user ensures that the abutment geometry can meet the material and toolpath constraints typical of dental milling and 3D printing. However, this compliance is not inherently guaranteed by the software itself. The user must define appropriate parameter limits and geometric logic within the Grasshopper script, based on prior knowledge of manufacturing constraints.

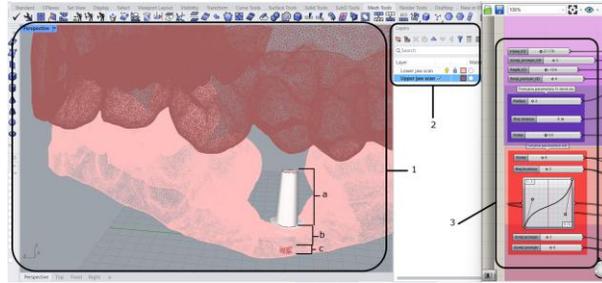


Figure 5: Abutment design interface in Rhinoceros 8 illustrating the modeling workspace and key viewports. The figure includes: (a) Prosthesis connection segment, (b) Transgingival segment, (c) Implant connection segment, alongside interface elements: (1) Rhinoceros viewport displaying the model geometry and jaw scans, (2) Layers panel organizing the jaw scans and (3) Grasshopper interface showing parameter adjustments.

Compatibility with dental production tools is addressed through the ability of Rhinoceros to export the final geometry in widely supported formats such as STL or STEP, which are required for integration with CAM systems used in dental manufacturing. However, it is important to note that Rhinoceros does not natively generate toolpaths or machining strategies; external CAM add-ons, such as RhinoCAM, are necessary to bridge the design with actual manufacturing preparation. Patient-specific jaw scans play a critical role in ensuring that the final design is anatomically aligned, but they do not directly influence manufacturability. Instead, they provide the basis for establishing design references and anatomical boundaries, which the user must subsequently evaluate and adjust according to manufacturing constraints. Within the Grasshopper environment, predefined parameters govern the essential dimensions and features of the model, but their effectiveness depends on how well the script is structured to reflect technological limitations, such as minimum wall thickness, tool clearance, or support geometry. Further steps are required to fully prepare the geometry for manufacturing. These include checking and correcting surface continuity, ensuring closed solid geometry suitable for machining, and applying any post-modeling operations required for fixture setup or milling simulation (C3).

The modeling process in Rhinoceros, supported by Grasshopper, relies on a parameter-controlled approach, where the organization of modeling steps and the sequence of parameter definitions are entirely determined by the user. In this case, the model for the custom dental abutment was manually constructed, with parameters defined based on clinical design needs, such as implant connection dimensions, transgingival contour shaping, and prosthesis connection alignment. While this implementation was developed from scratch, parametric workflows in Rhinoceros do not necessarily require building models entirely from the beginning. A predefined geometry, such as a static CAD model or a previously scripted parametric template, can also be used as a starting point. The level of technical expertise required to navigate this system is closely tied to the complexity of design modifications for the dental abutment. For basic adjustments, such as modifying the abutment height or base diameter, users interact with number sliders in the Grasshopper interface, which provide a visual and accessible means of adjusting values. For more advanced modifications, such as reshaping the transgingival emergence profile, users need to engage directly with the Grasshopper visual programming script, modify data flows and mathematical relationships between components. Organizational tools within the interface, such as Panels for labeling, Groups for visually structuring related components, and Scribbles for annotations, assist in keeping the script understandable, particularly when the model is developed collaboratively or requires future modifications. It is important to note that Grasshopper does not provide a predefined or guided workflow. The sequence of modeling actions depends on how the user structures the script. In this example, the user-defined progression began with the implant connection geometry, followed by the transgingival segment, and concluded with the prosthesis connection adjustments. While the

parametric structure allows for rapid updates to dependent geometries, the workflow itself remains fully manual and responsive to the user's design intentions. Predefined parameters in this context refer to those established during the initial script development for this abutment case, not to templates or libraries of prior designs. Users can work within these preset values for straightforward adjustments or choose to modify the underlying geometric definitions and mathematical relationships directly within the script to accommodate more complex design goals. Overall, the degree of manual involvement and control in Grasshopper depends on the intended depth of customization. For simpler modifications, users can rely on the established parameter managements within the script. For more comprehensive or unconventional designs, users need to engage more deeply with the script's structure to directly influence the geometric outcome of the model (**C4**).

5 DISCUSSION

The discussion evaluates approaches based on the predefined criteria, highlighting differences in parameter management, geometry modification abilities, manufacturing readiness, and workflow adaptability in section 5.1. Additionally, the findings are contextualized within existing research, reflecting on their implications and limitations in section 5.2.

5.1 Comparison of Approaches

The analysis highlights significant differences in how parameter management (**C1**) is handled within each CAD approach. ExoCAD provides an intuitive, dental-specific interface with predefined templates and the ability to add notes on specific case requirements, such as loose gingival conditions, peri-implantitis, or recessed gingiva, which introduce additional patient-specific design constraints [2, 13]. This aligns with Ahmed's observation that user-friendly interfaces are essential for broader clinical adoption [1], and expands on it by demonstrating how interface-level data integration supports clinical documentation in complex scenarios. The ability to directly incorporate scan data and soft-tissue context [3, 4] into the design environment further distinguishes ExoCAD from general-purpose tools. Conversely, engineering-based CAD tools such as SolidWorks and Creo offer more granular parameter management via parametric modeling environments and assembly-based constraints [5, 14]. While these capabilities correspond with the solid modeling principles discussed in the literature [10], they are rarely used in dental settings without significant adaptation. The approach demonstrated by Zhang et al. [11] confirms the feasibility of integrating SolidWorks into a dental workflow but also reveals a limited focus on geometric completeness rather than clinical context. As noted by Mari and Sacchi [15], these tools do not validate volumetric integrity in a dental-specific way, placing the responsibility for model viability entirely on the user. Similarly, Rhinoceros, a NURBS-based tool provides another layer of adaptability, supporting advanced parameter definition through visual scripting interface such as Grasshopper [14]. While these approaches align with the goals of personalized restoration design [9], they require advanced understanding of curve-based modeling [26] and are not inherently guided by dental anatomy. The necessity of scripting or numerical logic, described in prior work on computational design [12, 30], means that even though Rhinoceros is adaptable, its usability remains tied to user expertise. Tools like SimplyNURBS [29] attempt to reduce this gap but were not part of the evaluated workflow in this study.

SolidWorks and Rhinoceros provide greater adaptability in parameter management. For instance, both tools allow users to manipulate jaw scans or lock them in place, providing a more adaptable modeling environment. However, ExoCAD's data input functionality proves advantageous for patient management and complex cases, such as peri-implantitis or other jaw diseases, where additional design considerations must be documented because they indicate a new design abutment requirement. While Rhinoceros could integrate similar functionality using Panels, SolidWorks lacks a built-in equivalent, requiring integration with PDM or PLM systems for similar data management. Regarding parameter updates, SolidWorks takes a few seconds to refresh the entire design when a dimension is modified in the parameter table, whereas Rhinoceros offers real-time updates within

its interface, allowing for more immediate feedback. A key limitation of both SolidWorks and Rhinoceros is the need for dimensions of implant systems and platforms when modifying the implant connection segment. This could be addressed by linking an Excel table containing all relevant system data, enabling an automated interface to extract and apply parameters dynamically. In SolidWorks, this can be implemented using the *Design Table* functionality, while in Grasshopper, integration is possible through plugins such as *Read Excel*, *Bumblebee*, or *LunchBox*. This integration ensures consistent parameter definition and minimizes manual entry errors, though it requires ongoing maintenance of up-to-date implant system data which is an approach recommended by Magomedov et al. [8] and Ramiro et al. [13].

Regarding the modification of abutment geometry (**C2**) it varies across approaches. ExoCAD enables limited customization constrained by predefined templates. Control points in such tools allow basic shape adjustments but lack control over individual segments proposed in literature: implant connection, transgingival, and prosthesis connection segment [4]. In contrast, SolidWorks supports specific modifications of transgingival connection and prosthetic segments through dimension-driven sketches and parametric table constraints [11]. This allows users to replicate biologically relevant geometries such as conical or platform-switched connections [18]. Additionally, it allows full control over abutment geometry, though often at the cost of increased user effort and tool configuration [5, 17]. Rhinoceros, as a surface-based modeling tool, provides extensive control over freeform shapes. Grasshopper enhances this ability, enabling users to manipulate individual segments implant connection, transgingival segment, and prosthesis connection using direct geometry adjustments via number sliders and transgingival contour modifications via graph mapper. These findings align with Micevska and Kandikjan's research on the role of adaptable CAD tools in personalized design [14]. These modifications can be driven by mathematical curves or manual manipulation, enhancing both function and esthetics [14].

The model usability and manufacturing readiness (**C3**) of each approach also varies. ExoCAD supports direct STL exports and CAM integration, reducing the need for manual post-processing [5, 20, 21]. These features correspond with literature noting the role of standardized data export [19], which supports streamlined transfer to CAM environments. Its automated procedures reduce manual intervention, making it well-suited for standardized restorations, as noted by Magomedov et al. [8] and supported by Fuster-Torres et al. [20] in their assessment of CAD/CAM workflows. By contrast, SolidWorks and Rhinoceros require additional validation steps to ensure compatibility with dental CAM technologies. In the case of SolidWorks, this includes addressing features such as applying fillets appropriate for milling or verifying that overhangs and support structures are feasible for additive manufacturing. These adjustments must be considered during the modeling phase to ensure production compatibility. In Rhinoceros, users must confirm surface integrity and manufacturability, reflecting the challenges outlined by Elkhuizen et al. [19] when adapting general-purpose CAD tools for clinical use. These challenges include undetected discontinuities or overhangs that can compromise downstream milling or printing operations—issues previously discussed by Taha et al. [23]. SolidWorks mitigates this limitation by incorporating FEA simulation, which supports pre-manufacturing validation and structural optimization of implant components, as described by Alberto et al. [22].

Workflow design and the level of required expertise (**C4**) further distinguish these approaches. ExoCAD adopts a linear, guided workflow that streamlines routine clinical procedures, simplifying repetitive tasks and lowering the entry threshold for new users [2, 13]. However, this structure limits iterative design, making ExoCAD less suitable for experimental or research-intensive cases. On the other hand, SolidWorks and Rhinoceros support non-linear, iterative workflows, allowing for design revisions, advanced prototyping, and integration of research findings. The capacity to configure and revise the workflow makes these tools well-suited for academic researchers, engineers, and experienced dental professionals who work on atypical cases or require full control over geometry for experimental purposes. This capacity, while powerful, comes at the cost of greater technical complexity and a steeper learning curve. Rhinoceros requires expertise in visual scripting and parametric logic within Grasshopper, which Guo et al. [24] linked to improved modeling accuracy. Son and Lee [25] demonstrated that proficiency increases with repeated use, even among non-

specialists. Both tools rely on hierarchical modeling to structure the design process, providing users with better control over model evolution and refinement. However, this level of control can present a barrier for less experienced users unless reinforced through training or predefined templates [27, 28]. These characteristics make them especially valuable in academic and innovation-driven contexts, where custom designs and iterative exploration are prioritized. In conclusion, the choice of CAD approach directly influences the user's experience, design adaptability, and integration into clinical workflows. The following Table 2 presents a comparative overview of each approach according to the defined evaluation criteria.

Criteria	Dental approach with representative ExoCAD	Engineering approach with representative SolidWorks	NURBS based modeling approach with representative Rhinoceros
C1) Parameter management			
C1.1	Intuitive interface tailored for dental applications	Complex requires knowledge of parametric and surface modeling	Complex requires visual programming skills and surface modelling
C1.2	Optimized for specific dental workflows, direct integration with patient data, jaw scans, antagonist recognition	General engineering workflows, manual adaptation required for dental use	Adaptable but requires additional setup for dental-specific workflows
C2) Abutment geometry modifications			
C2.1	Cannot be modified due to predefined system constraints	Customizable via table modification	Customizable via number slider modification
C2.2	Limited adjustments via control points	Customizable via table modification	Customizable via graphs and number slider modification
C2.3	Automatic adjustments with predefined templates	Customizable via table modification	Customizable via number slider modification
C3) Model usability and manufacturing readiness			
C3.1	Automatically prepared for dental manufacturing technologies	Manual adjustments required for dental applications	Manual adjustments required for dental applications
C3.2	Compatible with dental equipment but not fully production-optimized	Needs adaptation for dental equipment	Compatible, but manual steps needed
C4) Workflow design and user expertise			
C4.1	Minimal expertise needed	Requires knowledge in dental design limitations	Requires knowledge in dental design limitations
C4.2	Minimal CAD expertise needed; user-friendly for dental technicians	Requires surface-based modelling skills, requires equation-driven parametric modeling	Basic CAD plus visual programming skills needed
C4.3	Linear, one-directional workflows streamline dental tasks but limit adaptability	Supports iterative workflows, ideal for advanced design and prototyping tasks	Iterative workflow with customizable processes

Table 2: Comparison between 3 different CAD tools.

5.2 Implications and Limitations

This study offers several practical implications, followed by limitations that should be acknowledged to contextualize the findings and inform future research. The focus on specific tools (ExoCAD, SolidWorks, and Rhinoceros) and their application within the dental industry may limit the generalizability of the results. Although these tools are widely used, their applicability varies depending on user needs and specific tasks. Consequently, the findings of this study may not necessarily extend to all dental design processes and applications. Based on the findings, the dental approach (ExoCAD) remains suitable for routine and standardized workflows. These typically involve cases with straightforward implant positioning, adequate bone volume, and regular soft tissue contours. In these contexts, the use of predefined implant libraries and guided steps is sufficient for generating clinically acceptable results. Engineering-based and NURBS-based approaches, although requiring more modeling experience, can offer advantages in complex or research-oriented cases. Such cases include implant placements in narrow ridges, asymmetrical soft tissue topography, or angulated implants placed to avoid anatomical structures. These conditions often require adjustments of screw channel direction, emergence profile shaping, or geometric alignment with reduced interocclusal space. Engineering-based approaches can support these tasks by allowing parameter-based definitions and consistency across design elements. NURBS-based approaches are suitable when the focus is on refining transitions and shaping surfaces where curvature and contours must be adapted manually. To clarify the distinction, clinical complexity in this context refers to implant position, tissue morphology, or case-specific constraints that affect design feasibility. Customization level denotes the extent to which an abutment must deviate from predefined geometries, including the need to adjust screw access direction, angulation, or emergence contouring. Each approach supports different types of adaptation: dental approaches are limited to predefined cases, engineering-based support parameter-based change propagation, and NURBS-based are used when free-form surface modeling is needed.

It is suggested that future work, such as Kosec's comparison of dental tools [6], should also include comparisons between different engineering and NURBS-based tools. This is particularly relevant given that engineering-based CAD tools, to support reliable applications in dentistry, must be adapted unless integrated with standardized implant systems [6, 27]. Furthermore, the qualitative nature of this research provides insights into user experiences but does not quantify the impact of different tools across a broader sample of users or tasks. While qualitative data offers an understanding of individual interactions with these tools, they may be limited in terms of generalizability and repeatability. Therefore, quantitative studies could enable a broader evaluation of CAD tool efficiency in different conditions and scenarios.

Additionally, prior familiarity with SolidWorks required extra measures to ensure objective assessment criteria and avoid biases influenced by personal experience. One avenue for future research involves the development of hybrid CAD tools that combine ExoCAD's predefined dental specific functionalities with Rhinoceros' adaptability. To go beyond standard restoration cases, such integration would require tools to handle emerging prosthetic conditions while maintaining data consistency. Rhinoceros' adaptability allows the creation of customized designs beyond standard dental constraints, making it valuable for experimental and research-driven workflows, particularly those involving atypical anatomies, irregular implant positions, or prosthetic requirements that do not conform to standard templates. Yet, these tools do not bridge the clinical-technical gap unless dental semantics are embedded, something currently underdeveloped, despite efforts like SimplyNURBS [29]. However, bridging the clinical-technical gap may require more advanced approaches. Approaches such as CATIA or NX, which unify parametric and surface modeling, could potentially reduce the disconnect between structured and free-form modeling observed in SolidWorks and Rhinoceros. In the current study, parameter-based modifications in SolidWorks supported consistent geometric logic but required workarounds to adapt to soft tissue morphology. Rhinoceros allowed manual control over geometry but did not include integrated dental libraries with predefined implant geometries, as found in ExoCAD. While ExoCAD provides ready-made components that match standardized implant systems and reduce the risk of dimensional mismatch, Rhinoceros requires the user to define implant segment parameters manually. This enables testing of custom

implant designs or alternative configurations but also requires the user to be familiar with dimensioning requirements that are acceptable for manufacturing. As a result, this workflow may be practical for engineering users, while it remains less accessible to most dental technicians, who typically rely on validated and workflow-integrated libraries rather than manual definition of implant parameters.

Adapting Rhinoceros features for dental applications could include the implementation of predefined dental-specific features or the automation of manual processes, enhancing usability in clinical settings. Additionally, workflow automation and user training remain crucial areas for further research. Developing algorithms that facilitate predefined modeling within Rhinoceros or integration with ExoCAD could enhance accessibility for technicians with varying levels of expertise. Design algorithm integration and real-time validation may streamline custom abutment workflows and reduce user effort. Guo et al. [24] emphasizes the importance of interface intuitiveness and user skill development in achieving high-quality outcomes. Similarly, Son and Lee [25] show that the iterative use of CAD systems improves user competence over time. However, translating these capabilities into widespread practice requires alignment with everyday workflows, which remain constrained by the high entry knowledge in parametric modeling [14], visual logic [12], and data structuring [30], which may limit the adoption of such workflows in practice. Training programs tailored to parametric modeling with Grasshopper or scripting in ExoCAD could broaden adoption and streamline daily workflows across the dental sector. Moreover, quantitative research would provide clearer insights into the practical implications of CAD tool selection. Metrics such as modeling speed, the required design iterations, and user satisfaction could inform evidence-based CAD adoption strategies. For instance, analyzing the time required for parameter adjustments or the frequency of errors in the design process could provide valuable data to improve these tools for specific dental applications. Furthermore, exploring collaborative design (co-design) methodologies could enhance cooperation among professionals with different expertise. Co-design enables simultaneous participation of multiple specialists in the design process, ensuring better information exchange and improved product quality. Integrating real-time collaboration plugins such as Speckle or Shapediver into Rhinoceros could support more streamlined workflows, reduce iteration times, and improve communication, accelerating model adaptation.

6 CONCLUSIONS

The evaluation of the three selected tools – ExoCAD, SolidWorks, and Rhinoceros – within the context of designing a custom dental abutment demonstrates tool-specific advantages and constraints that directly impact their suitability for this type of application. ExoCAD, as a tool developed specifically for dental use, supports streamlined processes for standardized restorations and provides integrated functions for anatomical alignment and scan management. However, during the modeling of the custom abutment, limitations were observed in adjusting complex geometries, particularly in the transgingival and prosthesis connection segments, where modifications beyond predefined templates were restricted by the tool's built-in constraints. SolidWorks enabled full parametric control over the geometry, including dynamic adjustment of implant interface dimensions, transgingival profiles, and prosthesis connection contours. The clear hierarchical structure of the model and the use of parameter tables supported iterative refinement of the design. Nevertheless, SolidWorks lacks embedded dental functionalities, such as anatomical scan alignment or automated margin definitions, which require manual input and interpretation of clinical data to establish appropriate references. Rhinoceros, enhanced with Grasshopper for parametric scripting, offered control over geometric relationships and enabled the creation of patient-specific transgingival and prosthesis connection segments. By defining custom parameters and using curve-based constructions, the tool supported adaptability in shaping the abutment geometry to accommodate specific anatomical conditions. However, as with SolidWorks, the absence of dental-specific functions meant that critical steps such as implant positioning and adaptation to soft tissue contours depended heavily on user expertise and manual adjustment of reference geometries derived from scan data. ExoCAD, while less adaptable for complex or non-standard cases, simplifies the design process for

routine clinical cases through its predefined processes and embedded dental libraries. Rather than indicating an absolute preference for one tool over another, the findings of this study emphasize the importance of selecting the tool according to the clinical and design requirements of the specific case. For individualized components such as custom abutments, tools offering detailed parametric control and surface modeling capabilities present advantages, provided that the user has the necessary technical knowledge. The main contribution of this study lies in establishing a comparative framework for evaluating dental, engineering-based, and NURBS-based CAD approaches in the context of custom abutment design. By linking modeling functions to clinical design requirements, this work provides guidance on selecting appropriate tools based on case complexity and user expertise.

Future research could explore the development of hybrid solutions that integrate advanced parametric modeling approaches with dental-specific functionalities. Approaches such as CATIA or NX, which support both structured and surface modeling in a single environment, should be evaluated to determine how and to what extent they can support the modeling of complex abutments. This is especially relevant in workflows where multiple components and anatomical references must be managed consistently and simultaneously. This may also help overcome some of the limitations observed in this study, such as the lack of associativity in NURBS modeling or the limited free-form capabilities in SolidWorks [10].

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Iris Huć, <https://orcid.org/0009-0008-6417-3863>

Petar Kosec, <https://orcid.org/0009-0002-7001-8815>

Tomislav Martinec, <https://orcid.org/0000-0002-6487-4749>

Stanko Škec, <https://orcid.org/0000-0001-7549-8972>

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