Mechanical Engineering – Scientific Journal, Vol. **40,** No. 1, pp. 23–31 (2022)
Number of article: 647
In print: ISSN 1857–5293
Received: February 5, 2022
On line: ISSN 1857–9191
Accepted: February 21, 2022
UDC: 621.798.147-036.5:7.05-027.22
https://doi.org/10.55302/MESJ22401647023j

Original scientific paper

DESIGN AND IMPROVEMENT OF A REUSABLE BOTTLE FOR SPORTS DRINKS USING VIRTUAL TESTING AND VALIDATION

Ana Jovčevska, Leo Kralevski, Ile Mirčeski

Faculty of Mechanical Engineering, "Ss. Cyril and Methodius" University in Skopje,
P.O. Box 464, MK-1001Skopje, Republic of North Macedonia
ile.mircheski@mf.edu.mk

A b s t r a c t: This paper presents the design process of an ergonomic reusable bottle for sports drinks using virtual testing and validation. The main goal was doing research in the field of already existing sports bottles, as well as creating a new and innovative sport's bottle design which implements good ergonomic principles and requirements. Some light is shone on the use of material, and the product manufacturing process, all with a goal to create a product which is of good quality, great performance and affordable price. A crucial point in the research is the virtual validation. The 3D model of the bottle design, as well as the core and cavity moulds, and the product simulation were created in the software SolidWorks. A further analysis was made using the software CATIA and Human Builder, to ergonomically analyze and verify said ergonomic reusable bottle.

Key words: reusable bottle; sports; design; ergonomics; mould; simulation; virtual simulation

ДИЗАЈН И ПОДОБРУВАЊЕ НА ШИШЕ ЗА СПОРТСКИ ПИЈАЛАЦИ ЗА ПОВЕЌЕКРАТНА УПОТРЕБА СО КОРИСТЕЊЕ НА ВИРТУЕЛНО ТЕСТИРАЊЕ И ВАЛИДАЦИЈА

А п с т р а к т: Во овој труд се претставува процес на дизајнирање ергономско шише за спортски пијалаци за повеќекратна употреба користејќи виртуелно тестирање и валидација. Главна цел беше истражување на веќе постојните шишиња за употреба при спортски активности и создавање иновативен дизајн на шише за употреба во спорт во кое се вградени добри ергономски принципи и барања. Се посветува внимание на употребата на материјали и на производствениот процес, сè со цел да се создаде производ со добар квалитет, одлични перформанси и пристапна цена. Клучна точка во истражувањето е валидацијата со виртуелно тестирање. Со помош на софтверскиот програмски пакет SolidWorks се направени: 3Д-модел на дизајнот на шишето, калапна шуплина потребна за процесот на инјекционо пресување и виртуелно тестирање. Дополнителна анализа беше направена со помош на софтверот CATIA и модулот за ергономија Human Builder со цел ергономски да се анализира и верификува ергономијата на шишето за повеќекратна употреба.

Клучни зборови: шише за повторна употреба; спорт; дизајн; ергономија; калапни шуплини; симулација; виртуелна симулација

1. INTRODUCTION

This research is focused on the process of an engineering design combined with an ergonomic approach in order to develop a plastic bottle used for sport's drinks.

Plastic bottles are one of the most mass-produced plastic products in the world nowadays. According to Mordor Intelligence its estimated CAGR (Compound Annual Growth Rate) from 2020 to 2025 is expected to reach around 6.5% [1]. This is a result of the low cost, increasing demand, recyclability, easily adapted designs, usage of colour, and much more.

Plastic bottles are an easy, affordable option for storing water and/or other liquids for refreshment during long walks.

During physical activities, the human body releases excess liquids in form of water droplets, sweat. Sweating is a bodily function which regulates the body's temperature, cooling it down during a workout.

A sportsman need to hydrate his body using water, or another liquid, which boost the energy and helps him to get through the daily exercises. Such drinks include isotonic drinks which contain electrolytes. With all that said, a good packaging of that liquid is required. A bottle needs not only to store the required beverage, but also needs to provide a good hand grip, to have appealing design and an affordable price. It is also very important that the product would be eco and environmentally friendly as much as it is possible.

The implementation of some ergonomic principles would improve the bottle's sales, considering they would help in the overall impression and user experience. However, those principles would increase the complicity of the shape and form, as well as the process' price of execution and production.

2. MARKET RESEARCH

One important step while designing a new product is observing and researching already existing products of the same kind. This process helps with analyzing the pros and cons of what the market has to offer, giving direct information. It is important for understanding what the customers want to buy and what they expect. Also, using the information gathered from the research we can target a specific target group, in this case sportsmen.

There is an endless amount of sport's bottles and plastic water bottles on the market today. They differ in size and colour, used material, whether they are reusable or recyclable, and many other aspects. The shape and form of the bottles are different as well. They do most of the product placement. If someone likes how a product looks, the product would catch the buyer's eye and he wouldn't hesitate to buy it.

In this paper we will present an observation and research of a few different sport's bottles.

POWERADE is a company which sells isotonic and sport's drinks. The POWERADE bottle is used for an isotonic sport's drink. This is a water bottle made from PET plastic for single use. It has an intriguing design, based on ergonomic principles, which include finger placement for better grip, holding area and good friction. An interesting addition, is the ability for different finger placement, across the whole bottle area (Figure 1). The cap and lip part are quite wide which could sometimes be a negative aspect, because sometimes while the user is drinking directly from the bottle it can result with spilling or choking.

Fig. 1. Powerade drinks (company Powerade, https://www.powerade.com)

This NIKE sport's bottle (Figure 2) has a different design. It is also a reusable water or sport's bottle. Its body has a rubber panelling on its side which helps with the grip, as well as a tilted head for easier and mess-free use. The bottle has a special lid which ensures fast and efficient hydration. The top can be taken off for the bottle to be refilled, and the diameter of the opening is quite big, for easier filling. In addition, the bottle is squeezable and leak proof.

Fig. 2. Nike 32oz HyperFuel (company Nike, https://www.nike.com)

The sport's bottle by the company O'Neill has very successful ergonomic and grip design (Figure 3). The bottle is panelled with rubber on both sides, so no matter which side the hand is on, the rubber ensures the bottle won't slip from the user's hands. The rubber is textured as well.

The shape of the bottle is quite small, which makes it easier to handle and transport. The curves of the design have a big impact on the ergonomics, as well. However, that means that this bottle holds a smaller amount of liquid.

The cap is a sport's bottle cap, which ensures fast and easy drinking. The top is removable, for easier pouring, mixing and cleaning. The entire top is covered with see-through plastic, which is a very good solution for hygienic purposes and accidental spillage.

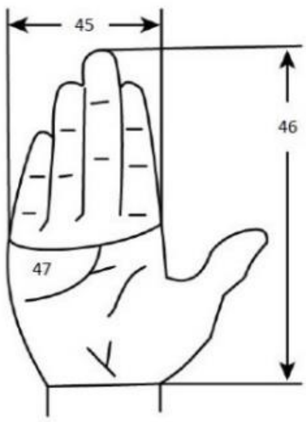
Fig. 3. O'Neill's bottle (https:// www.oneills.com)

3. ERGONOMIC REQUIREMENTS

After the performed market research, the main goal was established to make a better design for a sport's bottle than the previously observed and elaborated similar products. Some crucial aspects, which were necessary to be taken into consideration, were to provide: better ergonomic features for easy and comfortable hand (finger) placement, better way to decrease the slipping area and increase the friction area in order to obtain better bottle's grip, a lip and cap for quick access and usage, aesthetically appealing overall design and an affordable price for these qualities.

When designing an industrial product one of the main goals is for it to be usable for the majority of people. We had to provide a product that fits well most of the possible users [2, 3]. With that intention in mind, we had to examine the human hand size and its percentile, using anthropometric data [4]. Figure 4 shows the average hand dimensions and their percentiles for male and female hands. When designing a water or sport's bottle, we had to take into consideration the difference between a male and a female hand size.

In particular, the bottle has to be fit for a male's biggest hand size, and for a female's smallest hand size. If we want both sides to comply, we had to take into consideration the female side, specifically using smaller percentile female hand size and grasp [3]. That comes from the fact that both male and female users can be satisfied by the smaller sizes, considering both can use the smaller sized product, and the females' hands cannot use the bigger sized products.



45 Hand breadth. The breadth of the hand, measured across the ends of the metacarpal bones (metacarpophalangeal joints).

	Sample		Percentiles 1st	5th	50th	95th	99th
A	Men	Cm	8.1	8.4	9.0	9.8	10.0
		(in)	(3.2)	(3.3)	(3.5)	(3.9)	(3.9)
B	Woman	Cm	7.1	7.3	7.9	8.6	8.9
		(in)	(2.8)	(2.9)	(3.1)	(3.4)	(3.5)

46 Hand length. The distance from the base of the hand at the wrist crease to the top of the middle finger.

	Sample		Percentiles 1st	5th	50th	95th	99th
A	Men	Cm	17.3	17.9	19.3	21.1	21.9
		(in)	(6.8)	(7.1)	(7.6)	(8.3)	(8.6)
B	Woman	Cm	15.9	16.5	18.0	19.7	20.5
		(in)	(6.3)	(6.5)	(7.1)	(7.8)	(8.1)

47 Hand circumference. The circumference of the hand measured around the knuckles (metacarpophalangeal joints).

	Sample		Percentiles 1st	5th	50th	95th	99th
A	Men	Cm	19.2	19.9	21.3	23.0	23.7
		(in)	(7.6)	(7.8)	(8.4)	(9.1)	(9.3)
B	Woman	Cm	16.7	17.3	18.6	20.0	20.7
		(in)	(6.6)	(6.8)	(7.3)	(7.9)	(8.2)

Fig. 4. Average hand sizes and their percentiles [4]

In conclusion, the bottle's width (its diameter) should be between 60 mm and 80 mm [3], which allows the hand to be positioned therein nicely while offering a good grip.

Regarding the bottle's cap, a few types of caps are available. In order to make selection from available caps, we had to examine them independently.

Firstly, a regular screw cap lid would be a cheaper option, but it wouldn't be as effective as needed. A regular screw cap would be a good option when pouring powdered substances is needed. If a regular screw cap is selected, then the size of the lip and neck would be the next step which had to be determined. For a bottle which has needs of a wider neck, a regular screw cap would be applied.

For fast usage of the bottle, when the sportsman is in a hurry or has a limited amount of time to drink from the bottle, a hands-free solution is a good option, one that would unlock the cap within milliseconds. That could be done by implementing a pop top lid or a sports cap lid.

The pop top lid ensures quick access while simultaneously doing other tasks. The sport's cap lid has the same objective as the pop top lid, and the main difference is the opening of the lid. The sport's cap lid has a hinge that has to be swung open [5].

It has to be mentioned that the force needed to open the lids shouldn't be too big so that everyone can open it [6], and it shouldn't be small enough for the lid to pop open whenever or under small pressure from the liquid.

The next aspect to consider is the material selection. For this purpose, the most commonly used material is PET [7]. Its structure is considered safe to use in food the food industry [8].

It is a clear, colourless, yet strong plastic with good mechanical, thermal and chemical properties, as well as dimensional stability. Beside this, it is also resistant to moisture, alcohol, solvents, and impact [5]. This means this plastic is suitable and safe to use for food and beverage packaging.

A negative aspect might be the coefficient of friction. Considering most plastics are reinforced with additives, specifically functional additives such as slip agents, the surface of the bottle may not be ideal to use in a sweaty situation [9]. Slip compounds are added in order to reduce the surface's coefficient of friction, however, it is necessary to increase surface friction, which is the main reason for our decision for adding a rubber panel to the plastic design [10].

According to some psychological implications, consumers are more interested in products which are coloured. That is because colours help build a connection with or an attitude toward the product, subconsciously [11]. From this stand point, we had to think about using colours in our design, as well.

The process which is selected for production of these bottles is called blow moulding. By using this process, it is possible to provide any form and create any design we want. The most commonly used blow moulding process is extrusion blow moulding.

The process itself starts with a mould. The mould holds a shape of the desired bottle design. The plastic is inserted inside the mould and hot air is blown into the mould. The plastic is distributed and inflated to the walls of the mould, taking the mould's shape [8].

The piece which leaves the mould is left hollow and resembles a bottle ready to be filled with liquid [12].

The mould could be two pieced or three pieced, depending on the complicity of the bottle's bottom. If the bottom has a fairly complicated design, a special third piece is required.

The most commonly used material for the purpose of the mould is stainless steel [12]. This material is a tough, strong and hard material, with good ductility.

With all of this said, a crucial step in researching and creating a new sport's bottle would be its performance. Its performance depends on all of the previously mentioned aspects, and on the thickness of the bottle's walls.

In order to optimize the bottle's thickness, considering the production process, the use of FEM comes quite in hand [13]. By performing a finite element simulation, we wanted to find out the bottle's minimum thickness which would satisfy specific performance and mechanical constraints [14].

4. CONCEPTUALIZATION OF A REUSABLE BOTTLE DESIGN

The conceptualization and creation of a new sport's bottle starts with figuring out what are the key aspects to consider, the ones which are inevitable. Afterwards, ideas can be implemented into the design and changes can be made to improve the design even further.

The first aspect to consider is the size of the bottle. Size should tell how big a bottle is, how big its diameter is and how much liquid does it hold. If a bottle holds too little liquid it wouldn't do its function properly, considering the user would either have to refill the bottle multiple times or to have multiple bottles to save time. If a bottle holds too much liquid, its size and proportions would be too big, resulting in a heavier bottle, one that is more difficult to handle. A practical water bottle would have to interact well with the user, be manageable and easy to transport, as well as fit into the standard bottle holders (such as bike or car bottle holders).

As previously mentioned, the main body of the bottle has to be equipped with an ergonomically approved handle. That could be made with three-dimensional protruding or sunken ribs, from two to four or five, where each finger would rest neatly. These areas could be parallel to the horizon, however for even greater comfort, they could be placed at a specific angle. This would ensure a much more comfortable and secure grip while handling the bottle, as well as providing additional control while pouring or drinking from the bottle.

The next aspect which needs to be analyzed is the material. The material which will be selected as final has to fulfil specific requirements and factors. Some of those include: availability to be made, transformed into the desired shape and design, the strength and force which it will need to withstand, the cost of the material and the production process and finally, the recyclability attributes it holds.

Materials which could be used in the production of a sport's water bottle are plastics, glass or food safe metals. This project will focus on the use of polymers in the process of bottle design. Specifically, the new sport's bottle will be made of PET plastic.

In order to model and test the product, we had to make a 3D model which was later virtually tested using a simulating software.

5. THE DESIGN OF THE REUSABLE BOTTLE AND 3D MODELLING

After considering all the important aspects, a new sport's bottle design was proposed (shown in Figure 5). The reusable bottle was modelled with application of the SolidWorks software, using advanced surface modelling.

The design itself includes an ergonomic grip for the fingers on one side, and an enhanced grip feature on the other side – a panel of rubber is placed on the external plastic surface of the bottle in order to increase friction between the hand and the bottle.

Fig. 5. Rendered image of the 3D model of the bottle

The neck of the bottle has a medium sized opening. The opening is not too small so that a small spoon or small measuring cup wouldn't be able to fit it, and it is not too big so that it causes leakage or spillage. The size is wider than a regular water bottle which ensures easier refilling.

The cap itself has a screw cap side which is screwed on the neck for maximum safety, and a pop top lid for quick and easy access to the liquid stored inside the bottle.

Additionally, the lid could be a special rubber lid, which lets liquid flow through when pressure is applied, for instance squeezing the bottle, squeezing the lid or suctioning the liquid from the bottle. Otherwise, when no pressure is applied, the cap would be leak proof and safe to use, handle and transport.

This bottle is made of PET, and it holds a volume of 750ml worth liquid.

The mould, shown in the Figure 6, is designed for serial production of the bottle. It is designed as a three pieced mould, considering it has quite a complicated bottom (shown in the Figure 7) which requires a separate part of a mould.

Fig. 6. Rendered image of the 3D model of the mould, core and cavity

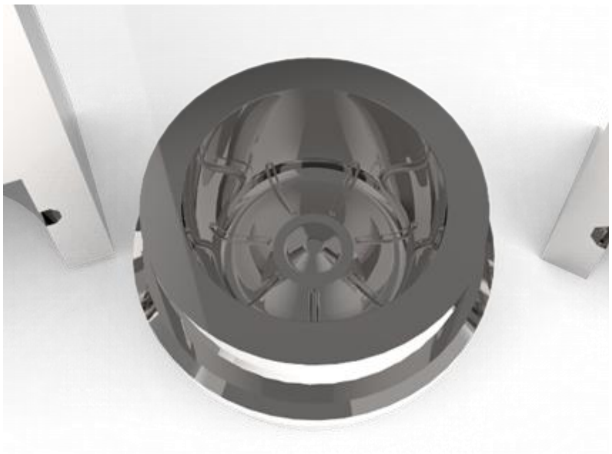


Fig. 7. Rendered image of the 3D model of the third piece of the mould, showing the complex bottom design

Having in mind that we wanted to achieve increased friction and grip area of the bottle we decided to place a rubber part to the bottle's design. The rubber could be applied to the bottle using the process called injection moulding. The rubber would have its own part in the mould, and it would be injected inside. Later, the plastic would be inserted in the mould using a preform and hot air would be blown inside the mould, causing the plastic to take over the mould's shape.

On the side, the caps would have to be made with injection moulding, and later the two parts would be assembled together into one.

6. FINITE ELEMENT ANALYSIS

The tests conducted using the finite element analysis allow optimization of the bottle's wall thickness using mathematical procedures and parameters.

Regarding this paper, the virtual testing using the FEA were made in the SolidWorks Simulation software package. The 3D model of the bottle was made in SolidWorks as well. Using this method, we can obtain information regarding the amount of stress (Von Mises) or strain the model can endure, under specific circumstances. The final result is optimization of the bottle, its characteristics and parameters, paying close attention to its stress handling capabilities.

The material used in the simulation is PET (polyethylene terephthalate), a thermoplastic polymer. PET plastic has the following material properties: density of 1.41 g/cm^3, melting temperature of 265°C, and tensile strength (Young's modulus) of around 60 MPa. Its yield strength is around 40 MPa.

When setting up the virtual testing, some boundaries and conditions have to be applied. For this specific test, we wanted to examine how much stress the bottle can endure during transportation. To set up the scene entirely, the bottle was set to be full (filled with water or another beverage of that kind).

Also, the fact that the bottles are transported in packs, in our case, packs of six bottles were taken into consideration. With intention to simulate the additional load on the top of the bottle 10 packs were placed. The weight of the additional packs simulates the force that was the key impact during the tests.

The 3D model is fixed at the bottom (Figure 8), which is a result of the vertical position of the bottle over the horizontal surface.

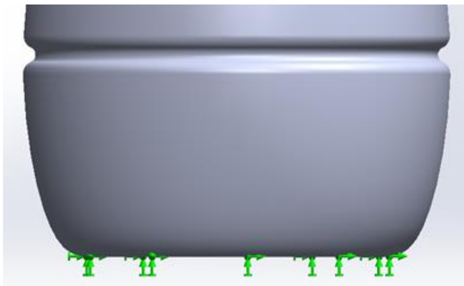


Fig. 8. (Green) fixture symbols, showing degrees of freedom at the bottom of the bottle

Regarding the external loads, the bottle is subjected to the weight of the overhead packs of bottles, meaning the force of the packs is equivalent to the unit of mass per the force of gravity (9.81 m/s^2).

For this analysis, the mass of the packs on the top of the bottle is 7.5 kg, which means that the force which the bottle is subjected to is around 73.575 N (Figure 9).

Fig. 9. (Purple) external loads and forces symbols which subject the bottle

In order to get fairly precise analysis results, we had to divide the 3D model into a finite number of elements. When those elements were created, a mesh, shown in Figure 10, is created. The mesh consists of 16580 triangles which represent each element, and the nodes which connect those elements are 33162 in total. The size of each element is 3 mm.

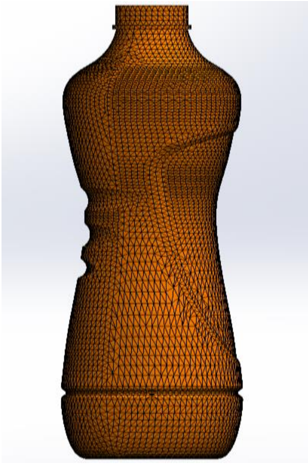


Fig. 10. The meshed model of the bottle

The goal of this test is to determine the best wall thickness, getting the wall as thin as possible, yet keeping the factor of safety in its allowable limits.

The tests started with 1 mm wall thickness and while conducting the analysis, it was optimized until achievement the thickness of 0.25 mm. The maximum value of stress found in the bottle with these criteria (wall thickness, force and external loads) was 26.16 MPa. The stress distribution and maximum value of stress is shown in Figure 11. Taking into consideration that the yield strength of PET plastic is around 40 MPa, the factor of safety, which equals to the yield strength over the maximum stress is 1.53. This is a value inside the factor of safety's limits and the stresses are in the bottle's elastic deformation range.

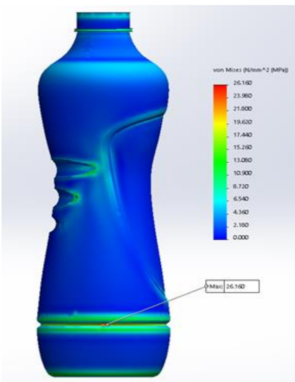


Fig. 11. Max stress (Von Mises) value found in the bottle while under external loads

The maximum displacement value obtained under the external loads is shown in the Figure 12 and it is 1.884 mm with location at the top of the bottle. The deformation is in elastic range.

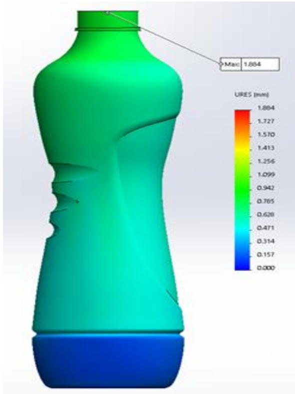


Fig. 12. Max displacement value found in the bottle while under external loads

In conclusion, this design is numerically verified with the help of the simulation (and the finite element analysis) and the properties of the bottle (the wall's thickness when using PET plastic) are optimized for maximum quality and minimum cost.

7. VIRTUAL ERGONOMIC ANALYSIS

A further note into the bottle's validation and virtual ergonomic testing was performed. By putting the 3D model of bottle into the software package CATIA and introducing a mannequin to the scene using the module Human Builder, we could furthermore see how the bottle performs in an ergonomic aspect. The Figure 13 presents a male mannequin from French nationality and 95th percentile, holding the sport's bottle in the right hand.

Fig. 13. 95th percentile male mannequin holding the sport's bottle

In order to fully examine the ergonomic features and perform ergonomic validation, both female and male mannequins were tested. Specifically, Figure 14 presents a 95th percentile male hand holding sport's bottle, and Figure 15 presents a 5th percentile female hand holding the same sport's bottle.

Both cases of the performed virtual ergonomic analysis verified the suitable ergonomic grip of the designed bottle.

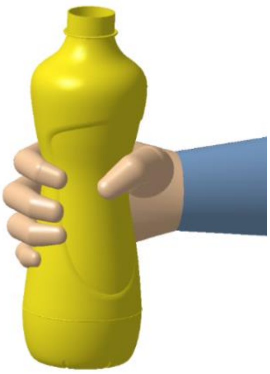


Fig. 14. 95th percentile male mannequin's hand holding the sport's bottle

Fig. 15. 5th percentile female mannequin's hand holding the sport's bottle

8. CONCLUSION

The main objective of this paper is design and improvement of a reusable bottle for sports drinks using 3D advanced surface modeling software, virtual testing and validation. In the paper, the overall process of creating an innovative design of a reusable bottle, ergonomic aspects into the design, reusable opportunities, aesthetically pleasing bottle which is virtually approved and numerically verified is presented.

The new concept design presented in this research offers improved ergonomic aspects and characteristics which are based on human percentiles and the everyday use this bottle is subjected too. Virtual testing was confirmed by using the software package SolidWorks Simulation, simulating processes with finite element analysis. The virtual testing included optimization and variation of the wall thickness, obtaining the suitable safety factor. The wall thickness of the bottle was optimized according to the used PET plastic material, initial and boundaries conditions. The optimum value which was obtained of the bottle wall thickness is 0,25 mm. The maximum value of Von Mises stress found in the bottle is 26.16 MPa. The yield strength for PET plastic is 40 MPa and the bottle in the elastic range. The factor of safety is 1.53 and that value is acceptable.

The model was tested in the software CATIA and module Human Builder to furthermore examine its ergonomic aspects, both on male and female mannequins.

The proposed methodology for design and optimization of a reusable bottle for sports' drinks produces results that reduce the time and costs for development process and preparation of manufacturing process, and lead toward sustainable design.

REFERENCES

Plastic bottles market – Growth, trends, Covid-19 impact, and forecasts (2021–2026): Available online: https://www.mordorintelligence.com/industry-reports/plastic-bottles-market (taken on 15.2.2022)

Toscano, R. A., Herazo, J., Millan, R. R., Palma, H., Martinez, J. (2019): Approach methodology for the sustainable design of packaging through computational tools: Case study: Water bottles, *Case Studies in Thermal Engineering*, Vol. **16**, pp. 1–11.

Lovett, J. (2013): *Engineering Design of a Disposable Water Bottle for an Australian Market*, https://eprints.usq.edu.au/24673/1/Lovett_%202013.pdf (taken on 15.2.2022)

Hand Anthropometry, Georgia Tech Research Institute, 2007.

Packaging Styles -– Bottle Caps, Available online: https://www.liquidpackagingsolution.com/news/packaging-styles---bottle-caps (taken on 15.2.2022)

Sohnle, S., Braun-Münker, M., Ecker, F. (2016): A comparative study of various screw caps. Is there any correlation between the results of a target group study and instrumental measurement? *Ernaehrungs Umschau*, Vol. **63** (9), pp. 186–191. DOI: 10.4455/eu.2016.039.

Demirel, B., Daver, F. (2009): Optimization of poly(ethylene terephthalate) bottles via numerical modeling: A statistical design of experiment approach, *Journal of Applied Polymer*, Vol. **114**, Iasue 2, pp. 1126–1132.

Kandikjan, T., Mircheski, I. (2020): *Design with Plastics*, Published by Faculty of Mechanical Engineering in Skopje.

Hansen, E., Nillson, N., Lithner, D., Lassen, C. (2013): *Hazardous Substances in Plastic Materials*, COWI in cooperation with Danish Technological Institute.

Derler, S. (2009): Friction of human skin against smooth and rough glass as a function of the contact pressure, *Tribology International*, Vol. **42**, Issue 11–12, pp. 1565–1574.

Shi, T. (2013): The use of color in marketing: Colors and their physiological and phsychological implications, *Berkeley Scientific Journal*, Vol. **17** (1). https://doi.org/10.5070/BS3171016151

Giridhar Reddy, K., Rajagopal, K. (2013): Blow mould tool design and manufacturing process for 1 litre pet bottle, *Journal of Mechanical and Civil Engineering* (*IOSR-JMCE*), Vol. **8**, Issue 1, pp. 12–21,

Huang, G., Huang, H. (2005): Thickness optimisation of blow molded parts using FEM/ANN/GA methods, *ANTEC 2005, SPE,* USA, pp 25–28.

Gauvin, C., Thibault, F., Laroche, D. (2004): Optimization of blow molded part performance through process simulation, *Polymer Engineering & Science.* Vol. **43**, pp. 1407–1414