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Towards systematic approach of mass customization in dental prosthetics

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Abstract: *Mass customization (MC) has revolutionized various industries by enhancing product outcomes and customer experiences. While extensive research has explored implementation of MC in architecture, automotive, fashion, furniture, customer electronics and medical industry, there is a notable gap regarding its application within the dental industry. This research analyzes the different implementations of MC in various industries and investigates their presence in the dental field. Despite existing studies in other domains, limited evidence exists for their integration in dentistry. This study explores specific areas in dental prosthetics to understand how MC principles and design approaches could enhance dental products. Advanced CAD tools optimized for personalization, additive manufacturing for personalized product production, and patient-specific implant planning were found to be prevalent. However, while customization and personalization aspects are emphasized, mass production aspects are less prominent. Integrating MC design approaches would enhance efficiency and broaden access to personalized dental care.*

Key Words: ***mass customization, seed design, dental prosthetics, DfMC***

1. INTRODUCTION

Design for Mass Customization (DfMC) is a product design methodology that allows customers to receive products tailored to their individual needs while benefiting from the economies of scale typically associated with large-scale manufacturing (Ogunsakin et al. (2021); Piller & Tseng (2009)). The initial step of the methodology is identifying customer needs through direct feedback to understand specific preferences. Products are then designed to enable modifications by breaking down the design to different segments to accommodate interchangeable modules or by enabling modifiable geometry to facilitate customization and streamline production (Gu et al. (2006)). To improve design-user interaction, mass customization toolkits are usually developed featuring 3D visualization, material selection and price feedback (Yavari et al. (2020)). Although DfMC proposes these generalized steps for MC, there is no standardized design procedure or approach for MC that can be used across different products. In practice, customization processes are often tailored specifically to the product in question. This means that while the fundamental principles of mass customization can be applied broadly, the specific steps and strategies employed can vary greatly depending on the product's nature, the industry's requirements, and the target market's unique needs.

MC has seen extensive applications across various industries. In retail, companies like Adidas and Nike allow consumers to design their footwear online, choosing colors, materials, and styles to match their preferences. Many authors emphasize that mass customization is enabled by CAD software, digital technologies (additive technology, CNC machining) and development of web-based toolkits that enable designer-user cocreation (Ozdemir et al. (2022)). In the automotive industry, manufacturers such as BMW and Audi offer options for customers to personalize their vehicles through various configurations, facilitated by digital tools and flexible manufacturing processes (Meng et al. (2022)). In healthcare, MC has been applied to improve patient outcomes through personalized treatments and medical devices. For instance, custom orthotics and prosthetics are designed using digital imaging and 3D printing technologies to match the patient's specific anatomical features, enhancing comfort and functionality (Barata et al. (2023)).

With the success of MC in these industries, different design approaches have been developed to facilitate the creation of products that align with its principles (Sharma (2013)). Two prominent approaches include open architecture (Bonev et al. (2015)) and seed design (Bingham (2016)). Open architecture divides the product into modules or components that can be independently altered or upgraded, integrates components from diverse manufacturers and allows for product enhancement and system expansion over time (Xiang et al. (2018)). Customers can then choose from a range of options, selecting and adding modules that meet their specific needs, thereby creating a product that is tailored to each customer (Koren et al. (2013)). However, the open architecture approach has its limitations, such as the complexity of managing numerous interchangeable

modules, ensuring compatibility across diverse components, and limitation in customization, i.e. meeting user needs (Zheng et al. (2019)).

Seed design, on the other hand, involves providing a basic product framework or "seed" that can be customized by the user (Y. Li et al. (2008)). This approach typically uses predefined parameters that users can adjust to create a final product that meets their specific needs. Seed design offers a structured yet flexible framework that streamlines the customization process, ensuring a balance between user autonomy and design constraints.

Seed design, due to its ability to create highly customizable products while maintaining production efficiency, is recognized as suitable approach for MC in medical industry. This approach ensures that medical device or implant is tailored to the patient's anatomical features, optimizing functionality and compatibility. The dental industry is a prime example where customized and personalized products are essential. Dental prosthetics and treatment plans require precise fitting and adaptation to individual patient needs, making the field well-suited for the application of MC.

However, despite the widespread recognition of MC as a production paradigm, there is limited scientific evidence on its application in the dental industry. While digital technologies such as CAD/CAM systems and 3D printing are being adopted to facilitate customization and personalization in dental prosthetics and orthodontics (Shaikh et al. (2021)), the systematic implementation of MC design approaches in dentistry remains underexplored.

Therefore, the objective of this paper is to propose a systematic procedure for implementing MC using seed design approach in the dental industry and to bridge the gap in existing research by providing structured steps for integrating MC into dental prosthetics. To achieve the research objective, existing case studies and procedures of successful implementation of mass customization have been analyzed to identify transferable strategies and best practices for dental prosthetics. Based on the insights from the literature review and case studies, a procedure for design for mass customization in dental industry has been proposed. Finally, the proposed procedure has been validated through case example – design of dental implant abutment (further in text abutment), a substructure connecting dental implant and prosthetic restoration (Fig. **1**).

2. MASS CUSTOMIZATION AND SEED DESIGN APPROACH

The seed design approach to mass customization offers a structured yet dynamic method for adapting a foundational product template, or "seed," to meet diverse customer needs (Bingham (2016)). This approach is characterized by the creation of a seed model that includes predefined but adaptable elements, which can be modified within certain constraints to tailor the product to user's specifications. The process usually begins by identification of customer requirements and features to be customizable. The following step is establishing a seed model that incorporates features applicable across various product variations. This seed model serves as the baseline from which customization parameters are defined, involving adjustments related to dimensions, materials, additional component choices, and functional enhancements specific to the product (Schulz et al. (2013)). Implementing seed design typically involves CAD software that supports parametric design, allowing designers to set specific constraints and rules for how each element of the design can be altered (Y. Li et al. (2008)). When a customer specifies their preferences, the designer adjusts the seed model within the established constraints, ensuring that the final product is customized according to customer's requests. In some instances, customers can make the customization by using product configurators (Rizzi et al. (2023)).

The benefits of the seed design approach include flexibility and scalability in product design, permitting a broad range of customization options without the complexity and expense of designing each new variant from scratch (Sikhwal & Childs (2017)). Also, in comparison with personalized products, separating product features into non customizable and customizable within seed design improves production efficiency through streamlined manufacturing processes, thereby reducing costs and shortening the time from design to market (Quan & Deserti (2009)). By using product configurators, the seed design approach enables customers to participate in product design, achieving a more involving design process (Gutai et al. (2023)). However, the seed design approach is not without challenges. The initial setup can be complex and resource-intensive, requiring careful planning to determine which aspects of the product should be standardized and which should be customizable (Taieb (2023)). Balancing the scope of customization options to satisfy consumer demands while keeping the production process manageable is a critical task (Hvam et al. (2020)). Furthermore, seed design often relies heavily on digital technology (Ozdemir (2022)) and software (Micevska & Kandikjan (2016)) for implementation, representing a significant investment and ongoing operational cost for businesses.

In practical applications, seed design is employed across various industries to facilitate mass customization. For example, in the automotive sector, consumers can customize their vehicles by choosing from a range of options for interior finishes, entertainment systems, and engine specifications, all within a predefined model framework (Keskin et al. (2017)). In the fashion industry, online configurators enable customers to select fabrics, cuts, and decorative elements for clothing based on a standard pattern that adjusts to their inputs (Bellemare (2018)).

The seed design approach holds significant importance in the medical industry (Bai et al. (2021); Spallek & Krause (2016); Üreten et al. (2020)), where products are not only tailored to the specific needs of each patient but are also customized to specific medical conditions or anatomical features. This approach ensures that each medical device or implant is precisely designed to optimize its functionality and compatibility with the patient's unique physiological characteristics, enhancing treatment outcomes and patient satisfaction.

A case study on mass customization of a continuous positive airway pressure (CPAP) mask (S. Li et al. (2020)) emphasized the importance of data acquisition in the early stages of the design, using facial images processed through a parametric design approach. By mapping key anatomical features from a point cloud data obtained by scanning to seed design CAD model, design time was reduced and the need for manual CAD modeling was eliminated. This approach made the design process more efficient and accessible. (Binder et al. (2023)) also discusses mass customization of scalp cooling caps, highlighting the necessity for gathering precise cranial data from the target group. Advanced imaging technologies like 3D scanning captured intricate details of the head's shape and size, forming the basis for creating customized products. This data was then analyzed and organized into size subgroups to enhance production efficiency for mass customization, demonstrating the detailed and systematical approach required to successfully implement seed design in medical applications.

The dental industry, a specialized branch of the medical industry, also relies on CAD/CAM processes for generating individualized products for patients, similar to the examples presented. Therefore, the dental industry, specifically dental prosthetics, already meets some prerequisites for mass customization, making it a potential candidate for the application of mass customization. The dental industry is also aiming for mass production of dental prosthetic components due to increasing demand and the goal of enhancing accessibility. However, current research does not cover a theoretical approach to implementing mass customization.

2.1 MASS CUSTOMIZATION IN DENTAL PROSTHETICS

Mass customization and personalization hold immense potential within the dental industry, particularly in dental prosthetics. This potential is driven by the need for precision and individual fit in dental components such as crowns, bridges, dentures, implant abutments, implant bars etc. Several studies highlight the advantages of applying mass customization in this field. For instance, (Vandenbroucke & Kruth (2008)) discuss the use of direct digital manufacturing to produce complex dental prostheses, which allows for the customization of dental components with high precision and material quality. The integration of technologies like Reverse Engineering (RE), Computer-Aided Design (CAD), and Rapid Prototyping (RP) facilitates the creation of tailored dental models that match individual patient anatomy, enhancing the accuracy and effectiveness of dental treatments.

Multiple patents have been published on mass customization in dental prosthetics such as patent by (Wrosz et al. (2009)). This patent presents a method for mass customization in the manufacturing of dental aligners, highlighting how digital tools can streamline the production process and improve the fit and function of dental appliances. Similarly, (Lauren (2004)) describes a mass-customization method for designing and producing complex orthodontic wireforms, which improves the efficiency and precision of orthodontic treatments by using computer-based design and production techniques. Additionally, (Sager (2009)) outlines a mass custom manufacturing system for dental crowns and components, using a master file to design and manufacture companion pieces simultaneously, which increases production efficiency and product consistency.

The increase of these innovative techniques and successful patent applications not only underlines the capabilities of mass customization to enhance dental prosthetics but also sets a foundation for its broader application within the industry. This transition from traditional manufacturing methods to advanced digital solutions represents a significant paradigm shift, aiming to resolve existing challenges in dental prosthetics production and meet the growing demand for personalized dental solutions.

The benefits of mass customization in dental prosthetics include enhanced efficiency, cost reduction, improved quality consistency, faster time-to-market, scalability, and higher customer satisfaction due to personalized products. By leveraging advanced digital manufacturing technologies, the dental industry can meet the diverse needs of patients more effectively and efficiently. Utilizing digital technologies like specialized CAD tools (*3Shape Dental System — Dental CAD Software for Labs* n.d.; *DentalCAD 3.1 Rijeka - Exocad* n.d.), CNC machining and additive technology dental professionals are able to create prosthetics tailored to each patient's unique oral structure, ensuring a precise fit and improved comfort. Despite the promising opportunities for mass customization in dentistry, scientific evidence supporting the widespread implementation and impact of mass customization design approaches is currently limited. While the dental industry is embracing digital technologies for customization, the lack of applied MC design approaches and procedures requires further research and studies. Some design processes, like dental aligners design and custom implant abutment design, implicitly align with mass customization and mass personlization (Kosec et al. (2024)). For instance, dental implant abutments can be designed using three different approaches (Benakatti et al. (2021)). First approach requires dental technician or clinician utilizing measurements and estimations of key oral dimensions, such as the depth and angle of implant placement, implant diameter, soft tissue emergence width, and the necessary height of the abutment's prosthesis connection segment for the restoration. Subsequently, the technician or clinician chooses a suitable abutment from the product catalog, which offers various product variants with different heights and diameters of transgingival segment and range of heights and angles of coronary segment of an abutment design. Consequently, the choice of the abutment is constrained by the dimensions provided by the manufacturer, thereby limiting complete customization of a product. Moreover, validating the chosen abutment is not feasible until physically placing it on a jaw replica or in the patient’s mouth.

Another option involves selecting a dimensionally predefined abutment via Computer-Aided Design (CAD) software, often characterized by a single variable dimension - the abutment’s prosthesis connection segment

height, with the remaining dimensions being non-customizable (Gallo et al. (2022)). While this approach enables fast implementation and visualization through CAD tools, using standard components implies its suitability for ideal scenarios where implant placement aligns with the axis of natural teeth, thereby reducing the number of cases in which it can be employed.

The third option entails designing a fully individualized abutment tailored exclusively to the patient's anatomical characteristics, ensuring optimal functionality and aesthetic appeal of the implant prosthesis (Târtea et al. (2023)). However, this approach demands significant technician expertise in CAD tool operation since it requires design manipulation using specialized CAD software. Also, individual production of such abutments hinders mass production efficiency, unlike premade options. Hence, this study aims to demonstrate the blend of customization and efficiency in implant abutment design following mass customization procedure defined using previous cases found in literature.

3. DESIGN STEPS FOR MASS CUSTOMIZATION OF A DENTAL ABUTMENT

Using literature review and examples of successfully applied mass customization, a MC procedure for designing dental abutments is proposed. This procedure aims to streamline the design process by customizing each dental abutment to the specific implant placement location and position, and anatomical features of individual patient.

1. Identification of general abutment requirements
2. Setup of abutment seed design - division of design into non-customizable and customizable segments
3. Collection of patient data
4. Customization of abutment based on patient data
5. Visualization of products in digital environment

In the initial step of the design process, the general requirements and features are defined. This stage is crucial for understanding the general functionalities that each segment of the design must fulfill. By examining various scenarios, the designer can identify different possible variations for each segment.

Once the general requirements are clarified, the designer establishes the seed design. The seed design is first divided into non-customizable and customizable segments. Non-customizable segments ensure connection interface compatibility with third party components (in this case implant). On the other hand, customizable segments can be tailored to the specific details and anatomical features of the patient. Segmentation is important since it establishes a solid foundation for the product, ensuring both reliability and consistency across various cases (varying implant types, depths or angles of implant placement, widths of the gum tissue opening etc.). By segmenting the design, it becomes possible to standardize certain aspects while still allowing for adjustments tailored to the unique specifications of each situation, thereby enhancing the product's adaptability and effectiveness. Additionally, it is crucial to integrate options that allow for straightforward modification of the geometry within the customizable segments, utilizing tables or a specialized user interface to facilitate these adjustments efficiently.

To precisely customize the abutment, detailed patient-specific data is collected. This includes precise measurements from digital scans, which provide a detailed 3D model of the relevant area and additional data about implant geometry, patient health, specific clinical and structural requirements. Utilizing the parametric capabilities of the CAD software (tables and user interface from previous step), the customizable segments of the seed design are then adjusted based on this data. Changes to dimensions like height, width, and orientation are iteratively refined, with continuous reference to the patient's data, to ensure the design meets all specified requirements.

The final step before manufacturing involves the visualization and simulation of the customized abutment within a digital environment. During this phase, a specialized dental CAD tool, such as the ExoCAD Virtual Articulator, enables the designer to assess how the product interacts with the surrounding anatomy, including the opposite jaw, adjacent teeth, and gum tissue. This step is essential for evaluating both the functional and aesthetic requirements of the abutment, allowing for the identification of any potential issues that could affect its performance. Visualization and simulation also serve as inputs for making any necessary minor adjustments before proceeding to final production, ensuring the product meets all specified requirements.

4. CASE EXAMPLE

To illustrate the practical application of mass customization (MC) in the dental industry, a case example involving the design of a customized dental implant abutment is presented.

A 55-year-old male patient presented with a missing upper left first molar (tooth #22). The patient had previously undergone a dental implant placement (Nobel Biocare Active 4,3 RP Yellow) and required an abutment and crown to complete the restoration. The primary goals were to achieve a precise fit of an abutment, optimal aesthetics, and improved functionality.

STEP 1: Identification of general abutment requirements and features

The design of the dental abutment comprises several critical segments: the implant connection segment, the transgingival segment and the crown or prosthetic connection segment (Fig. **1**).

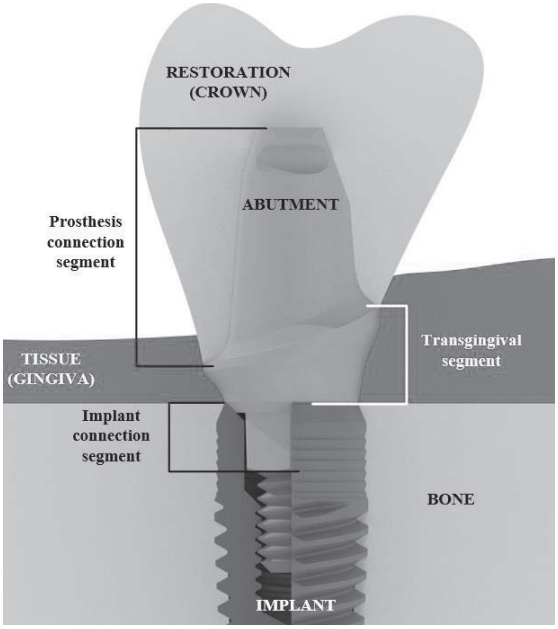

Fig. 1 *Implant abutment assembly*

The design of the implant connection segment (Fig. **2**) must provide precision fit with the dental implant to ensure stability of the abutment and required sealing properties. This segment is designed according to the geometry of the implant and includes a sealing surface and anti-rotational geometry. Sealing surface is designed to prevent bacteria or food particles from entering the implant cavity, thus preventing potential oral health issues. The sealing surface is typically conical, flat, or a combination of these shapes, varying the angle or the specific shape depending on the implant design. Anti-rotational geometry, as the name suggests, prevents the abutment (and subsequently the cemented crown) from rotating unexpectedly on the implant. It has a role to secure the correct rotational position of the abutment when it is being retained with a screw to the implant. Anti-rotational geometry must align with the implant's connection interface to ensure that both sealing and positional requirements are fulfilled. This abutment segment is vital for the long-term functionality of the dental implant and the overall restoration process. Since implant connection segment provides a connection interface compatibility with third party component – implant, it represents a non-customizable segment.

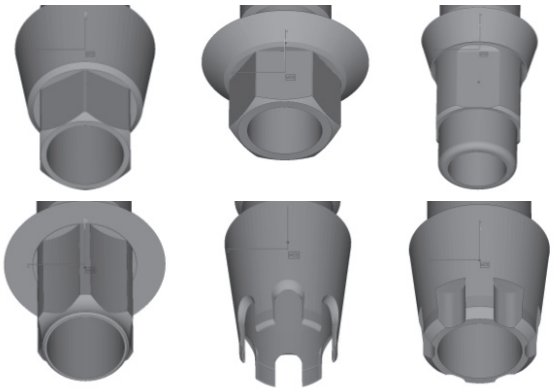

Fig. 2 *Different implant connection segments*

The transgingival segment (Fig. **3**) is also responsible for securing a sealing zone around the implant, however, it must conform to the shape of the surrounding tissue. The geometry of this segment transitions from the implant connection segment and is in contact with the tissue, creating an additional sealing surface. This segment's design is usually concave, narrower just above the implant and wider at the tissue surface. Transgingival segment should ideally be submerged at least 1.5 to 2 mm below the surrounding tissue surface to seamlessly blend with the natural gum line.

Fig. 3 *Transgingival segment of the abutment*

The crown or prosthetic connection segment (Fig. **4**) is designed to provide a secure base for the final restoration. It often includes retention features such as grooves, surfaces, or ridges, which aid in securely attaching the restoration using dental cement. This segment is essential not only for ensuring a minimal thickness of the chosen abutment material, providing structural integrity of the assembly, but also for providing sufficient space for the prosthetics. Additionally, the prosthetic connection segment is designed to accommodate adjustments in the mounting angle to align with the axis of the surrounding teeth, thereby ensuring a natural appearance and functional alignment with the patient's dental arch.

Fig. 4 *Prosthetic connection segment*

STEP 2: Setup of abutment seed design - division of design into non-customizable and customizable segments

With the general requirements and features of the implant abutment identified, a seed design was created using PTC Creo Parametric CAD software. This design included a non-customizable implant connection segment whose design corresponds the abutment connection interface of the Nobel Biocare Active 4.3 Yellow implant. The abutment connection interface of Nobel Biocare Active implants consists of a conical sealing surface and a hexagonal anti-rotational geometry.

Transgingival segment represents customizable design segment since the thickness and shape of the gum tissue depends on the tooth position, depth, angle and diameter of the placed implant and tissue health. Therefore designer

must be able to adapt the shape according to the unique anatomical features of the gum tissue.
Two transgingival segment dimensions were defined as customizable:

- transgingival segment width,
- transgingival segment height.

The seed design was designed with concave shape with minimal width of 4.3mm, which corresponds to the diameter of the placed implant, while the upper limit is unrestricted, and it depends on the measurements of the surrounding tissue. Also, its height is variable, with a lower limitation of 1mm. The lower limitation is set under the assumption that the implants are placed at least 2mm below the gum tissue level and for technological reasons, i.e., due to the minimum size of the milling tool used for machining – a Ball End 1mm.
Design of the prosthetic connection segment depends on width of the transgingival segment, minimal thickness of the prosthetic restoration, angle of placed implant regarding to the surrounding teeth, distance to opposite jaw and width of the space between adjacent teeth. Therefore, 4 dimensions were defined as customizable:

- prosthetic connection segment shoulder width,
- prosthetic connection segment angle,
- prosthetic connection segment height,
- prosthetic connection segment diameter.

At the transition from the transgingival segment to the prosthetic connection segment, is a shoulder support with a minimum width of 0.4mm that matches the minimum necessary thickness of the zirconia crown that fits onto the abutment. This shoulder support, along with the segment for receiving the prosthetic restoration, serves to transfer the load from the restoration to the abutment. Prosthetic connection segment angle is adjustable to align the axis of the crown mounting, with the maximum angle of inclination restricted to 30° to preserve mechanical integrity and due to rotational limitations of the milling machine axis. Height of the prosthetic connection segment is limited to minimum 4mm and a diameter of 3mm to ensure a necessary surface area for cementing of 35mm² (Carnaggio et al. (2012)). Upper limits are unrestricted.
The seed design was then parameterized based on the above, with constraints set for the ranges of possible values and linked to a parameters table (Fig. **5**).

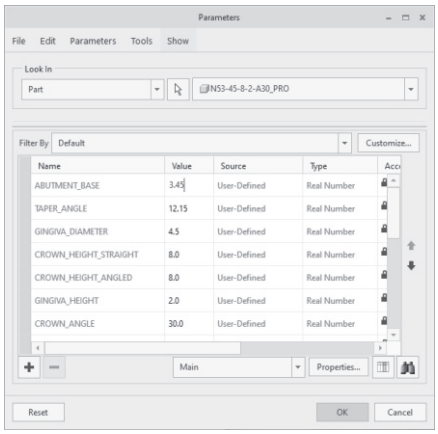

Fig. 5. *Parametrization of the seed design*

STEP 3: Collection of patient data
Using a high-resolution intraoral scanner, detailed 3D images of the patient's oral cavity, including the implant site and surrounding teeth, were captured. Key measurements were then recorded.

Measurements defining transgingival segment:

- soft tissue emergence profile width - defining the width of the transgingival segment = 4.1mm
- depth of implant placement – defining the transgingival segment height of the abutment = 5.2mm

Measurements defining prosthetic connection segment

- angle of implant placement – defining the angle of the prosthetic connection segment = 20°
- distance to opposite jaw – defining the height of the prosthetic connection segment = 4mm
- width of the space between adjacent teeth – defining the width of the prosthetic connection segment = 6.5mm
- minimal required thickness of the prosthetic restoration=0.4mm (zirconia)

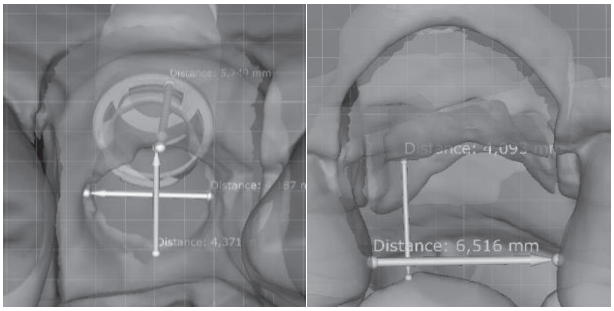

Fig. 6: *Measuring key measurements required for the abutment design*

Additionally, the clinician requires that the transgingival segment is 2,5 mm below the emergence profile of the gum tissue since the patient suffers from periodontitis – a gum infection that damages the soft tissue around teeth and could cause a gum recession in future.

STEP 4: Customization of abutment based on patient data
With the precise patient data in hand, the next step involves customizing the seed design of the abutment to the unique measurements of the patient anatomical features and patient specific clinical and structural requirements. This customization occurs in PTC Creo Parametric, an engineering CAD software where the captured data from the scans and from the clinician is used to customize the design. The customization using parametrization table is made by an engineer at this stage, since he is able to make changes on the seed design in order to achieve plausible result with given inputs. Also, during the customization, a dental technician participated in the customization process and gave additional inputs during the design which are not known to the engineer such as space required for the restoration regarding the tooth position and selected material, mounting angle given

the shape of the adjacent teeth, the amount of desired overlap of the transgingival segment and gum tissue etc. These changes resulted in following abutment design parameters:

Transgingival segment:

- transgingival segment width = 4,3mm
- transgingival segment height = 2,7mm

Prosthetic connection segment:

- prosthetic connection segment shoulder width = 0.4mm
- prosthetic connection segment angle = 20°
- prosthetic connection segment height = 4mm
- prosthetic connection segment diameter = 3,2 mm

Fig. 7 *Generated abutment design*

STEP 5: Visualization of abutment in digital environment

To visualize the abutment within the jaw and to verify that the designed abutment meets the given parameters and is suitable for the intended case, it is necessary to position it virtually on the implant. For visualization and verification, ExoCAD, a dental CAD tool, was used. An STL file, generated from PTC Creo Parametric, was imported into the ExoCAD interface and manually adjusted to align with the implant. After positioning, a cross-sectional view of the implant, abutment, and surrounding tissue was created to check the compliance with the initial set of requirements. During this verification, it was observed that it was necessary to further reduce the height of the transgingival segment by 0,5mm and decrease the diameter of the prosthetic connection segment to 3,0 mm. Based on the verification, minor adjustments were made to the design, and the visualization step was repeated to confirm the changes.

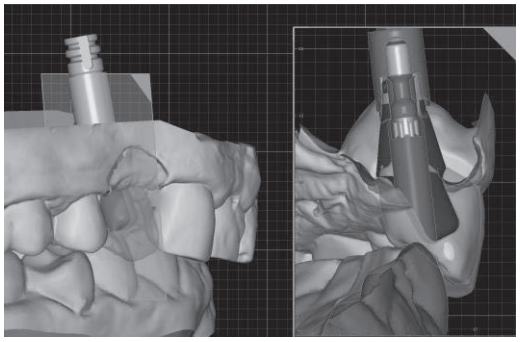

Fig. 8 *Visualization of the designed abutment on the implant*

5. DISCUSSION

This study advances the application of mass customization (MC) in dental prosthetics, particularly focusing on the use of digital technologies for designing dental abutments. The literature review highlighted significant explorations of MC across various industries, such as automotive and retail, where these strategies enhance both customer satisfaction and operational efficiency However, the adoption of this paradigm in the dental sector, particularly concerning production aspects and the use of specialized tools tailored for dental applications, has not been extensively documented.

Reflecting on the procedures in the literature, traditional methods of designing dental abutments often lacked the balance between customization and production on a large scale (Shah et al. (2014)). The introduction of CAD/CAM and digital technologies has shifted this paradigm, enabling a less time-consuming customization process (Mühlemann et al. (2021); Târtea et al. (2023)). However, the process is still not optimized for mass customization due to the lack of clearly defined procedures for MC. This paper builds upon these advancements and shortcomings by demonstrating a systematic approach to integrating MC in the design of dental abutments, leveraging a seed design approach facilitated by engineering CAD software.

The proposed design steps improve the existing approaches for abutment design by using a seed design approach. This enhanced the customization of an abutment by increasing the range of possible dimensional options and possible modifiable features while securing the technological and mass production aspect of the customizable abutment. This is achieved by controlled customization of the design parameters, constrained by the engineering and production requirements.

This study also underscores the importance of collaboration between engineers and dental technicians during the definition of initial seed design. The integration of both technical expertise and clinical insights is essential to meet the complex requirements of dental abutment design. Unlike traditional approaches for abutment design where MC requirements are often overlooked, recent research highlights the necessity for a collaboration (Oliveira et al. (2023); Ozdemir (2022)) between engineering and dental technicians to effectively achieve MC objectives within the dental prosthetics. Furthermore, the current reliance on engineers for the manipulation of CAD software points out a potential gap in the existing training of dental professionals regarding advanced digital tools. Addressing this gap could empower dentists and dental technicians to take a more active role in the design process, potentially leading to faster and more efficient patient care workflows. This shift could also reduce the latency in the design process, where direct input from clinicians could instantly influence the design modifications. This can be solved by developing cloud-based tools that enable real-time design collaboration between engineering and industry specialists (clinicians and dental technicians) (Y. Li et al. (2023)).

The paper also outlines a direction for future research by highlighting the necessity for additional development and testing of the suggested design procedure. It suggests that such research could lead to more refined processes that include additional steps for optimization, thus enhancing

the overall effectiveness of MC in dental prosthetics. Integrating more advanced, perhaps AI-driven tools could automate some aspects of the design process (Azadi & Nourian (2021); Siddique & Boddu (2003)). For instance, machine learning algorithms could generate abutment designs based on a database of previous successful cases, thus reducing the time required for the design phase.

6. CONCLUSION

This study demonstrated a practical application of mass customization using seed design approach. The study introduced a procedure using CAD software, which effectively balances customizable and non-customizable aspects of dental abutment design. This balance allows for enhanced customization without sacrificing the essential functionalities and standardization required for large-scale production. The proposed introduction of specialized, possibly web-based CAD tools aims to democratize the design process, broadening access for dental technicians and clinicians. This could potentially transform how customized dental solutions are implemented across the industry.

However, the integration of these innovative designs into scalable manufacturing processes remains a significant challenge, highlighting a crucial area for future research. Continued efforts are needed to refine these processes and to integrate automation and machine learning for optimizing design workflows.

Future directions should focus on enhancing CAD tools to be more user-friendly and accessible, enabling dental professionals to contribute more directly to the customization process without needing extensive technical knowledge. Additionally, further testing and development of the proposed design procedure are needed to fully realize the potential of mass customization in dental prosthetics.

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