Axiomatic design framework for innovation in dental implant manufacturing in Africa

Jacob Wafula[1], *Clint* Steed[*2], and *Ulanbek* Auyeskhan[3]
[1]Stellenbosch University, Industrial Engineering Department, 7602 Cape Town, South Africa
[2]Stellenbosch University, Mechanical and Mechatronics Department, 7602 Cape Town, South Africa
[3]Astana IT University, Department of Intelligent Systems, 010000, Astana, Kazakhstan

Abstract. The increasing need for patient-specific and affordable dental implants in Africa may be addressed by integrating a patient-centred design and manufacturing framework, such as axiomatic design principles. This approach remains underutilised in the dental manufacturing environment of the region, despite its promising outcome. Through two fictitious case studies, this study demonstrates how well the framework addresses the changing concerns of dental implant patients through design and manufacturing using independence and information axiom. The analysis also suggests the adoption of flexible and yet lean manufacturing methods, such as additive manufacturing, to mitigate the current challenges faced in the field of dental implant manufacturing.

1 Introduction

Customised dental implants offer a promising, long-lasting solution for tooth loss [1]. Typically, these dental implants are small metal of different shapes, produced in line with different standards, majorly the ISO 14801 on dynamic fatigue tests of implants and ISO 22794 on the biocompatibility of implants. They are surgically placed into the jawbone to replace a missing tooth root and securely support an artificial tooth or crown [2]. Beyond restoring the ability to chew effectively, they help maintain facial structure, which can otherwise deteriorate due to bone resorption. Moreover, dental implants can bring back the beauty of a smile, especially for individuals who have been deeply affected by tooth loss. In cases where temporary alternatives like dental bridges fall short, dental implants stand out as a durable and aesthetically pleasing choice [3]. However, the slow trend in adoption for dental implants in Africa may have been due to a lack of a design framework for incorporating customisation and cost-effective design for improved clinical outcomes for the majority of patients who are economically constrained [4].

One way to address the slower adoption of dental implants, as with other implants in Africa, has been the use of standardised designs. For example, a study on prosthodontists' preferences in South Africa found a strong preference for bone-level implant designs (84%) when placing fixed implant-supported prostheses, indicating a trend toward using standard implant designs to improve clinical outcomes and acceptance in the region [5]. A more

[*] Corresponding author: steed@sun.ac.za

advanced way is the use of scanning technologies to recreate a customised dental implant for improved patient performance [6]. Each of these two methods inevitably involves a trade-off in one or more of the aspects of functionality, independence of design parameters, and complexity, which axiomatic design seeks to optimise by ensuring functional requirements are met without unnecessary coupling or increased system complexity. To the best of our knowledge, no work has been reported that incorporates axiomatic design principles in dental implant manufacturing as a way of tackling the trade-off of availing customised dental implants at affordable cost to African patients with improved clinical performance, minimising dental implant failures that necessitate surgical revision associated with additional costs and excruciating agony for patients [7]. Furthermore, only a few studies are available on the integration of the axiomatic design framework in solving problems.

This study uses axiomatic design principles in the analysis of hypothetical dental implant cases. Axiomatic design is a systems design methodology that systematically translates customer needs into functional requirements and then into design parameters, guided by fundamental principles or axioms [8]. In the two hypothetical cases, patients' concerns were mapped into four axioms, namely: customer needs, functional requirements, design parameters and process variables. It is demonstrated in this study that a design framework based on axiomatic design principles could be a possible solution to this dynamic and patient-sensitive field, bringing about innovation and revolutionization in dental design, material and manufacturing. Also, this study acknowledges additive manufacturing (AM) methods such as selective laser melting (SLM) as having the potential to reduce trade-offs in dental implant manufacturing while tackling the limitations existing in dental implant manufacturability. It is, however, important to state that the scope of this study is primarily on dental implants installed permanently into the patients' jawbone.

1.1 Limitations in the existing dental implant manufacturability

High-quality dental implants with the required level of customisation while remaining affordable could assure satisfactory long-term performance, appealing to dental patients in Africa, enhancing acceptance and improving their quality of life [4]. However, customised dental implants to meet the vast and varying needs of patients are characterised by dynamic, intricate designs and the need for the use of diverse, suitable biomaterials [9]. For these reasons, it is difficult for conventional methods to accommodate the required level of customisation while remaining affordable for African patients.

1.1.1 Dynamic customisation of intricate designs

Dental implant components are geometrically complex [10], as described in Fig. 1. The implant root is often screw-shaped with varying designs and sizes, as well as intricate surface contours [11]. Recently, porous roots have been championed by practitioners for exhibiting exceptional clinical performance [12], but this further complicates the manufacturability when using traditional methods. The abutment geometry additionally varies in size and geometry, depending on the location of the crown to be replaced and the implant/root location [13,14], although the implant is always anchored at the closest point of dense jawbone from the affected site. These conditions have prompted the use of either straight or angled abutments [15]. Dental crowns are also characterised by complex, unique and irregular curves due to factors such as the geometry of adjacent teeth and the shape of the biting surfaces [14,16]. These described complexities and uniqueness of dental features make traditional manufacturing techniques, such as CNC machining, casting, and sintering, cost-intensive, as extra jigs and fixtures [17] or moulds are required for any design variation [18]. Yet, because of the features of the dental region, frequent alterations based on patient requirements are required. This makes the traditional manufacturing method unsuitable and negatively impacts their affordability for African patients.

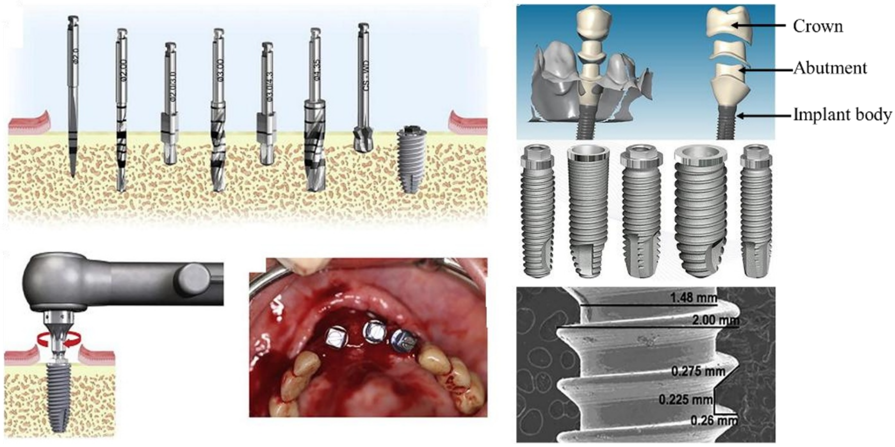

Fig. **1**: Examples of dental implant complexity in terms of size and shape *[19]*.

1.1.2 Diverse suitable biomaterials

A complete dental implant often requires the use of dissimilar materials, depending on functional and aesthetic requirements. Several biomaterials have been extensively researched and assessed, with these biomaterials found to possess unique strengths and limitations [20], often necessitating the use of varied materials for specific implant components to optimise performance and meet patient-specific requirements. Among the usable biomaterials, titanium alloys have been reported to be of superior qualities in terms of both biocompatibility and mechanical properties [21]; however, these titanium alloys are expensive compared to other metals such as cobalt-chromium (Co-Cr) alloys and surgical stainless steel [18], although they are less biocompatibility. In any of the material selected for dental implants, additional cost is incurred due to the difficulties in machining intricate designs with the traditional manufacturing methods [23], further affecting the availability and affordability of implants for patients.

AM, specifically, SLM, offers a promising solution to the limitations. Unlike traditional methods, this manufacturing technology exhibits the flexibility to manage dynamic and complex geometries [24], capable of utilising different and multi-materials with reduced waste and material reusability, as emphasised by Kumar et al. [25]. More precisely, every customised dental implant can be produced to the required tolerances without additional jigs or fixtures needed, thereby eliminating the additional cost. To this end, the integration of axiomatic design principles with AM adoption by African nations has the potential to ensure patient demands are met in the final dental implant, eliminate the need for regular dental implants' trial-and-error process and transform dental implant health throughout the continent.

1.2 Axiomatic design principles: brief overview

As stated earlier, axiomatic design is a systems design methodology that systematically translates customer needs into functional requirements and then into design parameters, guided by fundamental principles or axioms [26]. This framework was introduced by Num in the late 20th century as a shift from reliance on the trial-and-error method to a systematic and scientific design approach [7]. This framework uses independent axioms and information axioms to guide through four design domains [24], as shown in Fig. 2. These design domains are namely, the customer needs domain (CN), functional requirements domain (FR), design parameters/physical domain (DP), and process variables domain (PV) [25]. The CNs capture the raw desires and expectations of the customer, expressing the benefits or outcomes they seek from the product or system and representing the *"what"* from their perspective. In the FRs, the CNs are translated into a minimal set of independent and measurable requirements that define the performance targets or functions the system must fulfil. The DPs then focus on the *"how"*, specifying the design elements or components chosen to meet the functional requirements and transform them into tangible solutions. Finally, the PVs describe the manufacturing or implementation processes, along with their controlling variables, that are required to produce the design parameters and bring the design to life in practice, completing the journey from concept to reality [27]. The potency of this framework lies in its ability to independently map all customer needs into the final product or service while utilising the information axiom to choose the best solution in every domain if more than one solution exists. The process is done through iterative zigzag decomposition, ensuring the optimal solution is achieved and the product satisfies the customer. This design framework helps designers organise and evaluate design decisions systematically through these axioms, ensuring independence and minimising complexity for better design outcomes [28].

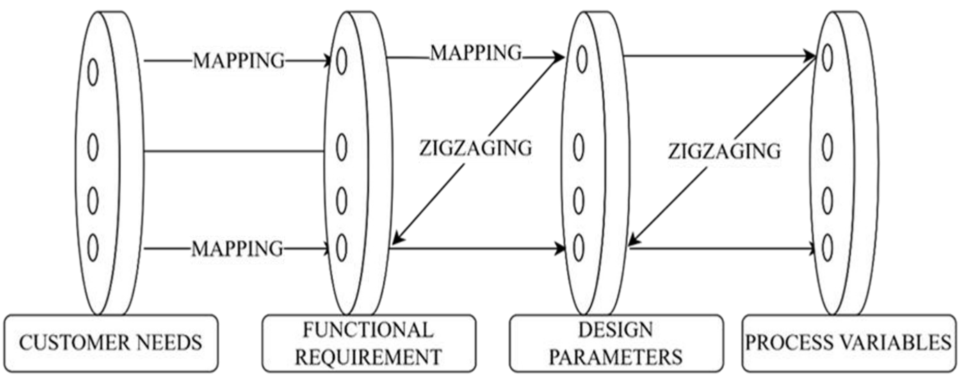

Fig. 2.2 Axiomatic design principles design process.

2 Methodology

2.1 Methods

To imitate the potential of the axiomatic design principle in addressing dental implants within the African context, this study involved the analysis of two hypothetical dental implant case studies using a customised axiomatic design framework developed from Suh's framework. The two hypothetical case studies, case study one and case study two, were randomly generated to depict the dynamic nature of the patient requirements with regard to dental implants, while affordability was stressed in both cases. Based on affordability and customisation as possible concerns inherent in dental implant patient cases, this study categorises this need into *convenience needs* and *affordability* to represent what dental implant patients desire under the CN domain. The two groups of needs stipulated under CN were then independently mapped into *usability* and *cost* under the FR domain, respectively. Consequently, the categories were mapped into *customised* and *cost-effective designs* under the DP domain. Lastly, the actualisation of these designs was categorised into *flexible manufacturing* and *lean manufacturing* under the PV domain, as shown in Fig. 3.

With this customised framework, both case studies were analysed tabularly, guided by available literature to demonstrate independence when meeting the depicted customer needs. In the case where multiple options (for instance, option A and B) were found to meet the design requirement, the information axiom was used in choosing the optimal design. A probability of each option to satisfy the functional requirement independently represented as (P(A∩B)) was calculated using equation 1. The design with the least information (*I*) was considered optimal as stipulated by Kulak et al. [29].

$$I = \log_2\left(\frac{1}{P_i}\right) \qquad (1)$$

where P_i is the probability of achieving the required solution in each domain, and I is the information axiom value per case.

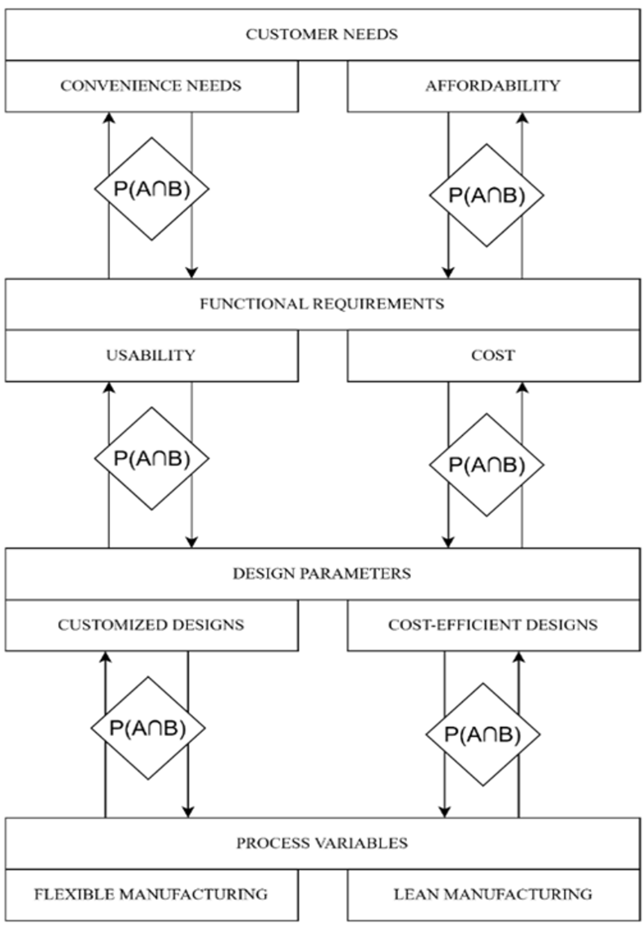

Fig. 3. Application of axiomatic design principles in dentistry.

2.2 Case studies

The case studies considered are as follows:

Case study one: A man in his 50s lost all four of his top molars due to periodontal disease. Upon assessment of his oral condition, it was found that jawbone volume at the proposed implant site had drastically reduced due to jawbone resorption and jawbone shrinkage that was caused by delayed treatment. The patient demanded affordable, long-lasting implants.

Case study two: The right central incisor of a 30-year-old patient was lost in a sports-related incident. The surrounding teeth are intact, and there was minimal bone loss in proximity to the lost tooth. Since the patient collaborates with clients, he was concerned about aesthetic requirements. The patient also desired to have a permanent implant to avoid bone resorption.

3 Analysis and discussion

The nature of the case studies in the current investigation is substantially closer to the real desires of dental implant patients in Africa, with preferences majorly on affordability and durable implants, while oral conditions, when accessed, are of different conditions in aspects such as bone volume at the proposed implant site. Using axiomatic design domains, these patients' needs were tabularly analysed for independence satisfaction through the design process to the manufacturing, as shown in Tables 1 and 3. The multiple design options reported in literature were also analysed for optimality using the information axiom afterwards.

Starting with case study 1, Table 1 gives the oral condition of the patient after assessment in terms of the uniqueness in terms of the level of bone resorption, which may not be likened to any other patient situation, in addition, economic constraints limited the patient to non-grafting methods before implanting and forced him to request affordable implants. These patients' desires may be fulfilled with the use of angular porous, low-cost titanium implant derived from the functional requirements of customised, enhanced stability, light, and low-cost implant. In actualisation of this implant that fully satisfies the patient's concerns, AM seems to be a viable solution.

Table 1. Case one analysis using Axiomatic design principles.

Customer needs	Functional requirement	Design parameters	Process variables
CN 1. Firm anchorage on small bone volume	**FR 1.** Enhanced primary stability	**DP 1.** Porous and surface-modified implant [30].	**PV 1.** AM for porous and modified implant surface
CN 2. working and long-lasting	**FR 2**. High-strength-volume ratio material	**DP 2.** Titanium alloy [21].	**PV 2.** Controlled implant density with AM
CN 3. Affordable implant	**FR3:** low-cost implant	**DP 3.** Low-cost titanium alloy material [22].	**PV 3.** AM for lean production
CN4. No bone grafting	**FR 4.** Customised implant for low volume	**DP 4.** Angled or zygomatic implant [15].	**PV 4.** AM for complex angles and geometry

When weighing between the design options reported in the literature for this case study, the information axiom analysis described in Equation (1) was used to determine the type of implant surface and the type of implant, as described in Table 2. A probability of the design to satisfy the patient's desires was allocated to each option from recommendations available in the literature, and the computation for the least information (I) was carried out. A porous implant surface having a smaller value of I (I = 0.152) compared to a non-porous implant surface (I = 0.515) has a higher chance of satisfying the patient's desires. Similarly, customisation of the implant (I = 0.234) could be more satisfying than the use of a standard implant (I = 1).

Table 2. Information axiom analysis for case study one.

Type of implant surface	
Porous surface	$I = \log_2\left(\frac{1}{0.9}\right) = 0.152$
Non-porous surface	$I = \log_2\left(\frac{1}{0.7}\right) = 0.515$
Type of implant	
Custom-fit implant	$I = \log_2\left(\frac{1}{0.85}\right) = 0.234$
Standard implant	$I = \log_2\left(\frac{1}{0.5}\right) = 1$

As in the case study 1, Table 3 shows the oral condition of the 30-year-old man described in case study two. Following the patient's desires, it can be seen that a combination of milling and AM methods could stand a chance of actualising a fully effective dental implant design for the patient's case.

Table 33. Case two analysis using axiomatic design principles.

Customer needs	Functional requirements	Design parameters	Process variables
CN 1. Instant use	**FR 1.** Improved both primary and secondary stability	**DP 1**. Customised threads and surface of the implant [31].	**PV 1**. AM for thread and surface customisation
CN2. Aesthetic crown	**FR 2.** Material with aesthetic properties	**DP 2**. Zirconium crown [32].	**PV 2.** Zirconia sintering
CN 3. Affordable	**FR 3.** Low-cost implant	**DP 3.** Use of dissimilar material [21].	**PV 3.** AM and CAD milling for different materials
CN 4. Maintained Natural gumline	**FR 4**. Tissue-like contour implant	**DP 4**. Customised abutment [33].	**PV 4.** CAD/CAM for Adaptable soft tissue contouring

Furthermore, comparing the options available for the various requirements using the information axiom design, Table 4 gives the computation of the least information (I) required in selecting the type of material implant and the customisation level of the abutment using literature-informed probability (P_i) for achieving the required solution [34].It can be seen that in this case, the use of a multi-material implant (I = 0.258) and customised abutment (I = 0.074) shows potential as a viable solution compared to single (I = 1.12) and standardised abutment (I = 0.286) for case study two.

Table 4. Information axiom analysis for case study two.

Type of implant material	
Single material implant	$I = \log_2\left(\frac{1}{0.46}\right) = 1.12$
Multi-material	$I = \log_2\left(\frac{1}{0.78}\right) = 0.258$
Customisation level of abutment	
Custom abutment	$I = \log_2\left(\frac{1}{0.95}\right) = 0.074$
Standard abutment	$I = \log_2\left(\frac{1}{0.82}\right) = 0.286$

4 Conclusion and future study

Previous research has explored standardised dental designs as a solution for tooth loss, while other studies have investigated the potential of advanced image scanning technologies to create fully customised implants tailored to each patient's unique anatomy. While the two methods have sufficiently helped in meeting the demands of the patient, the approaches could be inherently flawed with a trade-off, either in terms of long-term clinical success or affordability. This study utilises axiomatic design principles as a potential solution to dental implant challenges within the African context by analysing the hypothetical case studies that prioritise patients' needs and desires. The result of this study shows that this framework has the potential to bring innovation in patient-sensitive fields like dentistry, as it encourages independent satisfaction of the customer's needs, discouraging trade-offs. Both case studies analyses showed the potential of AM as flexible in accommodating patient needs, although limited access to AM technologies and skilled personnel in Africa still poses a challenge to fully implementation of affordable and durable dental implants. However, the hypothetical cases and analysis of this study may not fully describe the real situation in dentistry; its adoption and further development of an axiomatic framework in this field may have limitless innovation.

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