Application of a finite element method to predict fatigue life of the knee mobile bearing

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Application of a finite element method to predict fatigue life of the knee mobile bearing

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Abstract. Knee Arthroplasty is a surgical procedure where the patient's knee is replace by prosthesis. By using the finite element analysis method, we can properly estimate the life span of the prosthesis and also the polymer mobile bearing between the prosthesis itself. Most of the prosthesis have a long lifespan but not for the polymer mobile bearing. Having only average of 2.5 years lifespan, it is a hustle for the patient to come back every 2.5 years to replace a new polymer especially for the elderlies. This research is made to investigate and predict the fatigue life of the polymer mobile bearing via finite element method and thus to design a newly improved prosthesis model based on the commercially available. In this research, three different designs were made based on the currently available mobile-bearing design. Each of the design will undergoes different value of forces depending on three different of gait cycles which are walking, ascending from the stairs as well as rising from squatting. Based on the fatigue life prediction using finite element method, the proposed design (design 2) obtained the highest lifespan ranging from 1.0 x 10^6 to 1.2 x 10^6cycle and it is increase almost 50% of the commercially available design life cycle (8 x 10^5 cycle). Thus, it is can be concluded that the finite element method can be used to predict life cycle of the mobile bearing successfully and can be used as a guided to propose an improved design of the prosthesis.

1. Introduction

With Total Knee Arthroplasty (TKA) becoming the standard operative procedure for knee arthritis, the current knee prosthesis can be divided into 2 groups, namely fixed-bearing knees and mobile-bearing knees. Fixed-bearing knees is where the polyethylene tibial insert locked with tibial tray whereas the mobile-bearing designs allows movement and rotation between the tibial insert and tibial baseplate [1]. The fully nature of mobile-bearing implants will gives off a greater Ultra-High-,Molecularweight Polyethylene (UHMWPE) contact area and lower contact stresses results than the fixed-bearing implants [2]. It was often an argument that which of the implant is better, was it the mobile-bearing or the fixed-bearing? Mobile-bearing knee prosthesis was introduced with the aim to reduce polyethylene wear and component loosening [1].Studies was made extensively to determine the outcome between the 2 implants. After being reviewed for more than 9 years and follow-up of 7 years, patients indicated that 84% of those in the fixed bearing group and 96% of those in the mobile bearing group were satisfied or very satisfied with the outcome [3]. Another study also shows that although mobile bearing holds a higher advantage toward the fixed-bearing, both of them shows a very high survival rate up to 95% in a 10 year follow-up [1]. Another studies by Poirier et al. shows that the difference of using the fixed and mobile bearing prosthesis [3].

One of the major goal of mobile-bearing knee is to reduce the overall wear damage by increasing the contact area, while minimizing the constraint and allowing the knee to move in a natural state, by allowing the polyethylene bearings to move freely on polished plates on the upper tibia [1]. Wear-simulator studies indicate that fixed bearing design will have more wear and interface stress than the mobile-bearing prosthesis [4] which is the mobile-bearing is almost half of the one that is in the fixed bearing [1] in terms of wear rate. Retrieval studies and radiographic analyses show that the unicompartmental knee has a 10 year survival of over 97% [3] and has low rates of both linear and volumetric wear, as a result of high contact surface areas and low PE stresses throughout the range of motion [5]. There was no difference in the wear rate between the articular surface (0.028 ± 0.025 mm/year) and the backside surface (0.029 ± 0.017 mm/year). The averaged combined wear rate was 0.056 ± 0.034 mm/year [6].

Despite the longevity of the knee implants [1], wear and also fatigue damage of the Ultrahigh Molecular Weight Polyethylene(UHMWPE) are quite high due to the oxidation of the polyethylene. Till this date, there is lack of published report of research that study using finite element method on the interface failure of knee mobile bearing, so do the prediction of its fatigue although a lot of previous research did study related to fatigue life or failure analysis using finite element method [7, 8,]. The purpose of this study was to investigate the biomechanical performance of knee mobile bearing and to predict its fatigue life cycle using finite element method.

2. Methodology

The 3D models of knee implant based on available model in market (original one) were constructed using Solidworks Software as shown in figure 1.

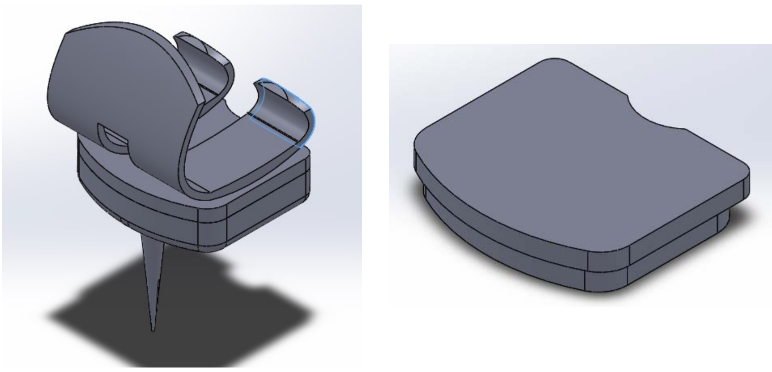

Figure 1. On the left is 3D model of knee implant based on available in market (original design) and on the right is a mobile bearing of knee implant

Based on finite element analysis result of original implant, we optimise it into two different design of mobile bearing of knee implant to improve its fatigue resistance. The two different designs (design 1 and design 2) of mobile bearing are as shown in figure 2.

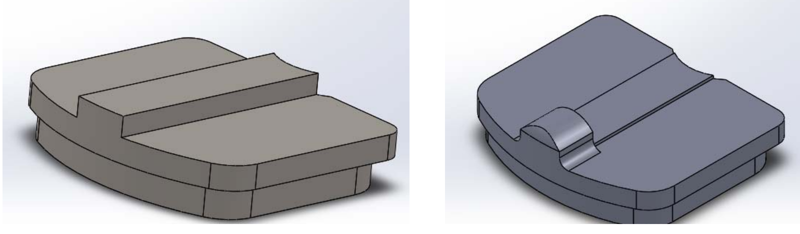

Figure 2. On the left is design 1 and on the right is design 2 of knee implant mobile bearing

The CAD 3D models then transferred to the modelling setup in Ansys Software for finite element analysis. Then, the 3D model is meshed with the total element was 9689 and a total of 19281 nodes after converged as shown in figure 3.

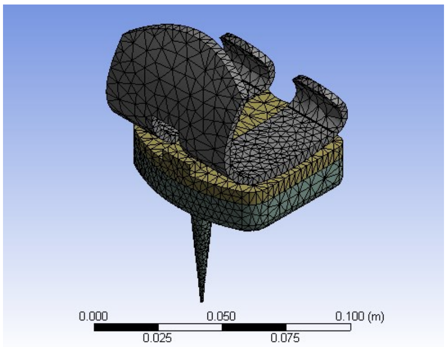

Figure 3. Meshed models of knee implant

After meshing the model, it is proceed to analysis settings. For the fatigue analysis, only force and fixed support is needed. The value of force are varies because of when the knees moves in a different motions, the knee will experience different value of forces. For this study, a weight of 100kg was chosen as the weight of the subject. Table 1 below shows the different type of force exerting on the knee with different motions.

Table 1. The different type of force exerting on the knee with different motions

Motion	Forces Times Range	Average	Weight(100kg)	Forces (N)
Walking	2.5-2.8	2.65	980.665 N	2598.76
Stair ascent	3.1-3.4	3.25	980.665 N	3187.16
Rising from squat	3.5-4.1	3.8	980.665 N	3726.52

The force exerted on knee implant was placed as shown in figure 4 below. While the lower part of the model (the base) was choose to be fixed.

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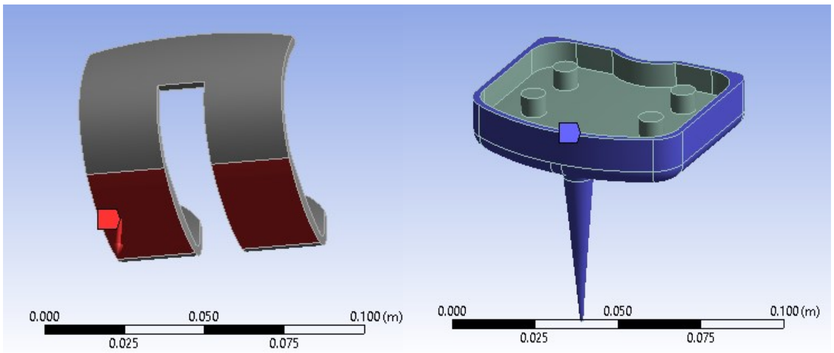
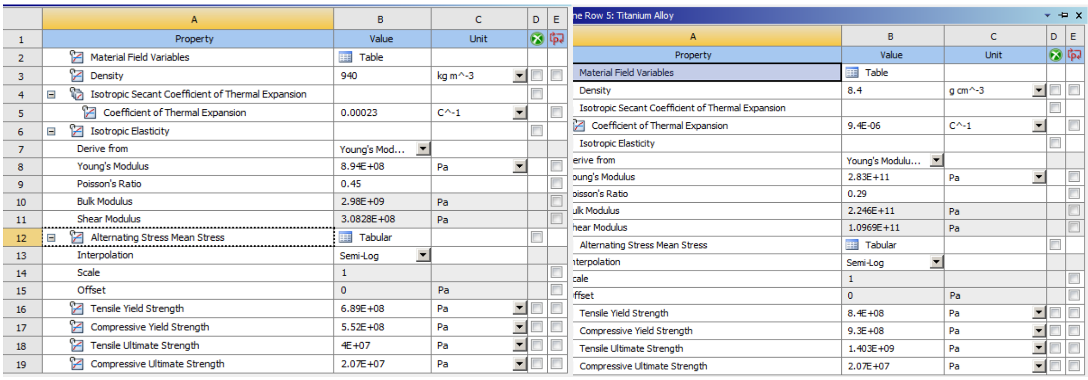


Figure 4. Force and fix applied at the model in Ansys Software

The finite element analysis is conducted which focus on static and fatigue analysis. While the properties for mobile bearing (polyethylene) and knee implant (titanium alloy) as shown in figure 5.



	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	940	kg m^-3		
4	Isotropic Secant Coefficient of Thermal Expansion				
5	Coefficient of Thermal Expansion	0.00023	C^-1		
6	Isotropic Elasticity				
7	Derive from	Young's Mod...			
8	Young's Modulus	8.94E+08	Pa		
9	Poisson's Ratio	0.45			
10	Bulk Modulus	2.98E+09	Pa		
11	Shear Modulus	3.0828E+08	Pa		
12	Alternating Stress Mean Stress	Tabular			
13	Interpolation	Semi-Log			
14	Scale	1			
15	Offset	0	Pa		
16	Tensile Yield Strength	6.89E+08	Pa		
17	Compressive Yield Strength	5.52E+08	Pa		
18	Tensile Ultimate Strength	4E+07	Pa		
19	Compressive Ultimate Strength	2.07E+07	Pa		

ne Row 5: Titanium Alloy

A	B	C	D	E
Property	Value	Unit		
Material Field Variables	Table			
Density	8.4	g cm^-3		
Isotropic Secant Coefficient of Thermal Expansion				
Coefficient of Thermal Expansion	9.4E-06	C^-1		
Isotropic Elasticity				
erive from	Young's Modulu...			
oung's Modulus	2.83E+11	Pa		
oisson's Ratio	0.29			
ulk Modulus	2.246E+11	Pa		
hear Modulus	1.0969E+11	Pa		
Alternating Stress Mean Stress	Tabular			
nterpolation	Semi-Log			
cale	1			
ffset	0	Pa		
Tensile Yield Strength	8.4E+08	Pa		
Compressive Yield Strength	9.3E+08	Pa		
Tensile Ultimate Strength	1.403E+09	Pa		
Compressive Ultimate Strength	2.07E+07	Pa		

Figure 5. Mechanical properties of mobile bearing (polyethylene) and knee implant (titanium alloy)

After the material was assigned, the path function under construction geometry tab was set up. This purpose of using the path function is to pinpoint the results of fatigue in a certain path or lines only as shown in figure 6

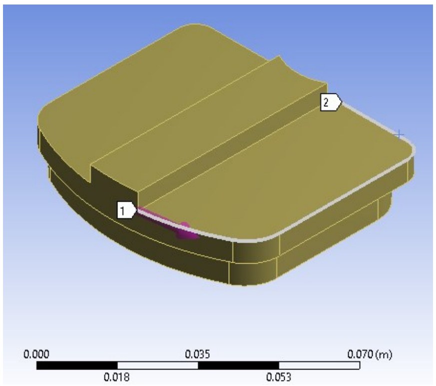
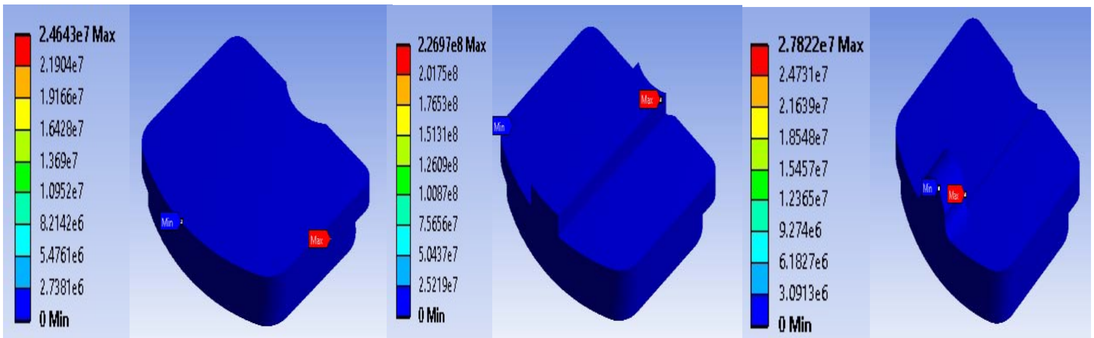


Figure 6. The path to pinpoint the fatigue result in a certain path

3. Result and Discussions

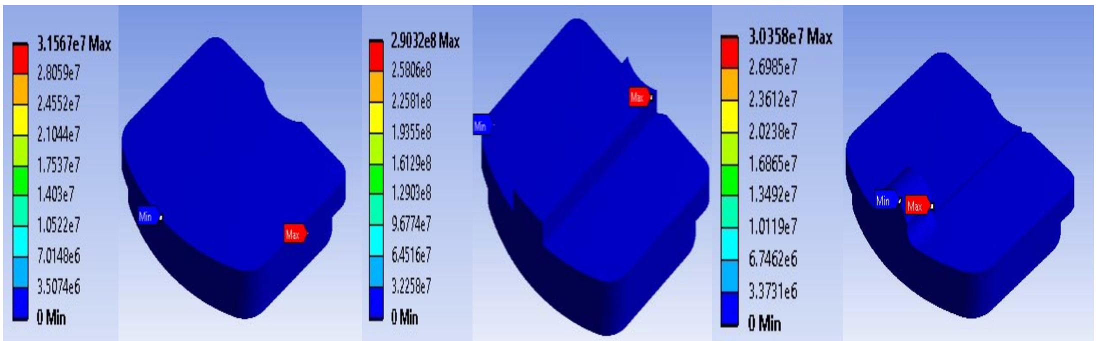
The finite element analysis result are divided to 3 different of motion to represent knee gait cycle which included walking, ascending stairs and rising from squat. The figure 7, 8 and 9 show the comparison of stress distribution between three different designs of mobile bearing when undergone 3 different type of knee gait cycle.



(a) (b) (c)

Figure 7. The comparison of stress distribution between three different designs of mobile bearing when undergone walking motion. a) original design, b) design 1 and c) design 2.

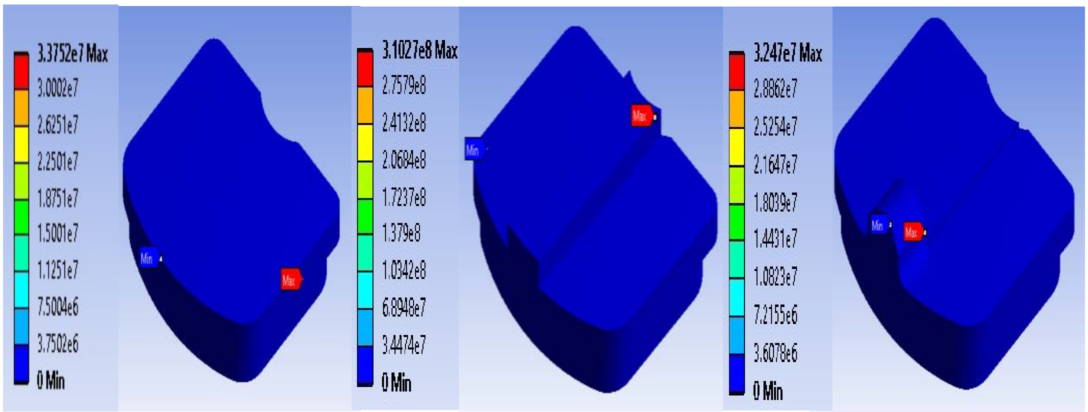
Maximum Stress of original design is the lowest among the three designs of mobile bearing of knee implant when undergone walking motion. All the maximum stress are below than yield strength of the mobile bearing which is 48MPa [9] except for the design 1.



(a) (b) (c)

Figure 8. The comparison of stress distribution between three different design of mobile bearing when undergone ascending stairs motion. . a) original design, b) design 1 and c) design 2.

Maximum Stress of design 2 is the lowest among the three designs of mobile bearing of knee implant when undergone ascending stairs motion. All the maximum stresses are below than yield strength of the mobile bearing except for the design 1.

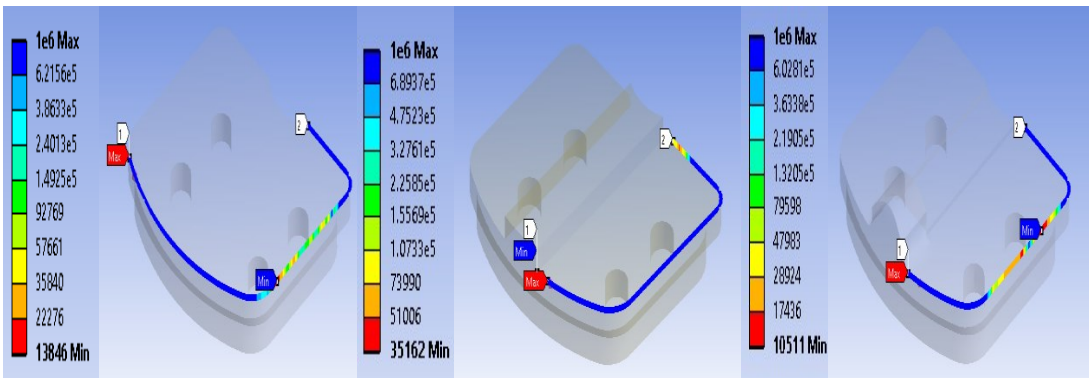


(a) (b) (c)

Figure 9. The comparison of stress distribution between 3 different designs of mobile bearing when undergone rising from squat motion. a) original design, b) design 1 and c) design 2.

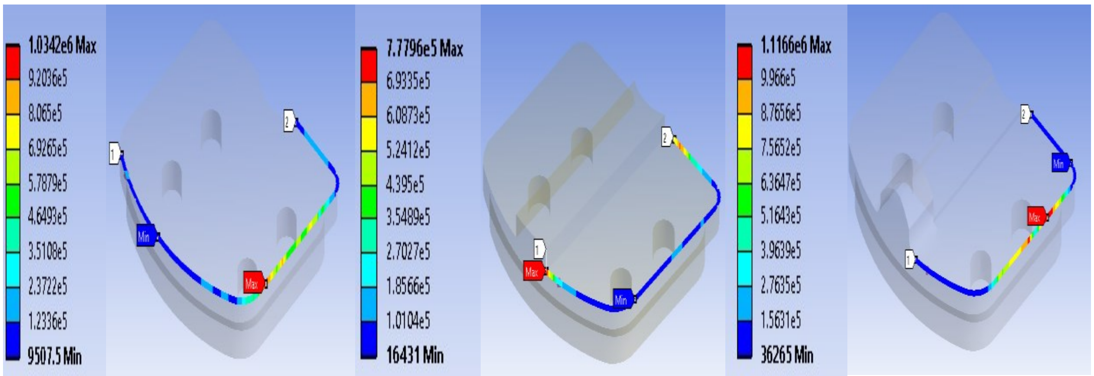
Maximum Stress of design 2 again is the lowest among the three designs of mobile bearing of knee implant when undergone rising from squat motion. All the maximum stresses are below than yield strength of the mobile bearing except for the design 1.

Based on the maximum stress results obtained, it is can be concluded that the most critical motion among the 3 motions (walking, ascending stairs and rising from squat) is rising form squat since its maximum stress is the highest which is also reported by Merchetti et. al when he did study related to squat exercise [10]. Thus, the fatigue life is predicted based on S-N curve of rising from squat motion. The figure 10 and 11 shown the stress and fatigue life cycle along the created path for the three designs of mobile bearings.



(a) (b) (c)

Figure 10. The stress distribution along the path of three different designs of mobile bearing when undergone rising from squat motions which be used for S-N Curve graph plot. a) original design, b) design 1 and c) design 2.



(a) (b) (c)

Figure 11. The life cycle along the path of three different designs of mobile bearing when undergone rising from squat motions which be used for S-N Curve graph plot.a) original design, b) design 1 and c) design 2.

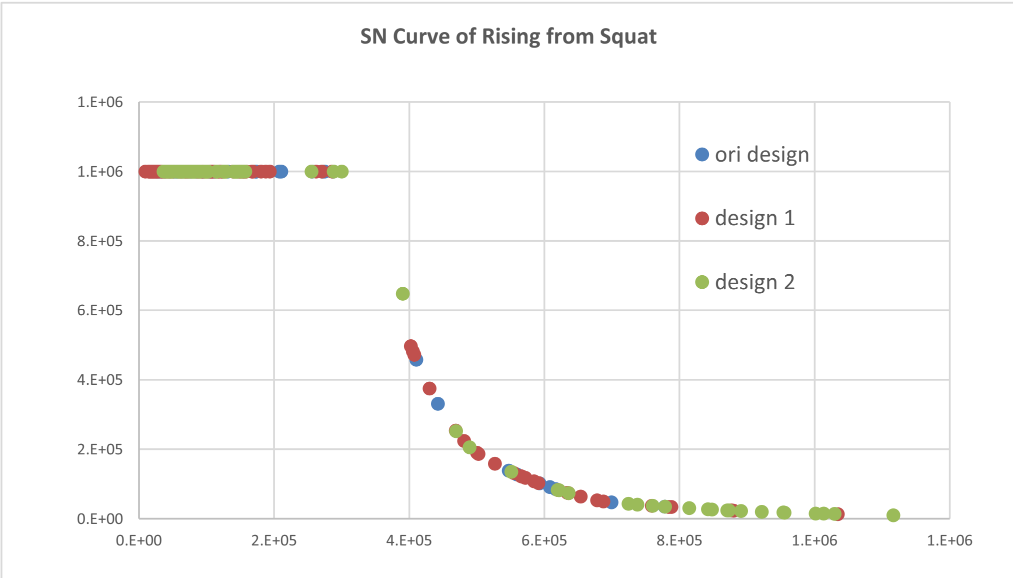


Figure 12. S-N Curve of rising from squat motion for three different design of knee impant mobile bearing.

From the graph shown in figure 12, the degradation point starts at $3X10^5$ cycles and the highest life cycle is for design 2, $1.2X10^6$ cycles. The design 2 was the optimum design of knee implant mobile bearing which the cycle life has been increases from the initial $8X10^5$ cycles to $1.2X10^6$ cycles. The high increment of the cycle life of the improve design (design 2) can be claimed due to its geometrical shape which is no sharp edge and also has middle support which is acted as a rib to increase its structural strength if compared to the original design.

4. Conclusion

It is can be concluded that the finite element method can be used to predict life cycle of the mobile bearing successfully and can be used as a guided to propose an improved design of the prosthesis which it shown that the increasing of fatigue life cycle from the initial $8X10^5$cycles to $1.2X10^6$cycles. However, although the improved design (design 2) is better than original design in term of fatigue life cycle, we are not considering the cost of manufacturing which as far as we concern that the addition of rib in design 2 could possibly increase the cost of manufacturing due to the extra manufacturing process needed. This costing factor is ignored first as our primary objective is just to investigate and predict the fatigue life of the polymer mobile bearing via finite element method. Further study definitely will take into account all aspect including costing to make it more real and practical.

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