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Sustainable design of a plastic toothbrush: a case study of design for disassembling and materials recycling

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Abstract

A toothbrush is one of the most widely used oral care items that help remove debris from the mouth and keep it germ-free. More than 3.5 billion toothbrushes are purchased each year. A market valued at USD 6.90 billion in 2022, with an estimated annual growth rate of 4.1% through 2029. More than 75% of toothbrushes sold are of the traditional manual model [1]. Growing awareness of the environmental implications in the use of disposable toothbrushes has prompted all major manufacturers to develop "eco-friendly" products, whose approach is based on three different strategies: the use of biopolymers; the use of natural materials such as bamboo; or the use of replaceable heads. However, each of these solutions hides critical issues: most bamboo toothbrushes have mechanically anchored nylon bristles that cannot be disassembled and are vulnerable to early aesthetic degradation; biopolymer toothbrushes do not show significant lifecycle environmental benefits when compared to their traditional polymer equivalents; and toothbrushes with replaceable heads are often abandoned in use due to a perception of poor hygiene, which grows with time. Based on previous LCA analyses that highlight the potential environmental benefits of a fully recyclable toothbrush embedded within an economic scheme of recovery and reuse of its materials [2-3], the paper aims to describe the environmental redesign process of one of the most popular and pervasive mass market products: the plastic disposable toothbrush made through the multi-shot injection moulding process. The project, developed within the School of Architecture and Design of the University of Camerino, is characterized by innovative technical and formal solutions that can improve the environmental performance of the product through the strategy of design for disassembling. The developed solution allows the aesthetic and ergonomic qualities of the product to remain the same and, at the same time, allows the end user an easy and intuitive disassembly of the toothbrush at the end of its life, solving the crucial problem of removing the nylon bristles. In conclusion, the paper presents a concept of a product in line with SDG goal 12, as it aims to make the production of a mass market product currently considered critical more rational and responsible.

Sustainable design of a plastic toothbrush: a case study of design for disassembling and materials recycling

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Abstract. Toothbrush is one of the most widely used oral care items in the world. Growing awareness of the environmental implications in the use of disposable toothbrushes has prompted all major manufacturers to develop "eco-friendly" products, whose approach is based on three different strategies: the use of biopolymers; the use of natural materials such as bamboo; or the use of replaceable heads. However, each of these solutions hides critical issues: most bamboo toothbrushes have mechanically anchored nylon bristles that cannot be disassembled and are vulnerable to early aesthetic degradation; biopolymer toothbrushes do not show significant lifecycle environmental benefits when compared to their traditional polymer equivalents; and toothbrushes with replaceable heads are often abandoned in use due to a perception of poor hygiene, which grows with time. Based on previous LCA analyses that highlight the potential environmental benefits of a fully recyclable toothbrush embedded within an economic scheme of recovery and reuse of its materials, the paper aims to describe the environmental redesign process of a plastic disposable toothbrush made through the multi-shot injection moulding process. The project is characterized by innovative technical and formal solutions that can improve the environmental performance of the product through the strategy of design for disassembling.

1. Introduction

Throughout history, various tools have been used to maintain personal oral hygiene. The toothbrush is one of the most used oral hygiene items, helping to remove debris from the mouth and keep it free of germs. The earliest toothbrush we have evidence of, used for more than 3,000 years, is the miswak or siwak, a tooth-cleaning stick made mainly from the root of the Salvadora persica tree. (Shirzaiy, Sarani and Bagheri 2016). The toothbrush as we know it is thought to have been invented in northern China in the 15th century and later imported to Europe by travellers. It consisted of a bamboo handle with boar hair attached to one end. However, the invention of the modern toothbrush is generally credited to an English merchant named William Addis, who made a bone and horsehair toothbrush in 1780. The first American patent for a toothbrush was filed by H.N. Wadsworth in 1857. In 1938, the introduction of nylon made it possible to produce the first toothbrush with plastic bristles: the Doctor West's Miracle Toothbrush. Since then, the formal and material evolution of this simple but essential product has basically come to a standstill. In fact, since 1954, the year in which the Broxodent mechanical wall brush was created, the evolution of the product's design has focused mainly on its mechanisation and, more recently, on its digital extension in the form of an information service (Bellis, 2021).

More than 3.5 billion toothbrushes are purchased each year. This market was worth USD 6.90 billion in 2022, with an estimated annual growth rate of 4.1% until 2029. Currently, the toothbrush market can be divided into two macro-types: the first is the manual toothbrush, with its typological and formal variations, which accounts for approximately 75% of the market share of toothbrushes sold each year (Fortune Business Insights, 2022); the second is the electric toothbrush, with all its functional variables and peculiarities.

Manual toothbrushes can be distinguished by five factors: shape of the brush head (rectangular, elliptical, and diamond-shaped); replaceability of the brush head (fixed or removable); hardness of the bristles (soft, medium, and hard); bristle layout (flat, slanted, wavy, and bunk); shape of the handle (straight, angled, offset, and angled offset). In addition, the handle may have silicone moulded parts to increase grip. Handles with grips are usually more ergonomically shaped to give a firmer grip when brushing and less wrist fatigue. Electric toothbrushes can be divided by: head shape (round or elliptical); type of movement (rotary, oscillating, or pulsating); and speed of movement (sonic 200-400 Hz and ultrasonic up to 2,000 Hz). All have a large body to house the motor and batteries, and all have the possibility of changing heads. In addition to being larger, the handle is never different or more ergonomic in shape (Hovliaras et al., 2015).

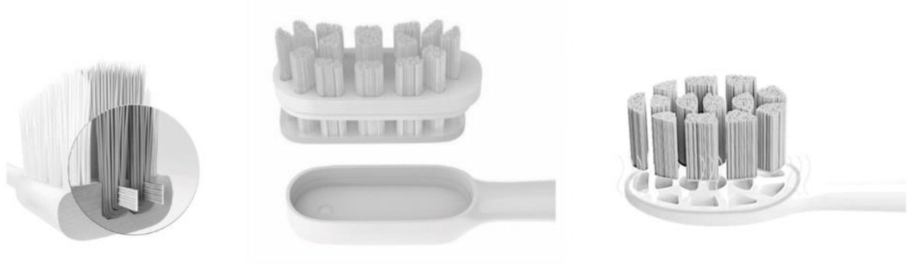
Toothbrushes can be further divided into three product categories: household, travel, and special purpose. Household manual toothbrushes are the most common on the market, aimed at users of all ages and used exclusively in domestic context. Their lifespan is closely linked to bristle wear and is generally around three months. Almost all electric toothbrushes fall into this category. Most toothbrushes in this category can be considered disposable, except for electric toothbrushes and manual toothbrushes with interchangeable heads, which allow the handle to be reused. Travel toothbrushes are formally and functionally related to the household typology but are characterised by their small size due to the use of compacting and folding strategies.

Often this type of product comes in kits with a basic amount of toothpaste for use while travelling. In some versions, the heads are pre-impregnated with toothpaste and do not need to be rinsed to meet the necessity of travellers who do not have access to a bathroom. Finally, special toothbrushes refer to specific contexts or categories of users, such as fingerbrushes for certain forms of disability, 360° bristles, for maximum security prisons, etc.

In terms of production, and considering only manual toothbrushes at this stage, there are two main aspects to consider: the material and production technology of the body, and the material and attachment technology of the bristles. The choice of material for the body is mainly determined by the type of product (disposable or with interchangeable heads), the expected duration of use and the area of application. Polypropylene (PP), polyethylene (PE), bamboo and silicone are the most used materials. Aluminium is also used for toothbrushes with only replaceable heads. Nylon is mainly used to produce toothbrush bristles and is currently the only alternative considering the basic factors of durability, stiffness control and production costs. However, there are alternatives such as boar hair, PBT and PLA, which are used for small market shares and niche products. Wild boar hair has been abandoned in favour of nylon, which is better at preventing bacterial proliferation and is less rigid, an essential factor in preventing corrosion of dental enamel and possible injury to gum tissue with consequent recession. PBT and PLA, on the other hand, show an accelerated loss of performance, reducing the product's service life.

In today's toothbrush manufacturing, the most common method used to anchor the bristles to the brush head is a technology called Traditional Tufting (TT). This process, which is usually fully automated to maintain a high standard of hygiene, consists of inserting the nylon bristles into the holes in the brush head and then clamping them with metal staples. In some of the most advanced processes, the tufting machine can fill 900 holes per minute, working with great precision. It is representing one of the most difficult and crucial steps in the innovation of this type of product. In addition to the TT technology, new bristle anchoring technologies are being optimised with the aim of eliminating metal staples, the critical aspects of the process. Over time, toothpaste creeps into the holes and meets the metal component, leading to increased bacterial growth and premature corrosion. This established technology has been joined in recent years by two others: Anchor-Free Tufting (AFT) and Pressure Tufting (PT). In AFT technology, the bristles are attached to a plate without metal staples. The plate is then joined to the body of the toothbrush. In this way, the product consists of two macro-components. PT technology is more recent and allows the bristles to be anchored to the toothbrush without the use of metal staples or plates. The steps in this process are to melt the end of the filament assemblies, insert them into the holes and press them in. The fused section is locked into the hole by expansion due to the pressure applied.

Figure 1. From left to right: TT, AFT and PT technologies.

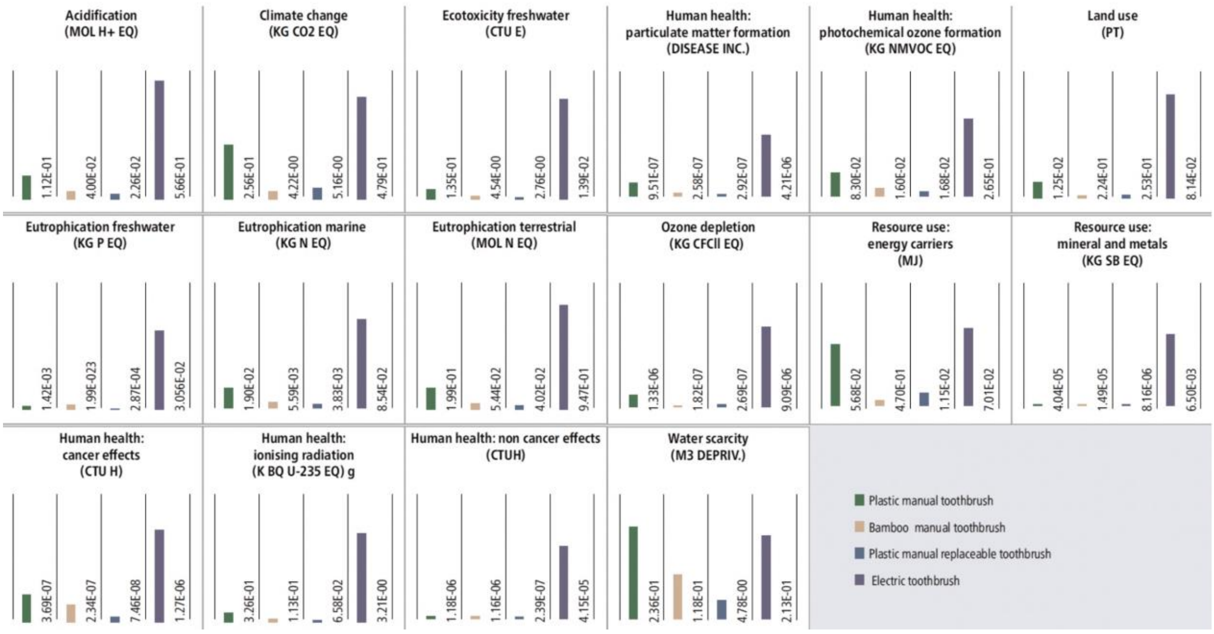


The growing awareness of the environmental impact of the use of disposable toothbrushes has led all major manufacturers to develop "eco-friendly" products based on three main strategies: the use of biopolymers, the use of natural materials such as bamboo, or the use of replaceable brush heads. However, each of these solutions hides critical issues and a Life Cycle Assessment (LCA) approach is required to consciously assess the environmental performance of the toothbrush.

2. Literature Reviews

Although the toothbrush is a widely recommended health care device worldwide, there is still little quantitative data available on its environmental impact. Two life cycle assessments (LCAs) of this type of product have now been carried out, funded by the Eastman Dental Institute of University College London (UK) in partnership with the Dental University Hospital of Trinity College Dublin (Ireland). The first study (Lyne et al., 2020) considered four types of toothbrushes: plastic manual, bamboo manual, plastic manual with replaceable head, and electric. The LCA was conducted from cradle to grave, i.e. from production to disposal. The functional unit was defined as the individual use of a toothbrush over a time of five years, the usual battery life of an electric toothbrush.

Figure 2. LCIA results (Lyne et al., 2020).

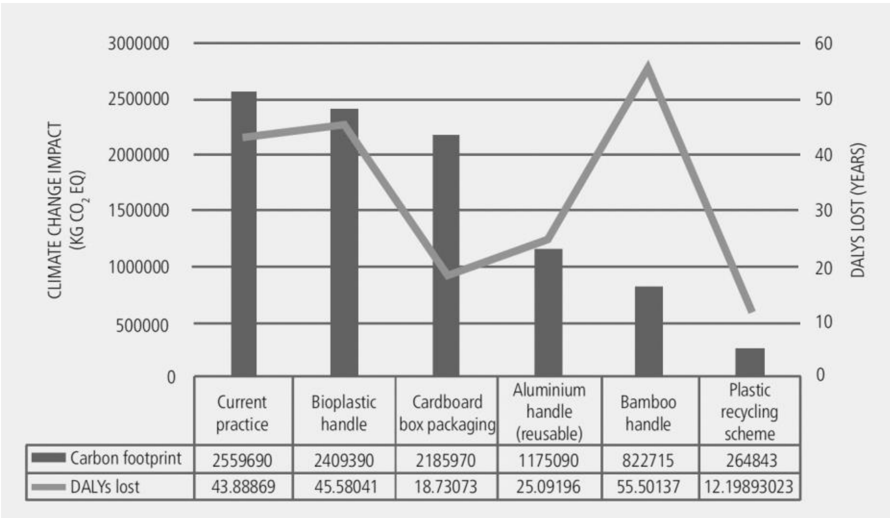


The results of the study show that the electric toothbrush has the highest impact in all categories except water scarcity. The plastic toothbrush with replaceable head and the bamboo toothbrush have the lowest impacts in 11 and 5 of the impact categories respectively. The material used is the main contributor to the environmental impact of the plastic manual toothbrush and the one with replaceable brush heads. PP, used for the handles, was the largest contributor for these two types of toothbrush (37% and 33% respectively). The electric toothbrush was the heaviest product at 1.42 kg. The largest contributor to the total impact was transport (47%), followed by materials (46%).

This comparative LCA showed that a plastic replaceable head manual toothbrush and a bamboo manual toothbrush perform better than both traditional plastic manual toothbrushes and electric toothbrushes in each of the impact areas considered in this study. The study shows that the best environmental performance is currently achieved by the toothbrush that rationalises the use of material, i.e. the toothbrush with a replaceable head, or changes the origin of the material, i.e. the bamboo toothbrush. The electric toothbrush has the highest impact, as the impact of the numerous components must be added to the impact of the battery and the use phase. However, the study makes some assumptions that should give us pause for thought. The first is that the motorised body of the electric toothbrush is used by a single user and is disposed of after five years. Instead, the possibility of sharing the motorised handle should be considered and a reduced battery life due to increased recharging cycles should be evaluated. The second assumes that the nylon bristles of the brush head and the associated metal staples are removed from the bamboo brush. This seems impractical in real life, as the authors themselves state.

In the same year, the authors carried out another interesting study that highlighted and deepened specific aspects of the previous work (Duane et al., 2020). The same LCA methodology was used, following the EU Product Environmental Footprint guidelines. The aim was to model the best possible toothbrush using two assessment parameters: DALYs (disability-adjusted life years) and carbon footprint. One DALY represents the loss of the equivalent of one year of full health. DALYs for a disease or health condition are the sum of the years of life lost to due to premature mortality (YLLs) and the years lived with a disability (YLDs) due to prevalent cases of the disease or health condition in a population. (World Health Organization, 2023). Starting with the standard manual toothbrush, the study considered four types of handle material: bioplastic, bamboo, aluminium, and recycled plastic. Only for the aluminium toothbrush was the possibility of replacing the brush heads with bristles considered.

Figure 3. Toothbrush modelling results for climate change impact and DALYs (Dune et al., 2020).



All scenarios considered show an overall improvement in the carbon footprint compared to current production, but the results for DALYs vary widely. Using bioplastics instead of PP only improves the carbon footprint by 6% and increases DALYs by 4%. Using bamboo handles reduces the carbon footprint by 68% while increasing DALYs by 26%. The optimal balance between the two values is expressed by the fourth, ideal model, which uses a plastic recycling scheme and expresses a 90% and 72% improvement respectively. In this model, the nylon bristles have the greatest impact, accounting for 90% of the carbon footprint. However, the toothbrush with the recycled plastic handle requires the manufacturer to take responsibility for the recovery and recycling of the toothbrush.

This study shows how a toothbrush made from recycled plastic in a circular system is the environmentally preferable option that results in the least loss of DALYs. In the win-win scenario, the manufacturer would have to provide a logistical facility to collect used toothbrushes and their packaging. Nylon bristles, for which there are no marketable alternatives, and degraded plastic would be removed and disposed of and replaced with an estimated 10% virgin plastic.

The LCA, which complements the first one, shows how the bamboo toothbrush loses effectiveness when considering DALYs together with the classic environmental impacts. This is due to its high water consumption, which drastically increases its DALY. The best compromise is therefore a toothbrush that uses a circular material scheme, assuming that it is possible to collect most of the used toothbrushes. Furthermore, in this LCA, the plastic toothbrush with replaceable head, which performed well in the first LCA, is replaced by a toothbrush with replaceable head and aluminium handle, which has a higher production impact than PP. It is assumed that the reason for analysing such a brush, which is not explicitly stated by the authors, is probably due to less aesthetic degradation of the aluminium handle. Less aesthetic degradation also means a greater likelihood that the user will not feel the need to replace it soon. In fact, the aluminium handle was assumed to have a lifespan of 20 years, which is highly unlikely in actual use conditions.

To conclude the reflections suggested by the two studies mentioned above, and to extend the analysis also to the perceptual and cultural aspects that condition the use of toothbrushes, we can state that:

- common bamboo toothbrushes employ nylon bristles attached by staples that prevent their disassembly and material recovery; they are subject to early aesthetic degradation due to the biological nature of the material, more easily attacked by fungi and bacteria, which can be limited with additional finishing processes whose impact is, however, to be assessed; the shape of the toothbrush is almost always very simplified in order to optimise the use of the material and reduce production time, with a consequent reduction in the ergonomics of the product;
- biopolymer toothbrushes do not show significant lifecycle environmental benefits when compared to their traditional polymer equivalents;
- toothbrushes with replaceable heads perform well overall, but in real-life use have shorter replacement times than expected and are often abandoned due to a perceived lack of hygiene, which increases over time; within the life cycle environmental assessment, the impact due to the necessary handle sanitisation processes that are required each time the brush head is replaced should also be considered;
- the electric toothbrush is the product type with the highest impact, without demonstrating significant benefits in terms of dental caries or periodontal disease prevention compared to its manual counterparts (Lyne et al., 2020).

3. Phases and Method of Design Research

Based on the results proposed by the above-mentioned LCA studies, which highlight the potential environmental benefits of a fully recyclable disposable toothbrush placed in an economic scheme of recovery and reuse of its materials (Ellen MacArthur Foundation, 2017), this paper describes the environmental redesign process of one of the most widespread and pervasive mass market products: the plastic disposable toothbrush made by the multi-shot process.

The project, developed within the School of Architecture and Design of the University of Camerino (Italy) as the final work of the student Alessio D'Angelo (supervisor Prof. Jacopo Mascitti), is characterised by technical-formal solutions capable of improving the environmental performance of the product through the DfS strategy of disassembly. The solution developed maintains the functional, aesthetic, and ergonomic qualities of the traditional product, but at the same time allows the end user to disassemble the toothbrush easily and intuitively at the end of its life, solving the key problem of removing the nylon bristles.

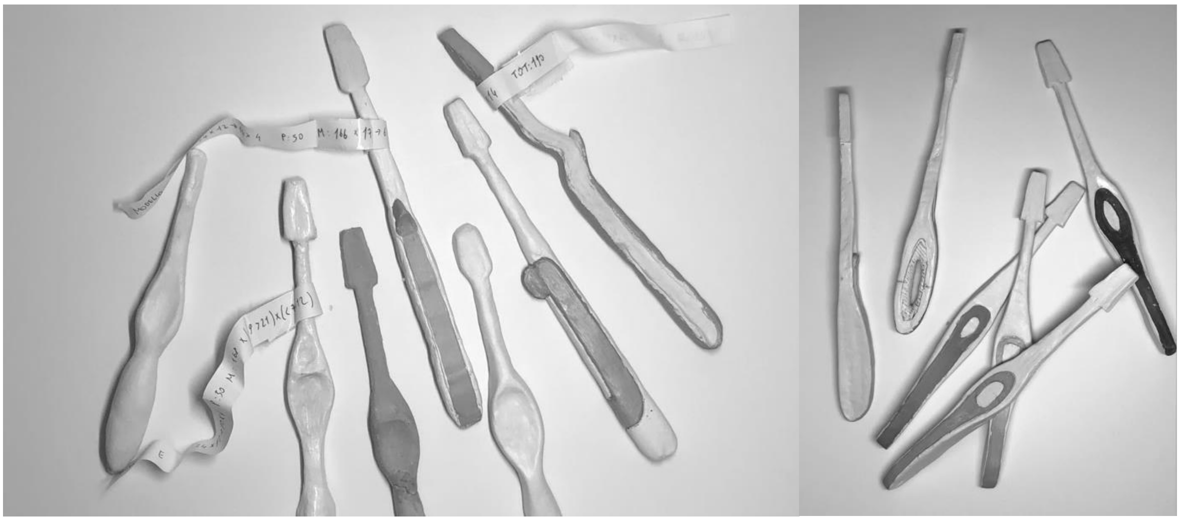
The methodology adopted to achieve the intended objective consisted of six macro-phases: (i) morphological and ergonomic analysis of a representative group of manual toothbrushes; (ii) definition of priority criteria for design development in response to the objective of increasing the environmental sustainability of the product and the circularity of materials; (iii) development of product concepts and production of study and verification models; (iv) identification of materials and production processes (body and bristles) in line with the project objectives; v) design development through the creation of virtual models of the product and production moulds; vi) final prototyping. In the first phase, ten toothbrushes were considered, selected on the basis of specific characteristics such as overall size, shape and angle of the handle, shape of the head, and ergonomics of the grip points.

Figure 4. The ten toothbrushes considered in the first phase of the research.

The first phase of research helped to define the optimal product size, handle shape, and head angle and shape. At the same time, the knowledge gained from this phase is being used to investigate priority design intervention strategies to improve product performance in terms of material circularity.

In the second phase, priority design development criteria were defined on which to base the development of the plastic disposable toothbrush concept capable of optimising the disposal and recycling phases. The main strategy considered was Design for Disassembling (Vezzoli and Manzini, 2008, p. 181). At the same time, it was decided to enable the end user to separate the components and eliminate the equivalent industrial process. Particular attention was paid to reducing the material used and rationalising the shape while maintaining correct ergonomics. The industrial processes considered were Pressure Tufting bristle anchoring technology without metal staples and co-moulding for the entire toothbrush.

Figure 5. Study models made during the third phase of the project.



The third phase led to the creation of seven different concepts which, thanks to different technical solutions, made it possible to disassemble a traditional plastic toothbrush into its different material components and to separate the handle from the bristles. The design phase of the new product was supported by the creation of 15 study models, which allowed the optimisation and verification of the different design solutions that were hypothesised and then incorporated into the final solution.

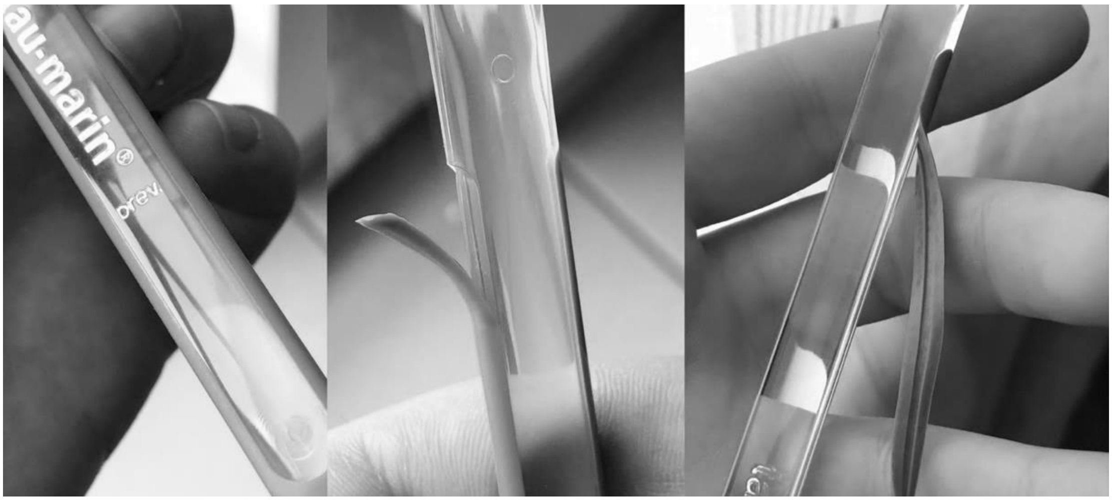
The choice of material and production technology in the fourth phase was influenced by one of the case studies investigated in the first phase of the project. In general, co-moulding is a production technique for plastic products that is avoided in the context of sustainable design because it creates a bond between two different materials, making any hypothesis of recycling futile, regardless of whether one or both are recyclable. In fact, once melted, they must be considered as a single material that cannot be recycled because the two basic materials, although compatible, do not have the same chemical properties, which has a negative impact on the disposal phase. It is not surprising that this technique is widely used in the world of toothbrushes, as most toothbrushes cannot be recycled because the bristles are attached to the head with metal grafts.

The toothbrush from the Italian company Tau-Marin was of particular interest. It was developed in the 1970s in collaboration with the designer Gabriele Stocchi. Its peculiarity lies in the scaled cut of the bristles. However, it was the co-molding of the toothbrush that attracted attention, as it exhibited a peculiar behaviour unlike any other toothbrush on the market. In fact, by applying moderate force to the soft flap on the side of the handle, it was possible to remove it without too much difficulty, without leaving any residue and without breaking the component. This dynamic was certainly not anticipated by the company or the designer, and was therefore not included in the product communication. On external analysis, the dynamics could be determined by a few concomitant factors:

- the mould used to produce the handle must have been highly polished to give the component a shiny finish and make the surface less rough;

- the materials used for co-moulding (probably cellulose acetate for the handle and EPDM for the grip part) have a poor chemical compatibility, so that a chemical bond cannot be established and the two parts can be separated.

Figure 6. Tau-marin toothbrush and the soft flap peeling defect.



The fifth and sixth phases of the project involved optimising the design idea with the help of the Italian toolmaker Meccaniche Broemi and producing the final prototype.

4. The disassemblable toothbrush Ri-Brush

Ri-Brush is a disassemblable and recyclable plastic toothbrush that is proposed as a simple and inexpensive solution to fit into today's still niche market of environmentally sustainable toothbrushes. The project is based on the idea of a product that can easily and effectively respond to a recycling scheme for its materials, which can be activated by the end user. The product is essentially made up of two parts: a rigid structural body and a soft cover in which the bristles are embedded.

Figure 7. The Ri-Brush toothbrush.

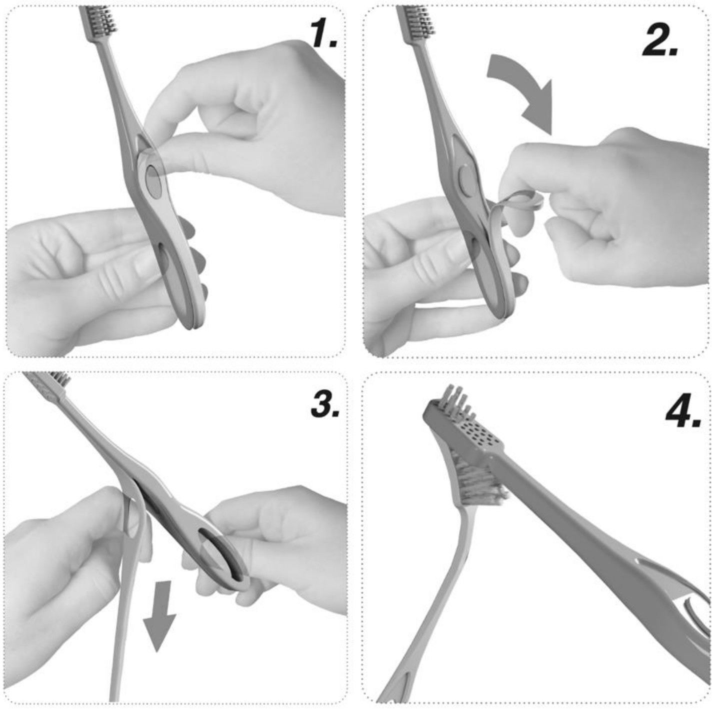
As seen in the Trinity College LCA study, a toothbrush that adopts a recycling scheme appears to perform better environmentally than all other types of toothbrushes. In that analysis, however, the ideal toothbrush using the recycling scheme did not have the possibility to be disassembled. This theoretically makes the developed design even more environmentally efficient than the toothbrush hypothesised by the research, as the industrial phase of product disassembly must be subtracted. Inspired by the dynamics observed in the Tau-Marin toothbrush, the product is made of two materials (PS and TPE-U) whose chemical compatibility during co-moulding is limited and therefore reversible. The product has a total weight of 23 grams, including the nylon bristles.

The disassembly process can be divided into four steps:

- Insert the finger into the tab on the front of the product and peel it off;
- when the first ellipse is reached, use the hole to insert the finger and continue peeling with more force;
- Use the second hole to continue peeling the back soft part up to the head;
- once at the head, continue peeling until the handle comes off completely, taking the bristles with it.

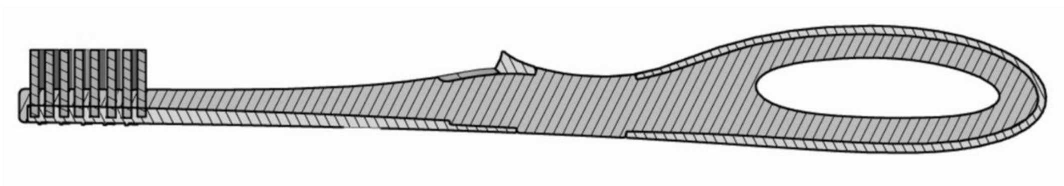
The hole in the handle has the dual function of reducing material consumption and providing a firm grip during the process of separating the handle from the body. Once the disassembly process is complete, the two components can be recycled separately.

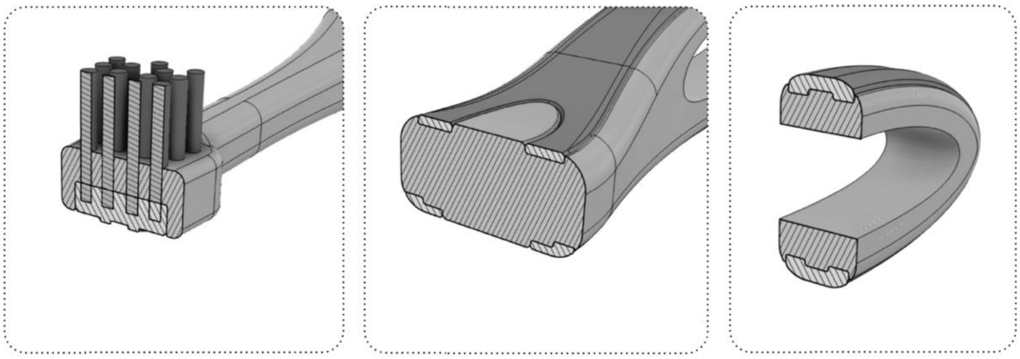
Figure 8. The four phases of disassembly process.



The PS handle, which accounts for about 80% (18 grams) of the product, can be disposed of in the plastics collection. The grip with the bristles undergoes a final process: the detachment of the head from the rest of the component. In this way, 3 of the 4 grams of TPE-U can be recovered and recycled. The remaining 2 grams of product material, i.e. the nylon bristles and the TPE-U they are anchored to, are discarded.

Figure 9. Longitudinal and cross section of the Ri-Brush toothbrush in which the TPE-U grip and welded nylon bristles are visible.





Ri-Brush has an ergonomic shape that easily adapts to the user's hand. Its development is based on the need to modulate the thickness of the handle and the soft grip according to the new feature of disassembly. The image above shows the longitudinal section of the toothbrush. In the areas where the brush becomes narrower, the thickness of the soft grip increases to prevent it from tearing during disassembly. The opposite occurs where the width increases and the thickness decreases.

In terms of bristle engagement technology, we opted for the PT discussed in the previous paragraphs. This is the only technology that meets the design requirements. The bristles are welded directly to the soft TPE-U part and become an integral part of it.

5. Conclusion

The paper presented the methodological process that, through the priority application of the Design for Disassembling strategy, typical of the Design for Sustainability (DfS) approach, led to the development of a new concept of a disposable and disassemblable plastic toothbrush, characterised by the use of co-moulding technology. The objective was to follow the design hypothesis proposed by Dune (2020) and his research group for a toothbrush that would adhere as closely as possible a pattern of recovery, recycling, and reuse of its materials. The decision to work on a plastic toothbrush produced using multi-shot moulding technology was driven by the desire to develop a product that could have a significant impact, in absolute terms of the number of products sold each year, on the issue of reducing the environmental impact of this common type of product. Based on what has been discussed and referring to similar commercial products, the advantages of Ri-Brush can be summarised as follows:

- the rationalisation of different polymer used for the production of the toothbrush, thanks to a new structural layout that allows the two main components of the product (body and soft grip + bristles) to be easily separated;
- the possibility of eliminating the critical component of the product (the bristles) in an extremely simplified way, allowing the recovery of more than 90% of the toothbrush material;
- a new, simple and effective strategy of user and product interaction allows the soft grip to be separate from the rigid body of the product at the end of the use phase;
- the possibility for the product to be returned directly to the plastics recycling chain by the end user, as an alternative to the costly product recovery and material reuse model proposed by the above study.

In conclusion, the methodological approach of the DfS, together with a design reinterpretation of the criticalities and opportunities offered by the consolidated technology of multi-shot plastic moulding, has allowed the development of a new concept of a more sustainable and circular disposable toothbrush. The main innovation driver of the new product is not the simple substitution of the polymer material with a natural one, whose technical specifications often require a reduction in the performance of the product, both in terms of ergonomics and hygiene, but an original approach to the initial problem (maintaining the co-moulding technology) and the consequent formal reinterpretation of the product. Once again, the significant results obtained demonstrate the innovative potential that DfS offers to designers and companies interested in developing products with high functional, environmental and economic performance, opening up the scenario for further promising development of this specific typology.

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