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Advancements and Challenges in Mass Personalization in Dental Prosthetics: A Comparative Analysis of CAD Tools

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Abstract: This research paper explores mass personalization (MP) within the dental industry, focusing on the role of computer-aided design (CAD) tools in facilitating mass personalization. Through a literature review, current approaches for design for mass personalization were investigated, and key characteristics of mass personalization influencing the capabilities and options of CAD tools were highlighted. Based on the literature review, key criteria for mass personalization were defined for assessing CAD tools. By conducting a comparative analysis of four dental CAD tools—ExoCAD Rijeka 3.1, 3Shape Dental System 2023, Straumann Nova 2023, and UpCAD by UP3D — the research identifies strengths and areas for improvement in their adherence to MP characteristics. Notably, while ExoCAD and 3Shape exhibit robust capabilities, limitations persist in the interpretation of design requirements and the automation of design processes. The paper proposes future research directions, emphasizing the integration of generative design and machine learning algorithms to augment automation and facilitate seamless communication channels between dental professionals and patients within CAD environments.

Keywords: Mass personalization, dental CAD, DfMP, mass personalization criteria, data-driven design
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1 INTRODUCTION

Mass personalization (MP) represents a transformative approach in manufacturing, revolutionizing traditional production methods by integrating product personalization into large-scale processes [3]. This production paradigm prioritizes customers' needs and preferences, offering tailored products on a previously unattainable scale through conventional mass production methods [16]. While the potential benefits of mass personalization are vast, developing a generalized methodology for

designing personalized products remains a complex challenge, particularly in effectively translating specific customer preferences into functional product features [3,51,73].
Central to the realization of mass personalization is the role of computer-aided design (CAD) tools [48], which are instrumental in translating customer preferences into tangible design parameters. These sophisticated software applications utilize parametric modeling, generative design algorithms, and digital communication channels to create highly customized products [31,44,64,66]. However, despite these technological capabilities, the lack of a comprehensive design framework specifically tailored for mass personalization often complicates the seamless integration of personalized products into existing manufacturing processes [73].

The dental industry presents a unique context where the demand for personalization is not just desirable but necessary due to the individualized nature of dental anatomy. Dental prosthetics, including crowns, bridges, and implants, require an exceptionally high level of personalization to ensure they meet the functional and aesthetic needs of the patient [65,68]. Precision in design and fit between components is critical, as even minor discrepancies can lead to discomfort, improper function, or aesthetic dissatisfaction. CAD tools in dentistry translate intricate patient-specific data, such as intraoral scans and detailed anatomical measurements, into precisely tailored dental prosthetic solutions [20]. By leveraging advanced design techniques and digital technologies, these tools enable dental professionals to craft restorative prosthetic solutions that closely match the specific requirements of individual patients, significantly enhancing fit, comfort, and overall functionality [4].

Despite the potential of CAD tools in dental prosthetics, challenges persist in integrating mass personalization principles into the design process. The absence of design for mass personalization (DfMP) methodology impedes the advancements in dentistry and limits the accessibility of personalized treatment options. Without clear guidelines and criteria for integrating MP into CAD tools, the design process remains fragmented and less efficient, preventing the full realization of MP's benefits in dental care. This is further emphasized by the need for more studies in the literature regarding the impact of mass personalization (MP) on the dental industry and CAD tools in general. Moreover, there is a lack of a systematic review and analysis of MP outlining the specific features a CAD tool must possess to effectively generate designs for mass personalization.

This study aims to perform a comparative analysis of CAD tools used in the design of personalized dental prosthetics (in this study design of dental abutments), in accordance with defined mass personalization (MP) criteria. Dental abutments are intricate prosthetic components that demand high precision throughout their design and manufacturing processes. They act as the critical interface between a dental implant and the restorative crown, with their precise design being vital for the success of the entire dental prosthetic treatment. As highly individualized components, abutments must be custom-fitted to the unique anatomical features of each patient's oral cavity, ensuring a proper fit and optimal functionality. This need for customization places them at the center of mass personalization, highlighting their value as a model to assess how CAD tools handle personalized design tasks. The process of designing abutments can effectively demonstrate the capabilities of CAD tools, showcasing features such as parametric modeling, integration with digital imaging technologies (such as intraoral scans), and their capacity to create manufacturable outputs. Comparing these tools using mass personalization criteria while designing real-world components like dental abutments offers valuable insights into their efficacy, ease of use, adaptability, and conformity to MP characteristics. Through this analysis, this study aims to provide insights that could facilitate the integration of MP principles into the dental industry, ultimately enhancing the quality, accessibility, and affordability of dental prosthetic solutions. By evaluating the capabilities and limitations of these CAD tools, this study further aims to identify areas for improvement and contribute to developing advanced CAD tools for MP in the dental industry and beyond.

2 RELATED WORK

This section explores the diverse methodologies in DfMP, identifying distinct approaches that enhance product. The evolving landscape of MP has seen the emergence of several influential design approaches, each tailored to meet different industry needs while promoting design process efficiency and customer satisfaction. By examining these approaches, we can better understand the requirements for the integration of MP into CAD tools, which is crucial for addressing the unique challenges of product design for MP. The following delineates three primary approaches—open product architecture design, data-driven design, and seed design approach—providing an overview of their deployment and impact in the field.

2.1 Current MP Design Approaches

There are three main approaches to mass personalization design, as identified in recent studies. [12,49,56]: open product architecture design, data-driven design, and seed design approach. The open platform product architecture design approach, as proposed by Berry et al. [13], emphasizes the flexibility of a product structure achieved through the integration of common, customized, and personalized modules [37]. Common modules provide the core functionalities of a product, while customized modules enable the integration of new functionalities and technologies into the product. [38]. The most intricate aspect of this approach lies in the personalized modules, uniquely tailored to meet individual preferences and needs, thereby enhancing the overall user experience and satisfaction. Personalized modules require careful design and integration strategies to ensure they function seamlessly within the broader modular system [72]. However, reliance on modular structures can potentially limit the achievable degree of customization because these systems often constrain design options to pre-defined modules and components. This rigidity means that while modules can be swapped or modified to an extent, the fundamental architecture may not allow for completely unique or bespoke adaptations that fully address specific user needs. This setup can pose challenges for non-technical users, who might find it difficult to navigate the complexities of modular customization, thus restricting the accessibility and ease with which these systems can be tailored to individual preferences.

The data-driven design approach uses mathematical models and algorithms to improve open platform product architecture design approach [18], [19]. The data-driven design approach relies on user-generated data, which encompasses explicit user-provided information and implicitly gathered data through user behavior and interactions [80]. By analyzing this data, designers can gain valuable insights into user preferences, behaviors, and needs, guiding the development of personalized solutions. However, while the data-driven design approach enhances the customization process by leveraging user-generated data to tailor products to individual needs, it has limitations. One major drawback is the complexity involved in accurately interpreting and integrating vast amounts of data from diverse sources, which can sometimes lead to inconsistencies and inaccuracies in the final product design [54]. Additionally, the reliance on advanced algorithms and continuous data input can create a dependency on high-quality data [71], which may only sometimes be available. These challenges can hinder the seamless application of data-driven design in mass personalization, particularly in scenarios requiring rapid customization and real-time adjustments. To address these issues, the seed design offers a complementary approach. By focusing on creating a flexible, parametric template that can be easily adapted to specific customer requirements, the seed design approach simplifies the customization process and reduces the reliance on complex data analysis [16]. This approach enhances the practicality and efficiency of mass personalization, ensuring consistent and high-quality outcomes even in the face of data limitations. In a recent study, Ozdemir et al. [50] introduced a seed design approach to enable mass personalization through flexible initial product design containing both common and varying design aspects. The seed design template with variable parameters allows for customization to meet specific customer requirements, facilitating modifications and variations in design features [16]. Despite its efficacy in generating adaptable parametric designs, limitations such as insufficient interaction between functional and physical domains and inconsistencies in application protocols have been identified. Seed design emphasizes the critical role of design constraints [51] and underscores the need for enhanced consistency and empirical validation to assess its practical utility and robustness in real-world applications [49].

While various methodologies aim to establish systematic procedures for creating personalized products and services [16], there needs to be more evidence to confirm the effectiveness and scalability of these approaches [73]. Each approach integrates user input to varying degrees, ensuring the final product closely aligns with individual preferences and needs. However, they differ in their execution and focus. The open platform product architecture design relies on modularity and flexibility within predefined structures, while the data-driven design leverages extensive data analysis and algorithms to tailor products dynamically. The seed design approach combines elements of both, using flexible templates and parametric adjustments to achieve customization without the need for extensive data interpretation. These differences require different functionalities of CAD tools. The open platform product architecture design approach requires CAD tools that can handle modular components and facilitate easy integration of new modules. Data-driven design necessitates CAD tools capable of analyzing and incorporating large datasets, as well as integrating machine learning algorithms to automate design adjustments. The seed design approach demands CAD tools with robust parametric design capabilities and flexibility to accommodate varying design templates. By addressing these requirements, CAD tools can effectively support the diverse approaches of mass personalization, ultimately leading to more efficient and user-centric product development processes.

2.2 Criteria for Evaluating CAD Tools in MP Design

The product design process plays a crucial role in shaping the capabilities and functionalities required in CAD (Computer-Aided Design) tools [14,82]. Generally, CAD tools are used to conceptualize, embody, and visualize a product, providing stakeholders with tangible representations of products. To assess the current state of CAD tools regarding mass personalization, it is vital to acknowledge the influence of mass personalization (MP) on both the product design process and the CAD tools themselves. Specifically, it is important to identify which characteristics of MP directly impact the capabilities of CAD tools. The characteristics are organized into five groups: cocreation during the design process, design generation, design manipulation, design validation, and manufacturing.

Many researchers emphasize users' active involvement in the design process [23], underscoring the need for CAD tools to support collaborative design and designer-user product co-creation. This involves incorporating mechanisms within CAD tools for collecting and integrating customer feedback by annotating designs, suggesting modifications, and interacting with the design virtually.

Furthermore, intuitive and user-friendly interfaces in CAD software make it easier for non-professional users to engage in the design process [53]. Clear navigation, simple toolbars, and interactive tutorials help users navigate the CAD environment and contribute effectively to the design process. This also includes the tool's ability to guide designers systematically through the design process, providing step-by-step instructions or enforcing predefined rules to achieve desired outcomes. These features enable non-professionals to generate a usable product and facilitate consistency and efficiency in design execution, particularly in complex design scenarios [35].

One crucial aspect of the design process for mass personalization is understanding and synthesizing diverse user inputs to individual product requirements, characteristics, and constraints [18]. Methods such as Quality Function Deployment, combined with Function Decomposition and Aggregation methods [42], and Axiomatic Design method [40], are often used in the product design process. However, due to the characteristic of mass personalization that the design process itself should be more accessible to non-professional users, some authors [52,79] advocate for the integration of these methods into CAD tools for interpreting user data into product requirements and, ultimately, design parameters and constraints. If incorporated into CAD tools, they would greatly assist in defining user requirements, especially for users with less experience in product development. However, to enable this, CAD tools must have access to large amounts of data. While using AI systems is not mandatory, integrating them can significantly ease the process for users by assisting in interpreting and defining requirements [19,47].

When examining various design approaches, it becomes evident that each necessitates distinct features and capabilities in a CAD tool. Following the open platform design approach, Koren et al. [24] emphasize the importance of generating and using a "Module Library" by means of integration of common (standardized) modules. CAD tools should support adding and adapting customizable and personalized modules onto the common modules using interface standards published by module manufacturers [79]. Xiang et al. [79] emphasize the importance of designing interfaces that can connect modules in a manner that is both functionally and physically separated, enabling efficient organization of the production process. This also enables the easy assembly and disassembly of modules within the product architecture, allowing designers to work on individual modules without disrupting the core platform of a product. Similarly, Rizzi et al. [57] emphasize the need for CAD tools to enable direct parts customization through specifically designed common geometry of a product and allow geometry transition from predesigned product geometry to customized and personalized geometry. Moreover, the "seed design" approach [51] requires advanced parametric design options explored by Micevska et al. [44]. Such product configuration options must support creating and manipulating seed designs featuring parametric and interactive part manipulation. By incorporating parametric design features, such CAD tools enable designers to adjust design parameters within defined constraints, while interactive point, curve, and surface manipulations allow designers to make specific adjustments to the shape, size, and contour of a product.

Jiang's [33] data-driven generative design approach for mass personalization recognizes the need for design process automation. Traditionally, CAD tools relied heavily on manual input from designers to create and modify designs. However, with the incorporation of data-driven methods, CAD tools would harness algorithms to automatically generate design variations based on user preferences and interaction data, thereby reducing manual effort and boosting efficiency [41]. By leveraging existing designs, personalized user data, and user-product interaction data, CAD tools can produce designs closely tailored to individual user needs. For example, in designing a bike saddle [33], CAD tools can utilize data-driven generative design to adjust the saddle's shape and structure automatically, reflecting collected user preferences and interaction data. This represents a significant shift towards more personalized and user-centric design methodologies [56]. Moreover, the integration of generative adversarial networks (GANs) within this approach enables rapid generation of design variations, showcasing CAD tools' utilization of advanced machine learning techniques to enhance design efficiency.

Utilizing simulation options such as assembly, usage, and structural analysis [57,78] enhances the mas personalization design process in multiple ways. On the one hand, it enables users to participate in product analysis through visual representations of a product in its simulated environment [29]. By providing users with the opportunity to interact with virtual prototypes and observe simulated product behavior, CAD tools empower users to give feedback based on the application and simulation they experience. This feedback loop ensures that user preferences and requirements are accurately captured and incorporated into the design process, leading to more user-centric and functional product designs. On the other hand, simulation options also reduce the time needed to generate physical prototypes for the final product [34]. By simulating different usage scenarios and analyzing product performance virtually, designers can identify potential issues and optimize designs before producing physical prototypes. This not only saves time and resources but also enables rapid iteration and refinement of designs, ultimately resulting in better-quality products.

From a manufacturing standpoint, CAD tools should facilitate the translation of digital designs into physical products, ensuring that personalized designs are manufacturable. Therefore, CAD tools need to incorporate functionalities for assessing the manufacturability of personalized designs, simulating different manufacturing processes, and evaluating their impact on the final product [49,81]. Several authors [15,51,61] underscore the need for CAD tools to seamlessly integrate with digital manufacturing technologies that ensure manufacturability and quality and emphasize the mass-production aspect of personalization. By connecting CAD systems with digital manufacturing platforms, such as computer numerical control (CNC) machining, additive manufacturing (AM), and automated assembly systems, CAD tools enable the efficient translation of personalized designs into physical products at scale. This integration streamlines the entire production process, from design conception to final manufacturing, allowing for the rapid and cost-effective production of customized products. Bingham [16] and Ozdemir [50] examine the impact of AM on CAD tools, highlighting the significant role of CAD software in generating complex product designs following AM design rules.

By synthesizing insights from existing research studies related to MP, a list of design criteria for comparing CAD tools has been compiled (Table 1).

Criteria	Description
C1) Cocreation during the design process	
C1.1	ability to interpret customer inputs into product functional requirements
C1.2	ability to integrate individual user data into the design process
C1.3	capability to guide them through the design process following predefined procedures or rules
C1.4	ability to include customer feedback in the design process
C1.5	the ability of iterative design
C2) Design generation	
C2.1	ability to select the predesigned, standardized common module of the product
C2.2	ability to generate seed design automatically using input data and constraints
C2.3	ability to generate product design based on previous designs
C2.4	ability to change design constraints during the design procedure
C3) Design manipulation	
C3.1	support for parametric manipulation and customization of seed design
C3.2	advanced geometry manipulation techniques
C3.3	ability to use free-form options
C4) Design validation	
C4.1	ability to visually represent if the design exceeds design constraints
C4.2	ability to simulate the product assembly process
C4.3	ability to simulate product usage
C4.4	ability to perform structural validation of a product
C5) Manufacturing	
C5.1	ability to incorporate manufacturing requirements during the design process
C5.2	ability to directly integrate with different manufacturing systems

Table 1: List of design criteria for comparing CAD tools.

2.3 Mass Personalization in Dental Applications

Personalization in the dental industry is characterized by its focus on tailoring dental prosthetics such as custom abutments, crowns, bridges, and dentures to each patient's unique oral anatomy and functional requirements. This approach enhances patient satisfaction and ensures superior fit, comfort, and functionality, leading to improved treatment outcomes [70]. Traditionally, dental prosthetics have been crafted using manual procedures, which often results in suboptimal outcomes for patients [11]. However, the emergence of MP principles has ushered in a new era of personalized dental solutions, leveraging advanced design methodologies and digital technologies to cater to individual patient needs and preferences [63]. Specialized dental CAD tools play a key role in the implementation of MP in dentistry [36]. These advanced software programs make use of digital scanning, parametric modeling, and 3D printing technologies to create personalized dental products [58]. By incorporating patient-specific data from intraoral scans and anatomical measurements, CAD tools enable dental practitioners to develop customized restorative solutions that meet the unique needs of each patient.

The design of dental prostheses involves a collaborative process among dentists, dental technicians, and patients. While dental technicians typically operate these CAD tools, their expertise lies in dental practices rather than extensive CAD knowledge. Dentists and patients actively participate in the design process, providing insights into clinical needs and personal preferences for the product. Dentists consult with technicians on design-specific characteristics, such as the shape of the prosthesis, clinical requirements, and assembly preferences [11]. They also provide essential implant information and create replicas of the patient's jaw using either traditional impression methods or intraoral scanning technologies [62]. Patient involvement extends beyond providing intraoral scans or CBCT images; they also contribute individual preferences regarding prosthesis design and offer feedback after prototype manufacturing and mounting, aiding in refining the final product. Feedback from patients, communicated through various mediums such as videos, photographs, or verbal communication, is crucial for iterative refinement of the design. Dental technicians interpret this feedback, incorporating necessary adjustments into the CAD tool for further design. Once finalized, the prosthetic components are manufactured using milling or additive technologies, followed by manual finishing for color adjustment, polishing, and glazing [10].

Examples of successful implementation of mass personalization in the dental industry are currently scarce. While some may point to the production of Invisalign aligners as an instance of mass personalization, these claims lack scientific validation. Additionally, research on the analysis of dental CAD tools and the design approaches employed in these tools is limited, mostly viewed from the perspective of practical application [5,46,69] in the dental industry rather than the theoretical aspects of CAD tools and design procedures, or in the context of finite element analysis (FEA) and topological optimization for prosthesis design [23,76,77]. However, in recent years, there has been a notable increase in the number of studies highlighting the benefits of machine learning, particularly genetic algorithm-based (GaN) approaches, in dental design [7,9,27,32,59]. One noteworthy example is the comparison between a crown designed by a dental technician and GaN algorithm [24]. This study showcases the potential advantages of machine learning in dental prosthetic design, demonstrating that algorithms can match or even surpass human expertise in creating personalized dental prosthetic products. By leveraging such advanced technologies, the dental industry can significantly enhance the efficiency, scalability, and quality of products, ultimately leading to better patient outcomes and more accessible personalized dental care.

3 OBJECTIVE AND METHODOLOGY

This study explores the alignment of selected dental CAD tools with MP characteristics, providing valuable insights for their advancement in dentistry. Four dental CAD tools are compared to recognize their adherence to MP principles, uncovering their capabilities and limitations in this context. The study employs a set of predefined criteria for evaluating and comparing the CAD tools' performance regarding MP.

The selected CAD tools—ExoCAD Rijeka 3.1 [83], 3Shape Dental System 2023 [84], Straumann Nova 2023 [85], and UpCAD by UP3D [86] (further in text ExoCAD, 3Shape, Nova, and UpCAD) — represent a diverse spectrum of technologies and functionalities in the dental CAD software landscape. ExoCAD and 3Shape are prominent tools in the market, each offering distinct features. ExoCAD is an open system known for its flexibility and compatibility with various implant manufacturers, 3D scanners, and manufacturing technologies. At the same time, 3Shape excels with the TRIOS scanner integration, enabling seamless communication between clinics and laboratories. Nova is tailored specifically for the Straumann implant group, providing direct integration with Straumann hardware solutions. On the other hand, UpCAD, developed by UP3D, is an evolving CAD tool that offers fundamental design options for dental clinics and laboratories.

This selection ensures diverse comparison, encompassing established industry CAD tools, open and closed CAD systems and emerging technologies. The comparison focuses on the design of individual dental implant abutments—a critical element bridging the implant and the final dental restoration—using each CAD tool. The comparison of CAD tool capabilities and features followed predefined criteria, with additional validation conducted by consulting the CAD tool manufacturers' guidelines in cases of significant discrepancies.

4 CASE DESCRIPTION

For the CAD tool comparison, a case of a 30-year-old patient was selected, who had a tooth extracted at position 35, fifteen years ago. Early signs of periodontal disease, involving soft tissue recession, are also visible. A dental practitioner placed a Straumann implant, precisely a Bone Level type, with a diameter of 4.8mm and a length of 8mm. This case was deliberately chosen to maximize the capabilities of the Nova CAD tool. The Nova is specifically designed to work optimally with Straumann implants, and by selecting a case that involves a Straumann Bone Level implant, the study ensures that the tool's features and integrations can be fully utilized and evaluate. The therapy requires the design of a custom titanium abutment, onto which a zirconia crown will later be placed. Additionally, a jaw replica was created using the TRIOS scanner to fully leverage the integration benefits with the 3Shape.

The design of an abutment comprises of three main segments: implant connection segment, transgingival segment and prosthesis connection segment, shown in Figure 1. The design of the implant connection segment is defined by the connection geometry of a placed implant and fulfils the main functional requirement of an abutment – securing stability and sealing surface between the implant and prosthetic restoration (commonly named "passive fit" in literature). The transgingival segment is shaped around the oral tissue surrounding the implant, with the emerging contour of this segment replicating the natural emergence profile of a tooth. The prosthesis connection segment is formed according to the shape, size and type of prosthetic restoration attached to it using dental cement. Both segments are designed using specific guidelines for dental abutments known to dental professionals [2]. However, these segments are unique in shape and function since they are designed for a particular patient and have specific design requirements.

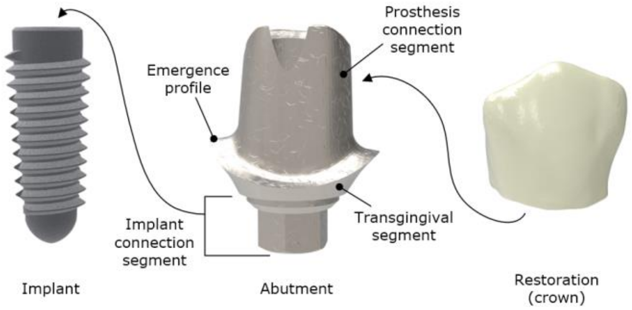

Figure 1: Abutment segments and connecting parts (implant and crown).

Design of an abutment is conducted using a specified procedure to ensure consistent evaluation of CAD tools. The design procedure comprises the following nine steps: **S1** - determining initial constraints (minimal thickness and cement gap between restoration and abutment), **S2** - inserting, editing and fixing scans of patient's oral cavity, **S3** - determining implant connection segments from the database, **S4** - defining emergence profile on the oral scans, **S5** - designing the transgingival segment, **S6** - approximate placement of the final restoration (crown) to determine the available space for designing the coronal part of the abutment, **S7** - designing the coronal part of the abutment, **S8** - final customization of the abutment design (using free form tools, adding custom-made geometries), and **S9** – modifying the design according to the feedback.

5 RESULTS

A comparison table (see Table 2) was compiled to demonstrate the performance of four CAD tools based on predefined criteria. The qualitative evaluation demonstrates the capabilities of each tool concerning individual criteria and describes the extent to which the criteria are met. If a tool lacks a capability that would enable it to meet the listed criteria, a minus sign (-) is entered in the corresponding field. The discussion below mostly follows the order of criteria as presented in the attached table. However, since certain features of CAD tools overlap, slight deviations from the described order are possible. It is important to note that the defined criteria table can be expanded or refined with sub-criteria. However, for the purposes of this study, an initial list of criteria for evaluating CAD tools for MP has been compiled. The criteria list will be expanded through further research on MP and the establishment of new approaches in design for MP.

<table>
<tr><th></th><th>ExoCAD Rijeka 3.1</th><th>3Shape Dental System 2023</th><th>Straumann Nova 2023</th><th>UpCAD</th></tr>
<tr><td colspan="5">C1) Cocreation during design process</td></tr>
<tr><td>C1.1</td><td colspan="4">-</td></tr>
<tr><td>C1.2</td><td colspan="3">• 3D scans, CBCT 3D models, photographs</td><td>• 3D scans</td></tr>
<tr><td>C1.3</td><td colspan="2">• each segment of an abutment is designed procedurally, wizard (step by step) mode and expert mode</td><td colspan="2">• each segment of an abutment is designed procedurally, wizard (step by step) mode</td></tr>
<tr><td>C1.4</td><td>• web based 3D model sharing option, available for free for patients</td><td>• case chat with option to share screenshots, 3D models, annotation, not available to patients</td><td colspan="2">• does not have integrated option for receiving feedback information</td></tr>
<tr><td>C1.5</td><td>• has the ability for incremental iterative design procedure</td><td colspan="3">• have the ability for iterative design procedure</td></tr>
<tr><td colspan="5">C2) Design generation</td></tr>
<tr><td>C2.1</td><td colspan="4">• implant connection segment is predefined using database of implants</td></tr>
<tr><td>C2.2</td><td colspan="3">• seed design is generated using input data such as oral scans, predefined design parameters, autodetected emergence profile, shape of the restoration, tooth position, implant placement, etc.</td><td>• seed design has generic shape; it is not shaped according to input data</td></tr>
<tr><td>C2.3</td><td colspan="4">-</td></tr>
<tr><td>C2.4</td><td colspan="2">• restricted ability to change constraints during design process</td><td colspan="2">• does not have the ability to change constraints during design process</td></tr>
<tr><td colspan="5">C3) Design manipulation</td></tr>
<tr><td>C3.1</td><td colspan="4">• each segment of the design is manipulated using parameters</td></tr>
<tr><td>C3.2</td><td colspan="2">• manipulation using predefined planes, curves, and control points
• option for adding additional control points</td><td colspan="2">• manipulation using predefined planes, curves, and control points</td></tr>
<tr><td>C3.3</td><td colspan="4">• available free form options (sculpt tools)</td></tr>
<tr><td colspan="5">C4) Design validation</td></tr>
<tr><td>C4.1</td><td colspan="2">• visual representation when design exceeds the defined constrains</td><td colspan="2">• does not support visual representation when design exceeds defined constraints</td></tr>
<tr><td>C4.2</td><td>• contact surfaces interference check</td><td>• contact surfaces interference check
• simulation of abutment screw and crown mounting
• mounting interference check</td><td colspan="2">• contact surfaces interference check</td></tr>
<tr><td>C4.3</td><td colspan="2">• jaw motion simulation using virtual articulator</td><td colspan="2">-</td></tr>
</table>

C4.4	-		
C5) Manufacturing			
C5.1	• Selection of predefined technology options (milling, additive manufacturing) • option to change technology parameters during design	• Selection of predefined technology options (milling, additive manufacturing)	
C5.2	• automatically generate manufacturing files • files include product part type and features information • direct integration with common dental CAM software	• automatically generate manufacturing files • files include product part type and features information • integration with Straumann centralized milling	• automatically generates manufacturing files • files include product part type and features information • integration with UP3D manufacturing technologies

Table 2: Comparison between four different dental CAD tools.

Starting with the criterion focusing on the CAD tool's ability to interpret instructions from the participants involved in the design process to design requirements—namely, the dental technician, dentist, and patient — an immediate limitation in the selected CAD tools becomes apparent. In the case scenario provided, crucial patient data regarding their health status and history, such as the onset of periodontitis and the absence of a tooth for 15 years, are outlined. These details are of great importance for the design process and must be considered during the design of the abutment. Due to the onset of periodontitis, adjustments to the depth of the emergence profile on the abutment become necessary during design of transgingival segment of an abutment. This entails adding a minimum of 2mm depth (or estimated value made by the dentist using patient history or in relation to surrounding teeth displaying tissue) onto the usual 1-2mm emergence profile depth. Additionally, the period of the absence of a tooth coupled with the chosen implant length indicates a diminished bone cross-section, directly impacting the implant assembly's stiffness and stability. In the context of abutment design, this underscores the importance of reducing cantilever loading on the implant. Unfortunately, beyond textual records within CAD tool's project manager, tools lack the automated capability to interpret such information into specific design requirements. Instead, the design process heavily relies on the experience and judgement of the dental technician. However, ExoCAD, 3Shape, and Nova facilitate the interpretation of given data by allowing the designer to simultaneously use different sources of patient's anthropometric data - 3D jaw scans, CBCT images and models, and photographs. The designer is able to upload the mentioned data into the tool's interface (Figure 3 and Figure 3) and use them while interpreting the given input data into requirements and to define parameters and constraints of the design (e.g., by measuring relevant structures on the jaw, visually comparing them with the designed product, etc.). Compared to other tools, UpCAD only allows 3D jaw scans as 3D design data, which is considered the minimum required for the design process.

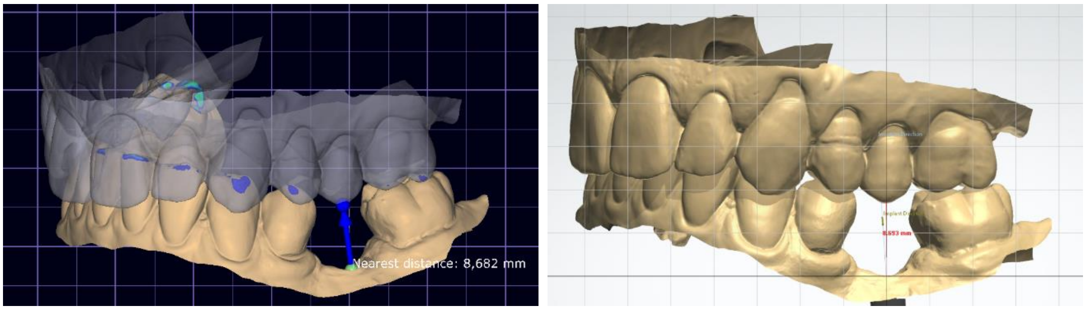

Figure 2: Imported 3D scanned data into each tool's interface (left – ExoCAD; right - 3Shape).

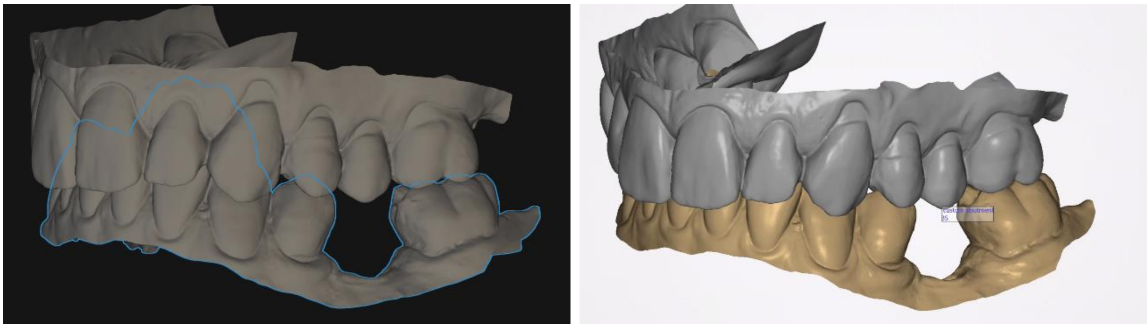

Figure 3: Imported 3D scanned data into each tool's interface (left – Nova; right – Up3D).

The design process is similar in all four tools, with minor differences among the steps, and they all support iterative design. This structured and iterative approach is important for an effective and consistent MP design process, optimizing workflow efficiency and maintaining a consistent design process across various projects. Additionally, iterative design facilitates continuous improvement and refinement, as patient feedback is incorporated into the design procedure to meet evolving requirements. Notably, ExoCAD offers an additional feature: incremental, iterative design using expert mode. This means that instead of reverting sequentially through steps for adjustments, modifications can be directly incorporated within a specific step of the design procedure. Following a change, ExoCAD autonomously adjusts the remainder of the design to align with the modified geometry.

ExoCAD and 3Shape both feature built-in mechanisms for communication and exchanging design information through web interfaces (Figure 4). With ExoCAD, users can review designed abutments within jaw scans, while 3Shape has the option of initiating Case chats for each case, offering options for sharing 3D models and images. However, neither communication mechanism enables annotating on the models, meaning that feedback from the dental technician must again be interpreted into requirements based on verbal and written information. Additionally, the 3Shape Case chat is only available to dentists, meaning direct sharing of designs with patients is not facilitated, whereas ExoCAD utilizes a free web application accessible to patients as well. On the other hand, Nova and UpCAD do not have any integrated options for sharing designs and receiving feedback, apart from exporting 3D models, saving screenshots, and sending them via email.

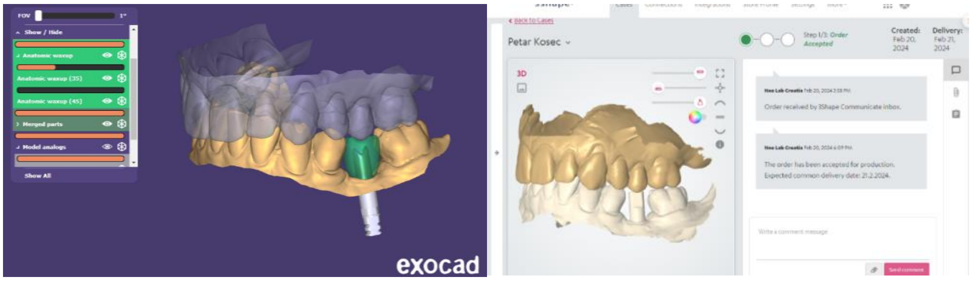

Figure 4. Web applications for reviewing the design (left – ExoCAD; right – 3Shape).

Abutment design in all four tools starts with defining the functional segment of the design (Figure 1), the implant connection segment. In the context of seed design, this segment serves as the foundational geometry for designing personalized segments of an abutment. Users select the implant connection segment through the tool interface, with predefined geometries set by the manufacturer (unmodifiable by the user). Using this geometry, manufacturers also define constraints for designing individual abutment segments, such as minimum height and width of the transgingival segment, minimum hole diameter for the screw securing the abutment to the implant, determining the minimum dimensions of the prosthesis connection segment, among others. This is similar to the open platform design approach, where the common module is defined and constrained by the manufacturer, while customizable and personalized modules are defined by the user.

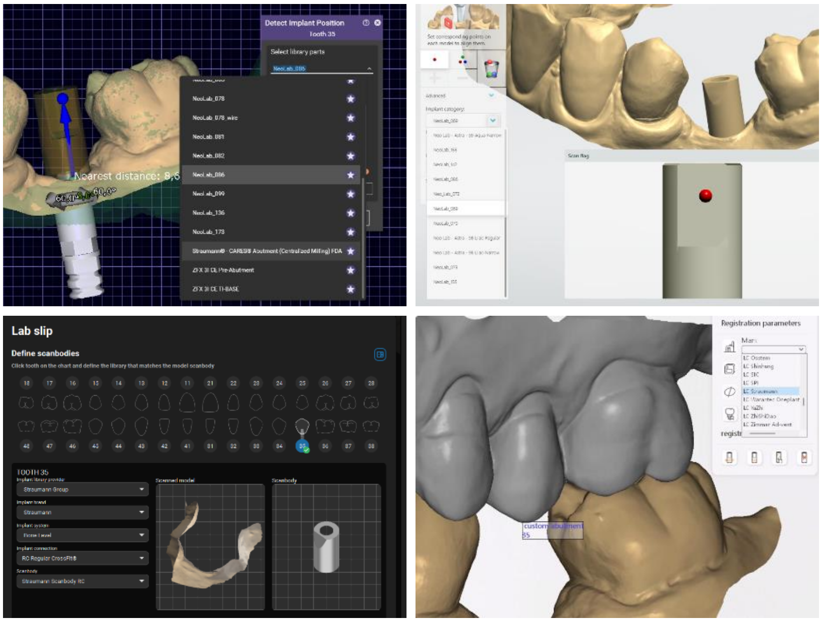

Figure 5: Implant connection segment selection (top left – ExoCAD; top right - 3Shape; bottom left – Nova; bottom right – Up3D).

ExoCAD, 3Shape, and Nova additionally offer the ability to generate the initial abutment shape based on loaded jaw scans, geometry around the implant, crown shape coming onto the abutment, etc. It is also based on basic parameters or constraints predefined according to the selected abutment and prosthetic crown material (minimum required thickness of titanium abutment and zirconia crown). This represents the second level of seed design in these tools, which refers to the individual segments of the abutment design. Additionally, custom parametric constraints can be added only in ExoCAD. However, this feature is not directly accessible to users; it requires customization of configuration files, which demands expert knowledge from the user. Nevertheless, the existence of such an option greatly enhances the possibility to generate secondary seed design, based on input parameters, that requires minimal changes to reach the final product. On the other hand, UpCAD does not automatically optimize or adapt the design of the abutment; instead, it provides a generic shape that the user can then modify using parametric modeling. In contrast, other tools also support parametric modeling but offer optimized and adaptable abutment shapes, thereby accelerating the design process.

During the abutment design, changing the defined constraints is only partially possible; they can only be adjusted within the range defined at the beginning of the process. Tools like ExoCAD and 3Shape offer continuous display and enforcement of minimum thickness requirements, enabling users to visualize designs below the set limits but preventing the generation of geometry violating these constraints in the final product. Similarly, these tools notify users if the designed abutment exceeds maximum limits, although they do not enforce corrections; rather, they serve as warnings. Nova and UpCAD provide comparable features, with the primary distinction from ExoCAD and 3Shape the inability to visualize designs below minimum thickness requirements. The mentioned restrictions are necessary to maintain the integrity of product geometry, preventing users from creating products beyond permissible limits. Consequently, neither the tool's automatization algorithm or the user can produce topologically invalid geometry during secondary seed design generation or advanced design manipulation. In order to enhance customization and individualization of the abutment design for each patient, all tools provide advanced design manipulation features using planes, curves, and control points. ExoCAD and 3Shape excel in this aspect by offering additional control points for manipulation, enabling the creation of more intricate geometries (Figure 6).

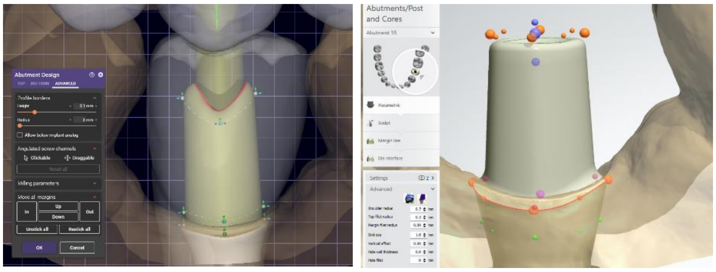

Figure 6: Design manipulation options in ExoCAD (left) and 3hape (right).

This capability also facilitates using sculpting options available in all four tools. Moreover, ExoCAD and 3Shape allow the import of custom functional geometry designed by third-party manufacturers or users, further enhancing the design's adaptability to diverse therapy needs and individual patient requirements.

For validation the implant assembly itself, only 3Shape can conduct assembly simulation to detect interferences between individual components during assembly. Other tools, like ExoCAD, enable checking for overlapping contact surfaces of the abutment with adjacent geometry (adjacent teeth, opposing teeth, and tissue). Additionally, both ExoCAD and 3Shape allow simulation of jaw movements, including chewing and sliding motions, using a virtual articulator. This then aids the dental technician in detailing the design to minimize stress on the implant assembly, considering that none of the mentioned tools have the capability to conduct structural analysis of the product.

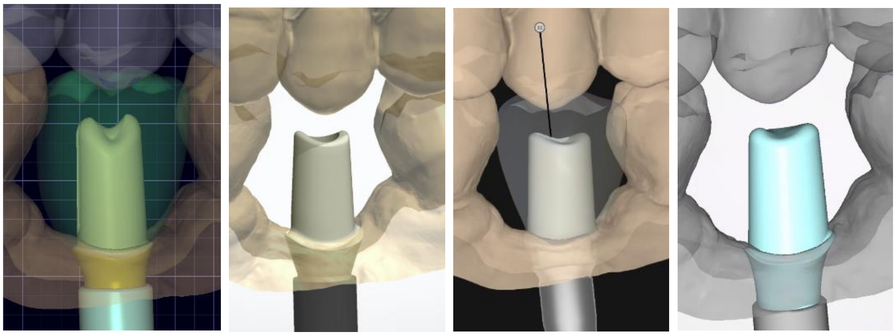

Figure 7: Designed abutment in (from left to right): ExoCAD; 3Shape; Straumann Nova; UpCAD.

It is important to emphasize that before the start of the design process, all tools allow for the selection of materials and manufacturing technology, which entails predefined design parameters such as minimum wall thickness, minimum transition radius from the emergence profile to the coronal part of the abutment, maximum radius of the abutment top, minimum thickness of the wall around the screw hole, coronal angle of the abutment, etc. These parameters can only be changed during the design process in ExoCAD and 3Shape, while designers must adhere to initially set parameters with other tools. At the end of the design process, all tools offer the capability to export the 3D model of the product in standard triangulation formats (STL, PLY, OBJ), which are then used in CAM tools. Alongside the models, the tools generate manufacturing files with data describing product features such as screw hole diameters, emergence profile, type of connection segment with the implant, used production parameters, and others. These manufacturing files enable the automatic detection of the mentioned features in CAM tools, which speeds up the entire product manufacturing process, which corresponds to the production aspect of MP. ExoCAD and 3Shape allow direct integration with commonly used CAM tools, enabling a seamless workflow and automated transfer of information without user intervention. On the other hand, since Nova is a closed system, the tool has direct integration only with Straumann's manufacturing processes, and UpCAD supports direct integration with manufacturing technologies provided by UP3D.

6 DISCUSSION

This comparative analysis of four presented CAD tools in the dental industry provides insights into their strengths and limitations in facilitating mass personalization (MP). While each tool demonstrates robust capabilities in various aspects of dental prosthetic design [1], they also share common limitations that hinder their full potential for MP [39]. A key challenge identified across the tools is interpreting and integrating complex, patient-specific data into the design process. Although tools like ExoCAD and 3Shape show strong capabilities in incorporating digital imaging and 3D scans [6], they rely heavily on manual interpretation by dental technicians. This reliance often results in inconsistencies due to subjective interpretations of clinical data, which echoes concerns highlighted in prior studies that emphasized the need for greater automation to reduce human error and increase output precision [25,27]. The current landscape of dental CAD tools shows a limited application of automation in converting patient data into actionable design parameters [67]. This gap is a significant barrier to achieving true mass personalization within the industry. Future enhancements could leverage artificial intelligence and machine learning to better parse and utilize patient data, thereby reducing dependence on manual inputs and enhancing the precision of dental prosthetics [7,30,45]. Another limitation seen in this comparison is the lack of effective communication between the designer and a client, a mass personalization characteristic emphasized by multiple authors [51,57,74]. Communication within CAD tools is crucial for refining the design process and enhancing collaborative efforts among technicians, dentists, and patients. Despite some tools supporting feedback integration, none currently facilitate real-time, interactive design modifications directly within the CAD environment. Enhancing these capabilities could improve the co-creation experience, aligning with recent research stressing the importance of interactive platforms in personalized medicine [21].

A significant technical challenge often encountered with these CAD tools is their reliance on faceted geometry, primarily because of its compatibility with additive manufacturing technologies [8]. Faceted models can limit the accuracy and aesthetic quality of dental prosthetics as they do not support the smooth, organic curves and surfaces typically required. This reliance on STL meshes, which represent objects as a collection of flat triangles, can impact mass personalization by restricting the precision of the fit and finish of the prosthetic devices [60]. Using Non-Uniform Rational B-Splines (NURBS) for geometry representation, could provide greater control and flexibility, allowing for more accurate and customizable designs that better meet individual patient specifications [55]. The implications of using faceted geometry extend to other parts of the design and also production process. For instance, generative design algorithms, which create optimized design alternatives, often struggle with STL meshes due to their lack of precision and complexity in representing smooth surfaces [17]. Generative algorithms typically perform better with more accurate and manipulable formats, such as those based on NURBS splines, which can more effectively capture the intricacies of patient-specific geometries [26]. Furthermore, the production phase, particularly in precision manufacturing, is affected as faceted models may not represent the exact geometry needed for high-quality dental prosthetics, potentially leading to issues in the final product's fit and function [28]. In addition to these design and production challenges, faceted geometry can complicate structural validation processes. Finite Element Analysis (FEA) tools, commonly used for stress testing and validation, often require precise geometric data to create accurate FEM (Finite Element Method) meshes. The inaccuracies inherent in faceted STL models can lead to errors or oversimplifications in the FEM mesh, impacting the reliability of the structural validation and, consequently, the safety and durability of the final prosthetic [75].

Moreover, the potential for generative design techniques to improve CAD tool functionalities in dental prosthetics is vast. By generating multiple optimized design alternatives based on predefined parameters and patient-specific data, these techniques could significantly enhance both the efficiency and customization of dental prosthetics. This aligns with literature highlighting generative design as a pivotal advancement for the future of CAD technology [22,24,43].

However, reliance on a small set of CAD tools and a specific focus on certain evaluation criteria may not comprehensively represent all the nuances of dental CAD tool capabilities across the industry. Additionally, the familiarity of the dental technician with ExoCAD might have introduced a bias towards its functionality and user-friendliness, potentially skewing the comparative analysis. Furthermore, the choice of a patient with a Straumann implant for the comparison was intended to showcase the capabilities of the Nova CAD tool, presenting an idealized scenario for that specific tool. These limitations underscore the need for broader and more diverse examinations of dental CAD tools in future studies.

The findings from this study underscore the need for continuous development in CAD technologies to support the nuanced requirements of mass personalization effectively. Future research should focus on developing more intuitive user interfaces to facilitate easier manipulation of designs and expanding the dataset to diversify CAD tool users. This would enhance our understanding of each tool's capabilities and limitations across a broader range of clinical and technical contexts. Investigating the interaction between these advanced tools and their users could also yield insights into how user interface design impacts the efficiency and effectiveness of the design process. Additionally, the integration of artificial intelligence and machine learning could enhance the automation of design processes, potentially transforming how patient data is interpreted and utilized in CAD systems.

7 CONCLUSIONS

Based on the comparative analysis of four CAD tools, it is evident that each tool offers unique strengths and limitations in addressing the demands of mass personalization in dental prosthetics. The comparison sheds light on key aspects such as the integration of patient-specific data, user interaction during the design process, and the capabilities of each tool to support iterative and collaborative design.

ExoCAD and 3Shape are highlighted for their robust functionalities, particularly in handling complex patient data through 3D scans and modeling. They also demonstrate advanced features that facilitate procedural design and iterative adjustments, which are essential for refining prosthetic fits based on precise patient needs. Furthermore, these tools offer better support for user collaboration, which is critical in the customization process, allowing dental professionals to engage more effectively with the design process.

On the other hand, Nova and UpCAD, while offering tailored solutions for specific hardware or regional markets, show limitations in flexibility and user interaction, which could hinder their application in broader scenarios where versatile design adjustments are required. The analysis underscores the importance of enhancing these tools to better accommodate a wide range of user inputs and to streamline the integration of new technologies like machine learning and AI, which could further automate and refine the design process.

In conclusion, while all tools exhibit potential in facilitating mass personalization in dental CAD applications, there is a clear need for ongoing development to address gaps in automation, data integration, and user interaction. Future advancements should focus on improving the intuitive use of these tools, enhancing their ability to directly incorporate real-time feedback, and expanding their capabilities to automatically interpret and apply patient-specific data, thereby reducing reliance on manual inputs and increasing the precision and efficiency of dental prosthetic production. This will not only improve the usability of CAD tools but also enhance the overall effectiveness of dental treatments and patient satisfaction.

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