OPTIMUM DESIGN AND RAPID PROTOTYPING OF MECHANICSM BASED ON CAD/CAE SYSTEM AND FUSED DEPOSITION MODELING 3D PRINTING TECHNOLOGY

L.T. Hung[1], C.T. Than[1], T.H. Nguyen[1], L.T. Long[2], N.V.A. Duy[1*]
[1]Faculty of Automotive, Mechanical, Electrical and Electronic Engineering, Nguyen Tat Thanh University, Ho Chi Minh City, Vietnam
[2]Faculty of Mechanical Engineering, Ho Chi Minh City University of Technology, VNU-HCM, 268 Ly Thuong Kiet Street, Ho Chi Minh City, Vietnam
Email: nvduy@ntt.edu.vn

Abstract

Materials' optimization for the product structure makes its weight smaller and easy to transport after manufacturing but still ensure the criteria of its strength, hardness, and capacity of good operation. These properties are extermely important and criteria need to be obtained in many field of aerospace, automotive, ship and other industries, etc. Besides, the optimization of product mass will save the materials and bring significant benefits for manufacturers and improve the environment. Thus, this paper presents the design and optimization based on the topology principles for machine mechanism and its rapid prototyping using CAD/CAE and FDM (Fused Deposition Modeling) 3D printing technology/additive manufacturing (AM). The machine elements or links are manufactured by PLA material on 3D Delta printer. The results showed that designed machine mechanism have the optimized geometry, reduced materials and satisfied the operation capacity.

Keywords: Fused deposition modeling; topology optimization; mechanical mechanism; CAD/CAE; 3D printing

Introduction

Mechanical fabrication technologies have developed strongly thanks to the development of science and technology and information technology. The appearance of computer-aided digital machining technology has changed the manufacturing process in industry. In recent years, when rapid prototyping technology appeared based on processing technology with the aim of creating product samples with plastic or wood in the shortest time to reduce design time, calibration, and product development and at the same time the customer has a more realistic view of the designed product.

Currently, rapid prototyping technology has developed rapidly and has become a fast manufacturing technology, also known as Additive Manufacturing (AM). This technology allows the fabrication of metal parts for direct use in layer by layer of materials, can be sprayed, laser printing technology, electron beam printing technology, etc. 3D printing technology allows machining of curved surfaces with complex profiles, machine elements with complex internal structures, of any shape that are difficult to achieve with traditional machining methods and digital machining technology.

It is thanks to this advantage of additive manufacturing and 3D printing technology that methods to optimize product designs have been developed and applied in production practice. Topology optimization is applied to optimize the shape, structure and cost of machine parts, ensure durability, and reduce the volume and volume of materials that make up the machine part. This is one of the decisive factors to reduce production costs, save materials, create competitive advantages in price and design of the final product into the market to meet increasingly high and fastidious demands of cutomer. For that reason, this paper studies and applies the geometrical optimization method to design the machine and mechanism structure and uses 3D printing technology for rapid prototyping of the mechanism structure with optimal shape and topology.

Topology optimization is a generative design of material distribution in a machine elements or a product with a certain physical design, applied load conditions and certain constraints to satisfy product goals such as satisfying the structural strength of the model while minimizing its mass, thus reducing weight and saving materials, etc. This method creates models that require only the volume of minimum raw materials needed to meet product requirements, helping to reduce material waste and costs.

With the combination of geometry optimization and the 3D printing technology to create a novel design technique in the field of mechanical engineering to optimize mass, volume and materials used to fabricate parts by 3D printing technology but still ensure the durability and mechanical properties of the designed product. The topology optimization will remove material elements that are not subjected to very small forces or internal stresses. The rest after removing those elements we get a geometry optimized shape.

Additive machining technology allows processing complicated surfaces, machine elements or product with complex internal structures with any shape. Due to the combination of the method of optimizing the geometric structure into the design of the parts together with 3D printing technique, it has opened up a completely new research direction and has many application opportunities in the future. It allows designers to design machine and mechanism to save materials, minimize weight while still ensuring the durability and rigidity of the parts during operational process. Several studies (Ping Yao et al. 2019; Evagelos T. 2021) presents the optimal technical application for brake structures and industrial robots.

Design of mechanism

In this research, the combination of a fourbar mechanism and a slider-crank mechanism is considered sharp optimization. The process of studying: (1) Develop a CAD. Model of the mechanism; (2) Draw free-body diagrams and solve all joints reaction forces of links in the mechanism; (3) Determine the shapes of all links; (4) Export the CAD files to STL files and G-code files; (5) Manufacture the links by 3D FDM (Fused Deposition Modeling) printing; And finally, (6) Assemble all links.
The mechanism in the Figure 1 has one degree of freedom. The link AB fully rotates with angle velocity 10 rad/s. The AD is the ground link. Using the graphical vector analysis (Liem, 2013; Hai, 2009), the velocities of B and C are 1 m/s, and 3 m/s. Velocities of E and G are 1.5 m/s. EG does not rotate and has 0 rad/s of the angle velocity. The acceleration of B is 1 m/s^2. Using the graphical vector analysis of acceleration (Liem, 2013; Hai, 2009), the accelerations of C and G are 80 m/s^2, and 15 m/s^2.
Analysis the force of these links, the free-body diagram of the links is presented in Figure 2 [3, 4]

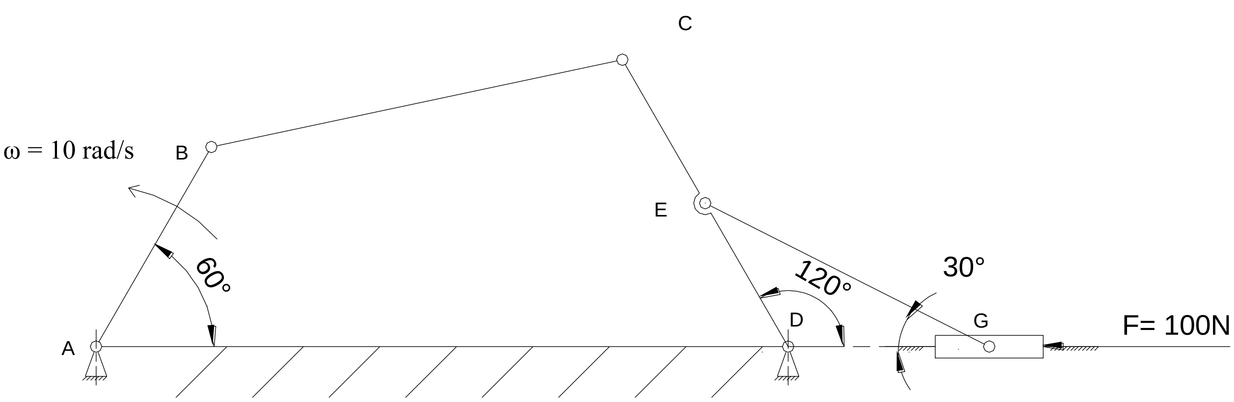
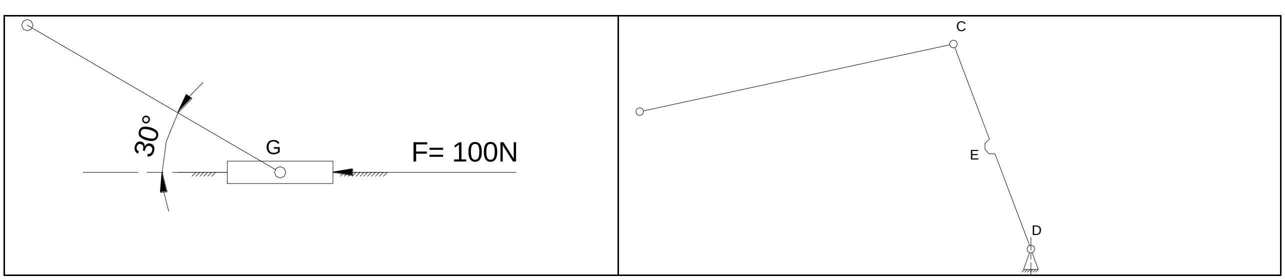


Figure 1: Graphical position analysis (link 1 = AB, link 2 = BC, link 3 = CD, link 4 = EG, and link 5 = Box G)
The Grashof condition: S – the length of the shortest link, L – the length of the longest link, P, Q the lengths of the other links, $S+L \le P+Q$. *AB* = 80 mm; *BC* = 210 mm; *CD* = 240 mm; *AD* = 300 mm; *ED* = 1/2*CD*; *EG*= 250 mm.
$AB+AD \le BC+CD \Rightarrow 80+300 \le 210+240 \Rightarrow 380 \le 450$, satisfied the Grashof condition.



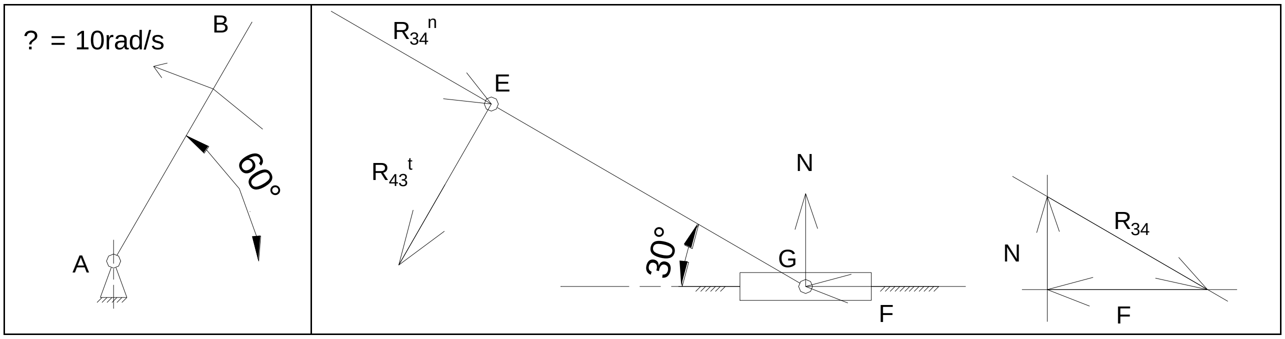


Figure 2: Free-body diagram of the links

Analysis for the link 4 and 5. The equation of equilibrium of the links:

$$R_{34} + N + F = 0 \tag{1}$$

The Equation (1) has two unknow variables, *E* and *N*. From the graphical force vectors in Figure 2, we get:

$$R_{34} = F / \cos(30°) = 200 / \sqrt{3} = 115.47 \text{ N}$$

$$N = F \times \tan(30°) = 100 \times \tan(30°) = 100 / \sqrt{3} = 57.73 \text{ N}$$

The three forces planar equilibrium, *N*, R_{34}, and *F* are concurrent at *G*. Their directions had been chosen is correct. Similarly, the graphical force vectors method is used to calculate the force and reaction of the other links.

$$R_{43} = 200 / \sqrt{3} = 115.47 \text{ N}$$

$$R_{32} = -48.81 \text{ N}$$

Hence, R_{21} = 48.81 N is parallel and reverse direction with R_{32} and R_A = 48.81 N.

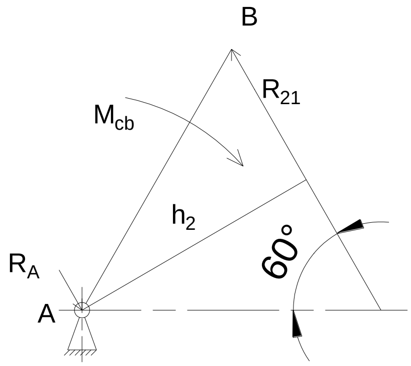


Figure 3: The moment equilibrium of link AB at point A

Because the $\vec{R}_{21}^{n}$ is parallel and reverse direction with $\vec{R}_{32}^{n}$, the angle between R_{21} the horizon, *AD* is 60°. From Figure 3, the required moment of equilibrium is M_{cb} = 3381.66 N·m.

Next step, the Working Model software is used to confirm the Grashof condition. Moreover, the behavior of all links are simulated, Figure 4. The real time reaction forces of joints are observed by many diagrams.

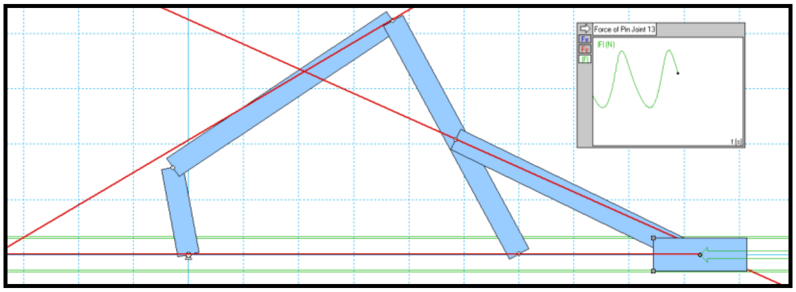


Figure 4: Simulation of mechanism in Working Model environment

Generative design (optimal topology design) with CAD/CAE system

Generative Design in Solid Edge integrates structural optimization in three-dimensional modeling tools, helping designers create lighter parts, reducing material waste in the manufacturing process. The design creates a weight-reducing geometric solution of a particular material that is optimized in a defined space taking into account allowable loads and constraints. These highly customized designs are well suited for casting or high resolution 3D printing, or they can be modified for traditional manufacturing (Siemens, 2020a,b).

To implement the analytical process, topology optimization of machine elements is based on assigning its materials. In this study, the structural steel material is selected in library of Solid Edge library. Then, we click to choose the function of *Greate Generative* Design to create an analytical environment such as *Generative Study*, we can make many *Generative Study* for the same machine elements with parameters of applied forces and its values in *Study Quality*. Next, we choose the *Design Space*. Next select *Preserve Region*, and select an important *Face/Feature* such as holes; then, *Offset* to the desired value in order to preserve these positions is not removed after model optimization [5, 6]. In the next step, we proceed to assign forces/loads acting on the part and assign constraints such as fixed mounts, rotary joints, etc. Finally, we conducted optimization analysis for machine elements or linkages, setting the parameters, and expected volume as shown in Figure 5.

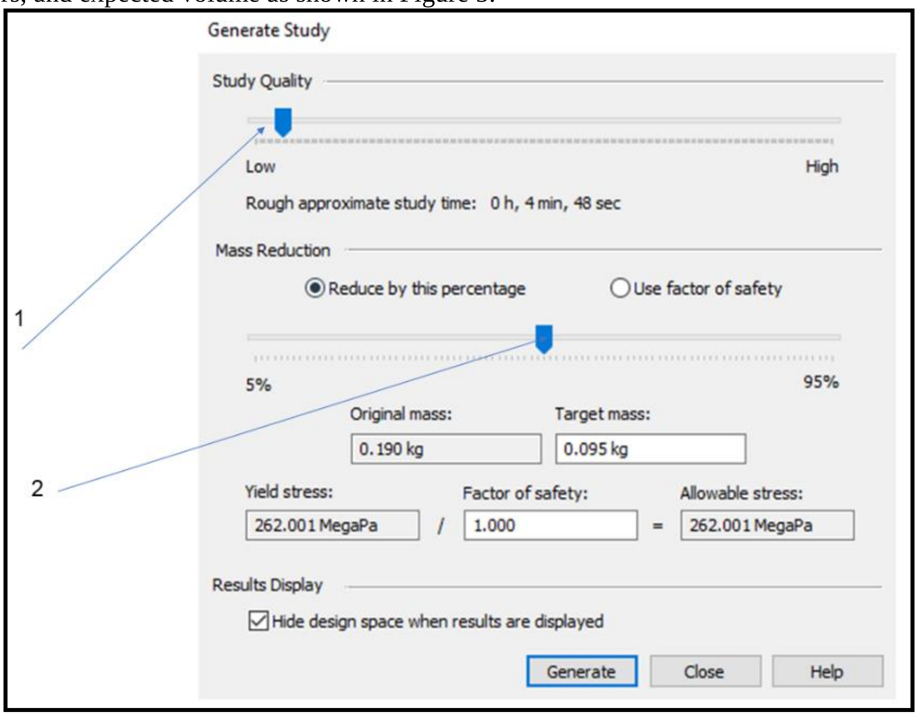


Figure 5: Optimal objectives (1: Product Quality; 2: Mass reduction)

Study Quality (1): this item we set the optimal quality value of the part, in this study the value of 15 was chosen. *Mass Reduction* (2): to reduce the mass of the part, we adjust by percentage or use the factor of safety. Here, we leave the default of the software to 50, which is a 50% reduction in volume compared to the original. After setting the parameters, the software calculates the weight of the part after analysis for direct comparison as shown in Figure 6.

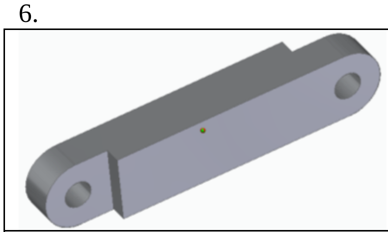
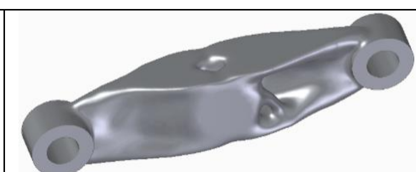
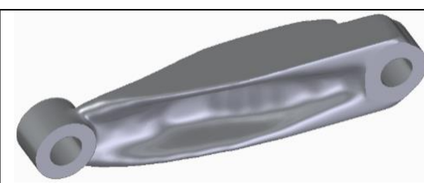
		
a) Initial part	*b) Optimal topology of part*	*c) Optimal topology part after reducing and adjusting its weight*

Figure 6: Optimal topology (generative design) of linkages in mechanism

Rapid prototyping based on FDM 3D printing

The topology-based optimal CAD model, after implementing the optimal product at the stage in the Solid Edge modeling environment, is exported to a file in STL format, with the support of MeshLab (2020) software only correcting common errors of the sample STL file format. After, we save the CAD models to the STL intermediate file to conduct layering and set the parameters to operate the 3D printer using Ultimaker CURA software (Ultimaker, 2020). In CURA, you can set printer operating parameters such as Prototyping build direction, print speed, extrusion temperature, layer thickness, fill rate, fill pattern, and build angle. Finally, we export to G-code to communicate with the 3D printer. The steps to export the STL file should note the parameters as shown in Figure 7. Figure 7 selects the smooth STL file mode (Fine) by default. The finer the mode, the larger the STL file size. Two important parameters to keep in mind when implementing a custom mode that allows the modifications are (1) the deviation between the actual profile and the approximate profile and (2) the angle between the two normals of the two adjacent triangle faces.

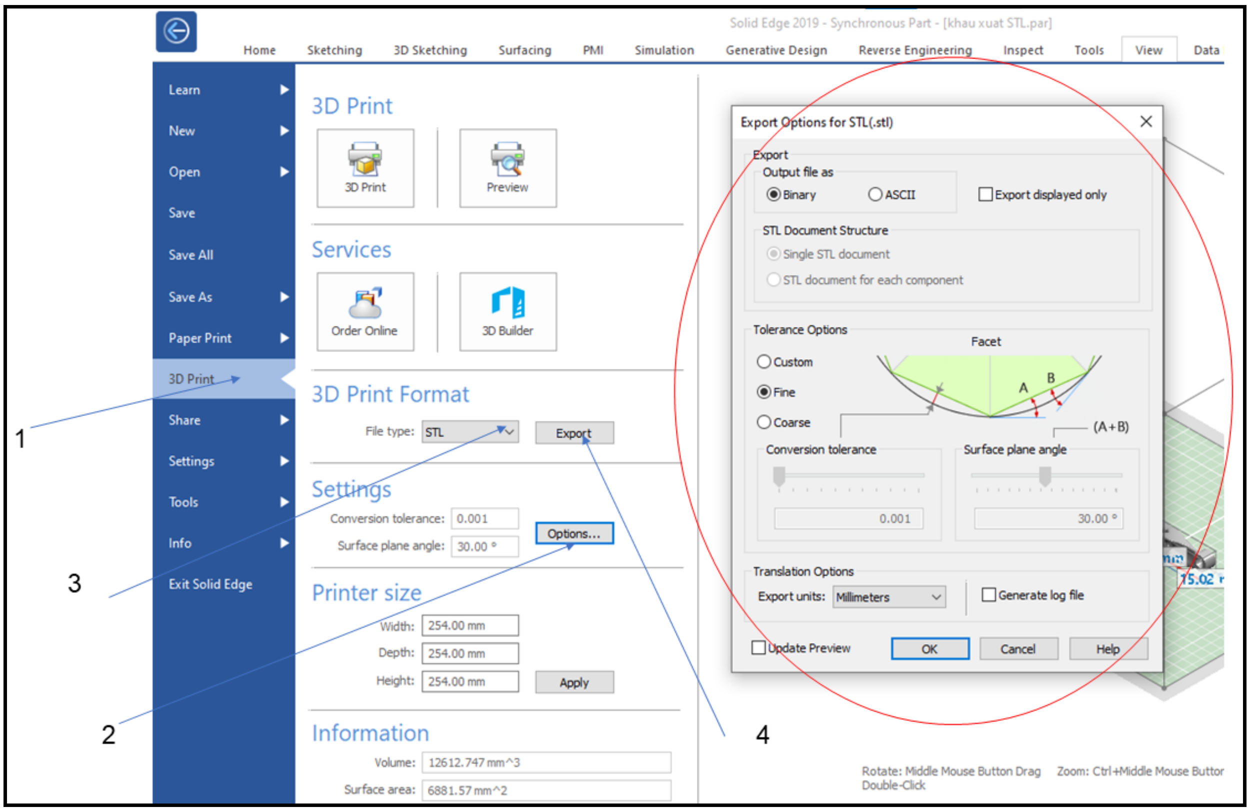


Figure 7: Setup the parameters when to export CAD model into STL file

Results and discussion

After implementing the research procedure of computation and design, a model of an extended 4-bar mechanism combining a slider crank with rotating and translational capabilities has been completed and tested successfully. The study has given the idea, design, simulation and optimization of the design for the mechanical system. Figure 8 presents the results of the design optimization of the links in the structure.

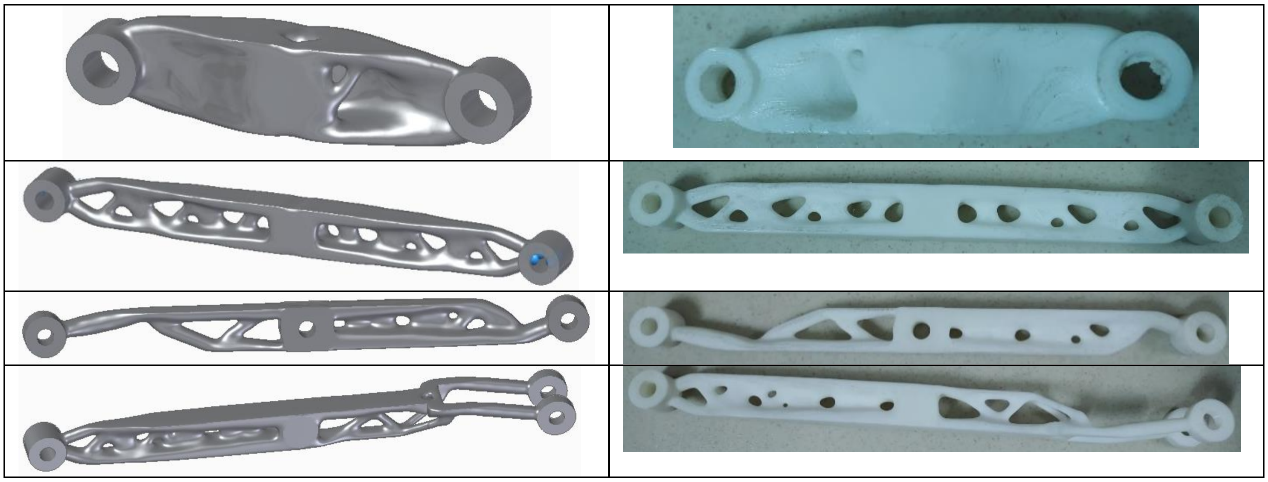


Figure 8: Results of topology design for an extended four-bar mechanism

Figure 9 shows the overall structure after assembling the optimal linkages. The mass of the links or the whole mechanism is reduced by 50% compared to the original, but the kinematic dimensions are kept unchanged so that the velocity and acceleration indicators are not affected after optimization. The volume of parts is significantly reduced but still ensures the operating conditions.

Figure 9: Mechanism model fabricated after performing optimal topology design

Conclusion

This paper presented the process of applying the design method using topology optimization to help the designer improve the product during the design process. The method allowed to optimize the material distribution and reduced the volume of material used while to maintain the mechanical properties of the part. The product and machine elements after optimization has been removed the unnecessary volume of the material but still ensures the design constraints. Therefore, this method is becoming the potential approach for advanced machining technologies such as additive technology to fabricate products with very complex shapes and structures.

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