Patient-Specific Three-Dimensional Bone Printing to Facilitate Educational Purpose & Practice Surgery: Creating a Blueprint in Perspective of Future Bangladesh

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Abstract

Currently, Bangladeshi surgeons approach surgeries by observing 2D reports or very often 3D photographic views of the affected body parts to assume a 3D construction of that body part, which is surely a difficult process and also may lack in assumption sometimes. Most often, students in operation theatre (OT) being large in number fails to understand the surgical procedures due to the lack of proper visualization. Even due to not having a sufficient level of experience, they don't get the chance to perform any practice surgery, so they have to learn only by visualization, which is definitely a long-time process. Moreover, medical students sometimes face financial problems in buying costly human bones. To get rid of these shortcomings, this study aims to introduce the manufacturing of patient-specific 3D printed models. Proper application of this technology will work as an aid to be able to provide low budget 3D printed human bones required for educational purposes, increase the learning proficiency of medical students by giving them chances to perform practice surgeries and also lessen patient's intraoperative bleeding time, anaesthetic exposure and heat loss through proper pre-surgical planning by surgeons as the outcome of practice surgery, which will lead to achieving a higher satisfaction level of the patients that promises to change the current medical scenario of Bangladesh tremendously.

Keywords
Three-dimensional (3D) Printing, 3D Modeling, Patient-specific, Human Skeleton, Surgical Practice

1. Introduction
The very concept of additive manufacturing can be owed to the success of 3D printing. It has utility in both the engineering and the medical sector. 3D printing is utilized for patient-specific simulations to enhance interactive results and this concept is being evolved as a mainstream tool. The objective is to reduce patient bleeding time, anesthetic exposure, heat loss, etc. Medical fields have seen a rapid use of this technology in instances like plastic surgery, orthopedics, and dentistry. For its expertise in producing real-life look-alike of objects, it can provide the clinicians with a tangible structure to examine patient-specific anatomy and pre-plan surgical procedures without having direct inspection of the patient. Patient-specific individualized simulation can be feasible for the treatment of complex diseases. It can enable the surgical team to plan and practice beforehand, predict the complications that may arise during the surgeries and take necessary precautions. 3D printed models also have the added benefit of being more anatomically precise than cadavers or animals, thus helping accurate learning. This system is increasing the possibility of successful outcomes, cost-effectiveness and time management, enhanced opportunities to gain experiences through learning proficiency, and above all providing security to human lives. Bangladesh is yet to adapt to the technology of patient-specific 3D printing. We are still clinging to the traditional, conventional methods of operation theatre which result in a great loss of time, cost efficiency and effort. The target of this study is to design a

system to incorporate patient-specific 3D printing for surgical and educational purposes that has an application to the life of the patients, in the medical field, engineering field, and industrial sectors.

1.1. Objective

The main objectives of the study are as follows:

1. To study the opportunities and challenges to incorporate patient-specific 3D printing technology in the medical field Bangladesh through conducting a survey analysis among Bangladeshi doctors and medical students to understand their acceptance level.
2. Estimating the material, cost and time requirements required for the blueprint of implementing the technology to produce low budget human skeleton.
3. Designing a simulation model and a web interface representing the system in perspective of Bangladesh.

2. Literature Review

Patient-Specific three-dimensional human bone printing is a service-oriented networked product manufacturing system in which service consumers are enabled of configuring, selecting and utilizing customized product ranging from different 3D printing software to reconfigurable manufacturing systems. This is accomplished through a synergetic integration of the key additive manufacturing processes. Several outstanding researches has been performed on the development of the concept, finding out the requirements and key characteristics of the topic.

Table 1 outline a summary of patient-specific 3D bone printing. It provides an overview on the main objectives & key findings which has been used as a guideline for the succeeding paper.

Table 1. Overview on Patient-Specific 3D Bone Printing

Sl.	Author	Year	Country	Objective	Key Findings
1	Nicolette, James and Nalini	2017	Australia	The objective was to print 3D MV models using 4 different methods to understand which method works best in terms of accuracy.	SLA comes out to be the most precise and polyjet to be the least precise. The respondents of survey agreed that MV model will prove to be helpful in surgical planning.
2	Roberto, Hannah and Samuel	2017	USA	To apply 3D printing technology in production of microtia reconstruction using CT image of opposite side, to increase surgical accuracy.	If produced commercially then cost will be reduced.
3	Manuel, Eduardo and Ana Vera	2018	Portugal	Using patient-specific 3D simulators for pre-surgical planning to facilitate coronary artery disease treatment.	The practice surgery helped to predict the possible complications beforehand.
4	Borja, Ricardo and Javier	2017	Spain	The objective was to apply patient-specific 3D printing in craniosystosis treatment to perform practice surgery.	ABS was found to be the best material for high-speed drill. This method reduced surgical time and increased the outcomes.
5	Kaifang Chen, Fan Yang	2019	China	The application of 3D printing for bicolumnar acetabular fracture fixation.	Using this method saved almost 30 minutes from each surgery and also increased the patients' satisfaction level.
6	Vaibhav, Rakesh and Prashant	2018	India	To create a blueprint for future orthopedics through discussing theoretical backgrounds of 3D printing technology.	Mentioned about 3D printing theoretical and the road ahead of this technology.
7	Dr. Daniel Thomas	2016	USA	Use of patient-specific 3D printing for knee implants to maintain precision.	Low-cost custom implants and a precision of around 25 micro meters.

8	Omkar Prakash and Mahesh Shivaji	2017	India	Review the application of patient-specific 3D printing in medical field.	Discussed about important applications along with challenges and scopes, which prove that this technology is clearly a blessing to the medical field.
9	Zhonghua and Dongting	2018	Australia	Reviewing the papers on the application of patient-specific 3D printing in renal diseases.	Intended to prove the feasibility of using 3D models for pre-surgical planning.
10	Philip, Jan and Paul	2016	Australia	The objective was to summarize the literature on surgical applications of 3D printing with economic and clinical outcomes.	Despite of having several advantages, further research is needed for a formal cost-effective analysis.
11	Hammad, Alastair and Shalin	2015	UK	To discuss about the current applications of 3D printing in surgeries.	There are 3 main medical areas where 3D printing can be applied: anatomic models, surgical instruments and implant manufacturing. Also, the cost and time involved need to be considered before implementing.
12	Dimitris, Peter and Amir	2015	USA	To discuss a review analysis on the 3D printing technology.	Discussed about 3D printing principles, techniques, clinical overviews and applications.
13	Elizabeth and Zhonghua	2017	Australia	To represent the application detail of patient-specific 3D models in hepatocellular carcinoma treatment.	May prove beneficial in reporting complex cases and the surgical planning. Also useful for trainees.

3. Research Methodology

Our research steps are as follows:

Step 1: Data Collection: Collection of data by surveying the feasibility of patient-specific 3D printing. Current problems faced and costings by consulting with the surgeons. Data of MRI, CT scan, X-Ray from the radiology department. Information about hardware, platform, software and infrastructure along with associated prices & time as well as the selection of proper material and the 3D printing process.

Step 2: Data Processing: The MRI, CT scan, X-Ray data of patients' bone that we collected from different hospitals were in DICOM file format that were converted to STL format to create printable 3D model data using different 3D printing software like Slicer, Blender, Meshmixer, PrusaSlicer.

Step 3: 3D Model Construction: To verify the data processing method we prepared a 3D model of one human skull & got that 3D skull printed using 'Prusa i3 MK3S' printer.

Step 4: System Evaluation: We started implementing the process for all-out DICOM file format data to convert them into STL file format to get the weight, cost and time estimation for all the 3D models using PrusaSlicer software & considered PLA as the raw material for printing and calculated the cost according to it. We compared the overall cost of 3D printing human bones with the original cost of purchasing human bones. Also designed ARENA Simulation for the whole process & designed a dummy website according to that system.

Step 5: Result Calculation Criteria:

- ➢Analysis of the survey output that was conducted among the doctors and medical students,
- ➢Production cost and time estimation of printing 3D printed human skeleton,
- ➢Calculation of other related manufacturing and non-manufacturing cost to estimate total per-unit cost,
- ➢Analysis of the output pattern of the system using ARENA simulation software to know the capacity of the system.

Step 6: Result Analysis: Result analysis and discussion based on the information of survey analysis, cost & time estimation and capacity of the system received from the simulation.

4. Survey Analysis

This survey was about patient-specific three-dimensional printing applications in the medical sector of Bangladesh. The survey started on 8 November 2020 & finished on 5 December 2020. Within this one-month interval, we were able to reach 111 survey candidates in total. All of the candidates belong to the medical sector. Either they were doctors or medical students. In the following **Figure 1- Figure 4**, the findings of the candidates, about each question and the overall results are presented and analyzed.

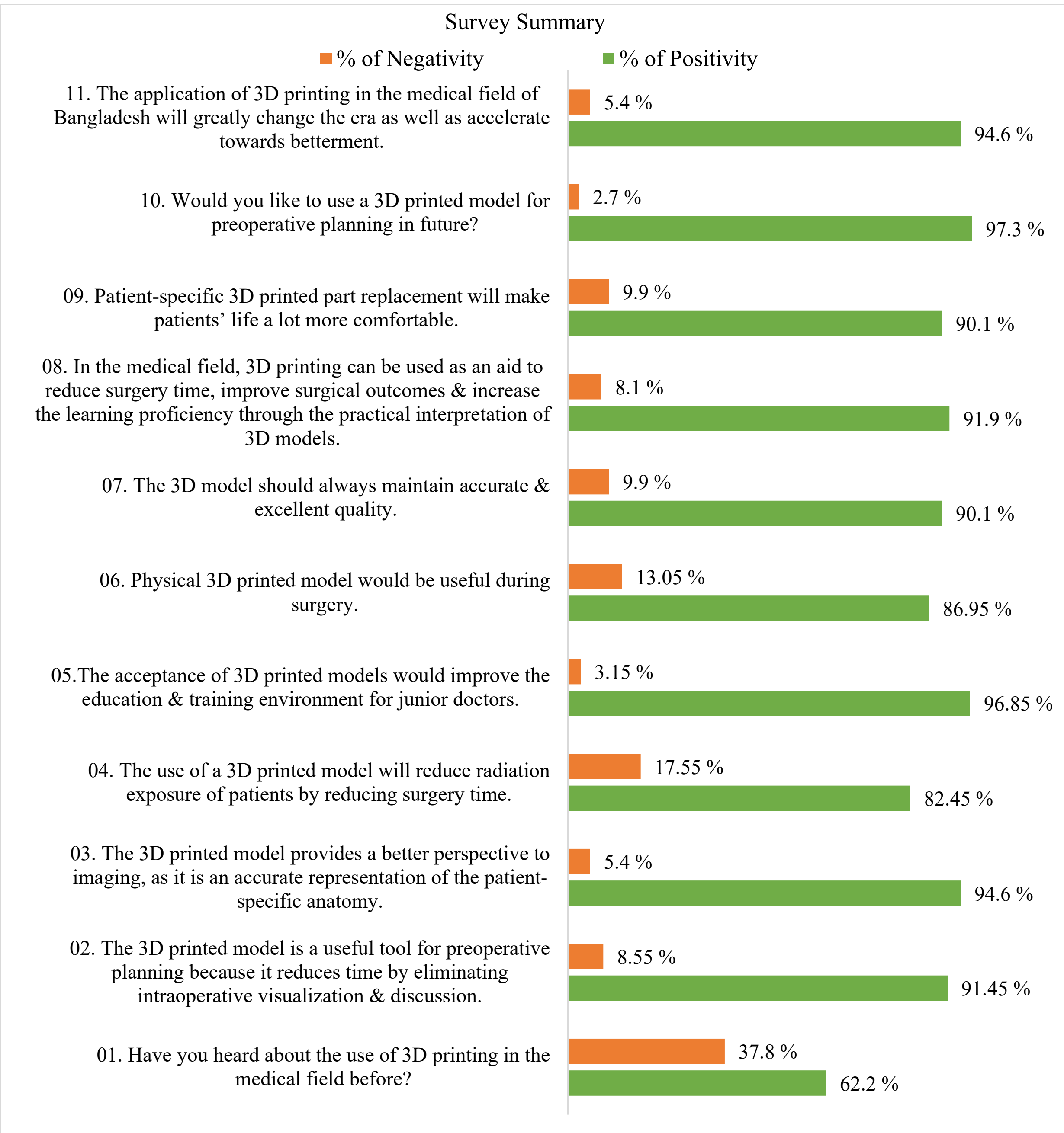

Figure 1. Positivity & negativity percentages of survey question no.1 -11

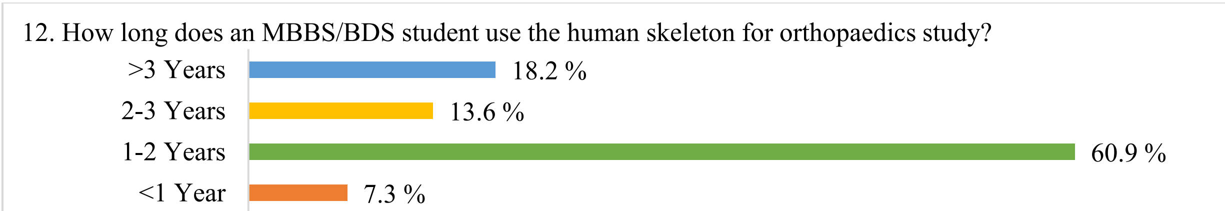

Figure 2. Response summary of survey question no.12

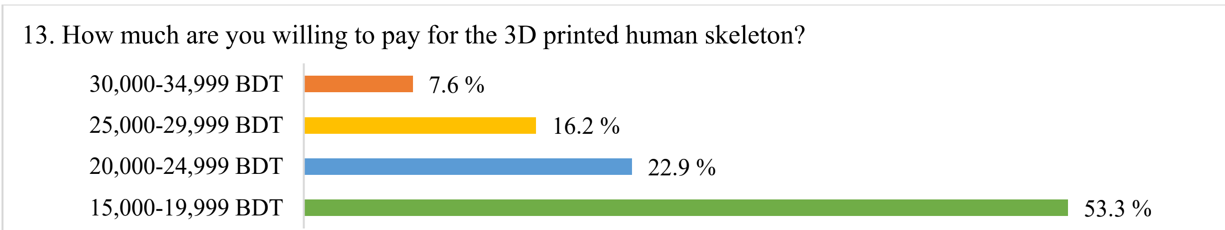

Figure 3. Response summary of survey question no.13

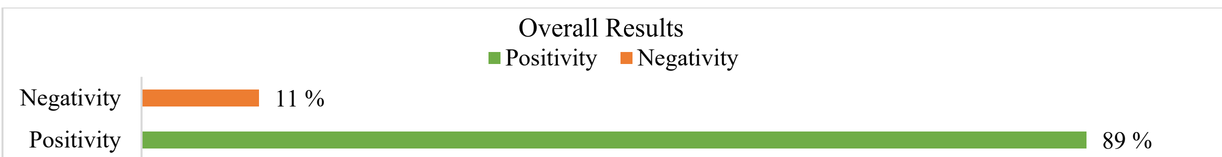

Figure 4. Overall positivity & negativity percentages of survey question no.1 -11

To summarize, it can be said that as the doctors & medical students responded more positively than we expected, so we hope when this 3D printing technology will be incorporated practically in the medical sector of Bangladesh, then everyone will accept them willingly and it will take them a long way to betterment.

5. Evaluation & Implementation

5.1 3D Model Printing

Initially, 2D data of human skull was collected from the Radiology Department of Rajshahi Medical and performed the tasks according to the methodology & got the skull printed using white PLA material to use this model throughout the survey process so that it would be convenient to explain the purpose as well as benefits of using patient-specific three-dimensional bone printing to the doctors & medical students. Some pictures of the printed skull are given in the **Figure 5**.

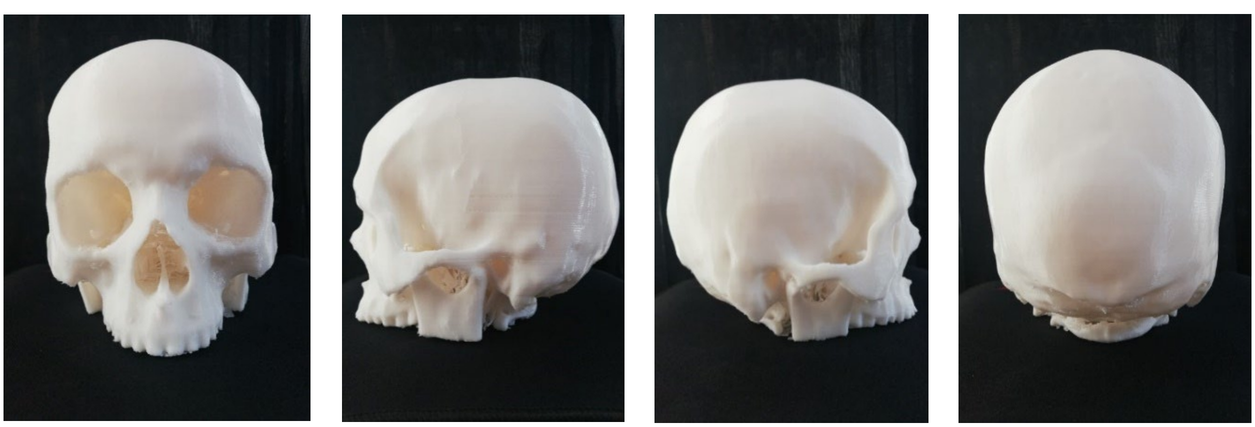

Figure 5. Front, Left, Right & Back view of 3D skull

5.2 Original Human Bone Cost & Weight Data Collection

Focused on collecting the data of original dry human bones of different ages for both male and female to compare with the weight of 3D printed bones' weight. Also collected the costing information to make a cost-based comparison.

5.3 Collected Bone Report Processing

Managed to collect a total of 88 data of different bones from eight different hospitals. Among them 30 were male skull reports, 30 were female skull reports and the remaining ones are of other bones of the body. Used PrusaSlicer to identify the weight with support and without the support of each bone & also got the time of printing with support and without support from this software. Then calculated the cost of three different categories. At first calculated weight without support, then without support and finally of supporting material. We calculated the costs depending upon the weight data. We multiplied each gram weight with the price of PLA, which BDT.5 per gram **(Table 2- Table 4)**.

Table 2. Total material cost calculation

Manufacturing cost					
	Cost object	Activity	Cost driver	Cost driver consumed/month (BDT)	Cost assigned/gm (BDT)
Direct materials	PLA	Printing	Amount of material	262850.47	5
	Superglue	Part joining	Amount of material	150	0.003
	CAD software	DICOM to STL processing	No. of hours	Free	0
Total direct material cost					5.003
Direct labor	Design engineer	CAD file processing	No. of labor hours	40000	0.76
Total direct labor cost					0.76
Manufacturing overhead cost					
Indirect materials	Internet connection	Subscription	Monthly	1200	0.02
	Electricity	Power supply	Monthly	10000	0.19
	Office rent	Work place	Monthly	15000	0.28
Total indirect material cost					0.49
Indirect labor	Technician	Material handling	No. of labor hours	15000	0.28
Total indirect labor cost					0.28
Non-manufacturing cost					
	Transportation	Product delivery	No. of deliveries	1800	0.03
Total cost assigned/gm (BDT)					6.56

Table 3. Cost calculation for male taking into account total material cost

Male							
Serial	Age	Total Cost (BDT)			Total Time (Minutes)		
		Fixed	Variable	Total	Fixed	Variable	Total
1	0-6 months	2077.75	929.01	3006.76	1216.87	969.79	2186.66
2	6 months- 3yrs	3481.96	1559.65	5041.61	3634.82	1628.13	5262.95
3	>3-13 yrs	9705.57	4118.54	13824.11	10131.68	4299.36	14431.04
4	>13-30 yrs	22298.62	9388.23	31686.85	23277.58	9800.39	33077.97
5	>30-45 yrs	24130.30	10154.68	34284.99	25189.69	10600.5	35790.19
6	>45-70+ yrs	22966.32	9598.42	32564.75	23974.60	10019.82	33994.42

Table 4. Cost calculation for female taking into account total material cost

Female							
Serial	Age	Total Cost (BDT)			Total Time (Minutes)		
		Fixed	Variable	Total	Fixed	Variable	Total
1	0-6 months	1946.88	802.93	2749.81	2032.34	838.19	2870.53
2	6 months- 3yrs	3297.66	1346.40	4644.06	3442.43	1405.51	4847.94
3	>3-13 yrs	9920.08	3962.71	13882.80	10355.6	4136.68	14492.28
4	>13-30 yrs	18843.44	7471.76	26315.20	19670.72	7799.8	27470.52
5	>30-45 yrs	19836.05	7860.89	27696.94	20706.9	8205.99	28912.89
6	>45-70+ yrs	18833.84	7445.64	26279.48	19660.69	7772.52	27433.21

5.4 Data for Simulation of the System

The data for preparing the model in the ARENA software is collected from the survey information and some other information provided by professionals. The time for preparation of 3D printed parts is taken from our calculations & the delivery time is considered regarding the standard delivery time in Bangladesh. The simulation model has been illustrated through **Figure 6** & the simulation outcome through **Appendix 1.**

Assumptions in the Simulation:

1. For the data used in the model, triangular distribution has been used based upon the information gathered from the survey and data calculation part collected throughout the period of this research.
2. During the simulation, it has been assumed that the inventory of PLA and other raw materials has not been gone below the safety stock. We designed the system considering that there will be 10 printers in the system.

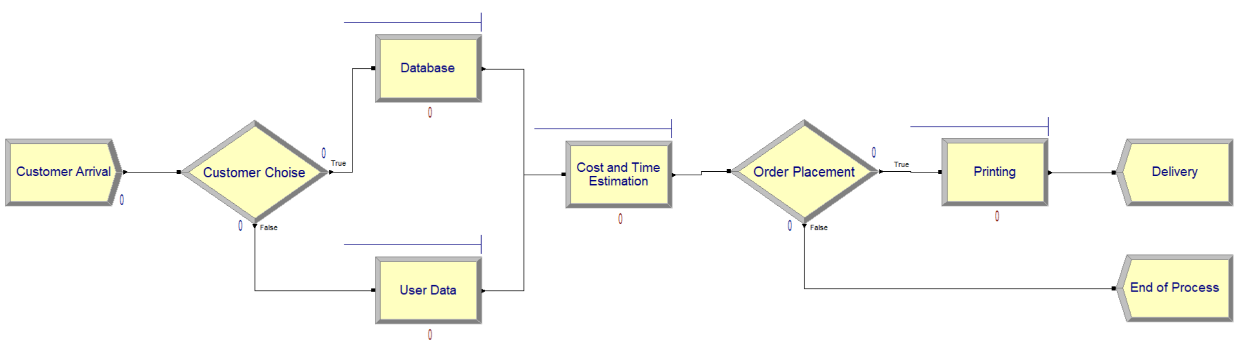

Figure 6. ARENA simulation model for patient-specific 3D printing method

5.4.1 Customer Arrival

The CREATE module has been used with the Random (Expo) distribution for customer arrival, where the time between arrivals is 8 hours, the no. of entity per arrival is 1 and the maximum no. of arrival has been considered 77.

5.4.2 Customer Choice

For this stage, DECIDE module named as customer choice was used and the type was 2-way by Chance with a true percentage of 60. After entering into the system, that individual has to decide whether they'll get 3D printed models from our database of different bones or they'll provide their personal reports to the system to get printed.

5.4.3 Database

The PROCESS module of standard type has been used with medium priority Seize Delay Release action. The resource was the System Database. The delay type was triangular distribution with the values of minimum 0.085 hours, maximum 0.167 hours and most likely 0.126 hours. This stage indicates that the customers will choose their desired criterion of the dataset to get 3D printed.

5.4.4 User Data
This stage is similar to the previous one but the resource was Personal User Data with the same action, priority and distribution as previous. Delay type was a minimum of 0.5 hours, most likely .75 hours and a maximum of 1 hour. After providing their dataset the customers have to wait this time for getting the next stage result.

5.4.5 Cost & Time Estimation
For this stage, the PROCESS module has been used with Web Interface resource & Seize Delay Release action. This process follows the normal distribution with a value minimum of 0.033 hours, most likely 0.0415 hours and a maximum of 0.05 hours.

5.4.6 Order Placement
Now comes again DECIDE module where the customers have to decide whether they want to place an order for printing or not. The type was 2-way by Chance with a true percentage of 97.

5.4.7 Printing
Then comes the printing process with PROCESS module & 3D Printer resource of triangular distribution. The values were minimum of 3.5 hours, most likely 16 hours and a maximum of 36 hours.

5.4.8 Delivery
After finishing printing, the process ends with delivery using DISPOSE module for this type of customers who have taken the printing service.

5.4.9 End of Process
The other type of customers who didn't take the service will go to the end of the process, for which we again used DISPOSE module.

6.4.10 Simulation & Result
A simulation of 30 days with 20 hours in each day has been considered. 100 replications of this simulation were made with 3 days warm-up period for attaining the best possible result. After the simulation, we have found that this model has the capacity of fulfilling 31 orders per month.

5.5 System Illustrating Web Page Design
In order to visualize the implementation of our system, we designed a dummy web page using HTML codes incorporated with JavaScript and CSS.

5.5.1 The Developed Web Page
Initially, entering into the web page using google chrome web browser we can see the HOME page. There are two options to select from, one is 'order with personal data' and another is 'order with existing data' (**Figure 7**). After choosing an order with personal data we'll enter into a page, there is a dummy option for uploading a file, after uploading the file it asks for some personal information so that the time and cost estimation can be notified, after which they may confirm their order (**Figure 8**). Again, if the option order with existing data is chosen, then it'll ask to choose the gender and age of 3D for the bones to be 3D printed, then click the submit button. Then it'll show detail time and cost estimation and two buttons will arrive, one places an order and another is going back. To place the order, one has to provide some basic personal information and confirm the order (**Figure 8**). The orders from both the systems will be listed in a google form. The google form link was incorporated in the HTML code, so when place order button is pressed, it calls the form link from the coding and the information is stored directly in the google form. Some screenshots of the developed dummy web page are given on the following pages.

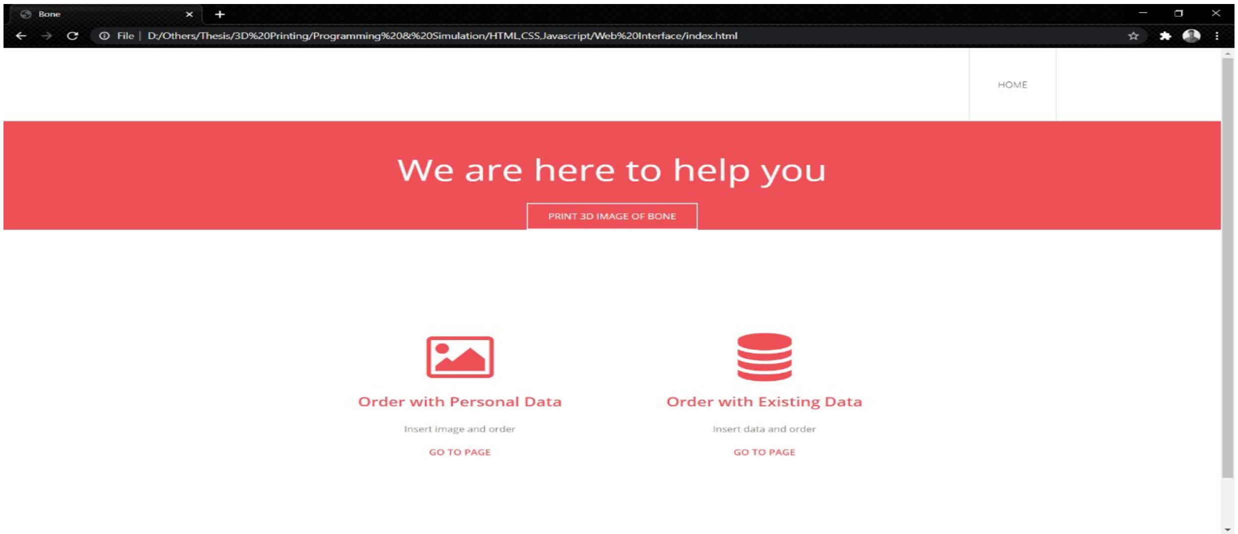

Figure 7. Web interface of the developed web page

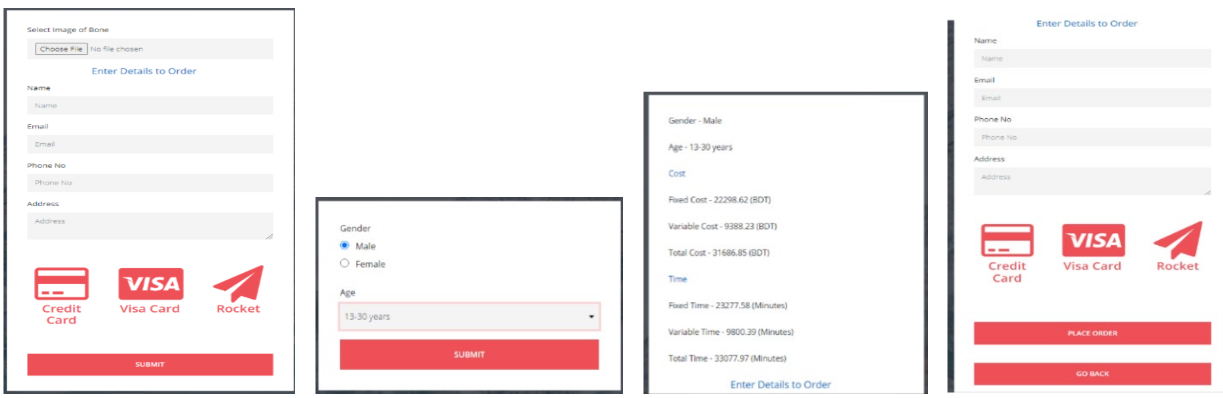

Figure 8. Web interface of the developed web page

6. Result

6.1 Results from the Evaluation of the Implementation of the System

Result analysis depending on individual criteria is described in this section.

Cost: Figure 9 shows the cost comparison among the average of actual bone purchasing cost to the average of 3D printed male and female bones for six different age ranges. Which shows that the cost has been reduced to a great extent.

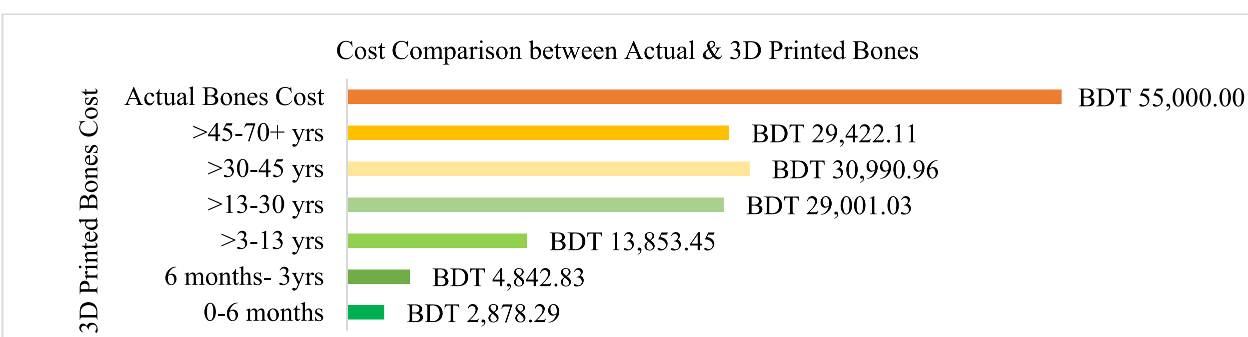

Figure 9 . Cost comparison between actual and 3D printed bones

6.2 Time
The customer may get service and leave the system in less than 7 days. It can be said that the time required to provide the service is quite optimum. (See **Appendix 1**).

6.3 Longevity
PLA may endure up to 15 years. So, definitely in terms of longevity along with the cost, it is obviously a better choice.

7. Future Scope
Future works include practical implementation of the proposed patient-specific three-dimensional human bone production, which if accepted wholeheartedly then one day it will radically change the health care system of Bangladesh and revolutionize modern surgery to an unimaginable level.

8. Conclusion
To provide a solution to the current problems, this paper presents calculations of cost and time regarding 3D printed bones. Also, the manufacturing and non-manufacturing costs were incorporated to get the final cost tables from the perspective of Bangladesh. This proposes to integrate 3D printing of different bones and a dummy web page to provide the facility among doctors and medical students in practical. This system is evaluated using a simulation model created in ARENA simulation software to get the capacity result. Again, the business side of this 3D printing systems compared by calculating unit product cost incurred in production. Finally, after evaluation of the implementation of this technology, the results indicate that incorporating this system in the real-life scenario may bring a huge development to the medical sector as well as to the country. The proposed web page model not just presents another plan of action to provide 3D printed bones, but additionally gives a promising approach to deal with the existing problems in Bangladesh and opening a new source to the manufacturing society in the near future.

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Biographies

Wardatul Akmam graduated from Rajshahi University of Engineering & Technology with a Bachelor's Degree in Industrial & Production Engineering in 2021. She is currently working as an Assistant Engineer having more than a year of experience in the field of Supply Chain at Energypac Engineering Ltd. Whose future prospects is to do further post graduate degree in Industrial Engineering. Her research interests include 3D Printing, Industry 4.0, Project Management & Supply Chain.

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Appendix 1. Simulation result of patient-specific 3D printing system.

2:49:46PM **Category Overview** February 26, 2021

Values Across All Replications

3D Printing System

Replications: 100 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	31

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Customer	17.8477	0.30	13.9561	22.1804	0.1248	35.8551

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Customer	0.00	0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Customer	165.19	5.94	100.87	236.82	0.00	414.13

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Customer	0.00	0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Customer	0.00	0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Customer	183.04	6.08	118.57	257.27	0.1248	428.17

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Customer	65.1700	0.96	49.0000	74.0000

Number Out	Average	Half Width	Minimum Average	Maximum Average
Customer	31.2300	0.53	24.0000	40.0000

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Customer	23.9061	1.00	11.8146	34.4184	0.00	53.0000