Northeastern University

OR 6205 Project

COST OPTIMIZATION OF 3D PRINTED BIO-IMPLANTS

by

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Abstract

3D printed implants are rapidly growing in production and demand. Their sales and production numbers are projected to rise even more, and it is therefore prudent to invest in developing 3D printing technology to increase the quality of life. Common obstacles to this could include but are not limited to, high initial setup costs, large transportation distance and unpredictability in the demand numbers.

This project was undertaken with the aim of optimizing the location of AM centers, such that all the demand is met within a network of interconnected hospitals ensuring optimal transportation distances while warranting price for the implants would be affordable. All the necessary data was gathered and evaluated for its applicability. The data was then used to formulate a balanced Integer Linear Programming (ILP) model algebraically. The problem was then modelled and solved using AMPL for finding the optimal location of AM centers.

The result was evaluated, and sensitivity analysis was performed by varying the demand data to further test the model.

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I. INTRODUCTION

i. Project Statement

The project aimed at determining the optimal number of additive manufacturing centers which could be setup at hospitals in Massachusetts, while minimizing the cost of setup. These AM centers would focus on manufacturing customized knee and hip implants. This decision-making exercise was executed using operations research techniques by building an algorithm using a mathematical programming language called AMPL.

The project started initially with research on understanding the current situation of knee and hip implant manufactured in Massachusetts. It further progressed with understanding additive manufacturing and its different techniques used for manufacturing implants. The research was then directed towards finding the required data to carry out the aimed analysis. This involved finding the average demand of customized implants in Massachusetts, the average production cost and rate of additive manufacturing of knee and hip implants, the average cost of equipment setup in a hospital, the average operational costs which included the standard operator wages in Massachusetts, the approximate distances between hospitals in and around Boston, the transportation costs in Massachusetts and the energy consumption.

Furthermore, a sensitivity analysis was done to determine the changes in the objectives by analyzing the changes in the demand and supply and changes in number of equipment used for manufacturing the implants.

ii. Background

Additive Manufacturing, commonly known as 3D Printing has been defined, according to ASTM F2792-12a, as a process of assembling materials layer upon layer to create articles from model data, as opposed to subtractive manufacturing methodologies (1).

It is a well-known fact that additive manufacturing (AM) technology, is not currently at a maturity level that makes it suitable for mass manufacturing. It is an expensive and time-consuming process compared to conventional technologies. However, additive manufacturing does have one significant advantage over more established approaches: the ability to make custom parts usually meant for short-run production. As a result, it becomes an ideal technology for fabrication of parts in industries that typically do not operate in economies of scale (2).

Most biomedical implants today are mass produced. This reduces the variability in the products as these implants are manufactured in fixed sizes, shapes and using fixed materials. Currently there are six major manufacturers in Massachusetts who account for more than 99% of knee and hip implants manufactured (2). Considering a smaller demand for a certain sized implant, which would have been mass produced, would lead to excess inventory which essentially would translate to material and energy wastage. This can be avoided with the high raw material efficiency and cleaner production associated with additive manufacturing (2). Customized manufacturing of such implants would be helpful in incorporating the anatomy of patients, in the design and manufacturing of the implant. This would also eliminate trial and error fitting process of the implant which consequently would result in a cleaner and much more sustainable manufacturing process. This will also reduce the chances of injuries, implant displacement or even rejection by the host body for the implant (3).

The method of producing customized implants has been gradually adopted into the healthcare industry, over the last 10 years, and is been used by very few hospitals or surgeons. However, the medical application of additive manufacturing is expected to revolutionize the medical and healthcare industry (4).

II. LITERATURE REVIEW

i. <u>Knee and Hip Implant Demand in Massachusetts</u>

More than 1 million Americans, every year, undergo total joint replacement surgery to recover from advanced knee or hip arthritis and function normally (5). These surgeries have increased in demand. In a study conducted by Krutz et.al, it was estimated that by 2030, the demand for primary total hip arthroplasties would grow up to 174% and the demand for primary total knee arthroplasties was projected to grow up to 673% (6).

In Massachusetts, according to the Center for Health Information and Analysis (CHIA), the demand for knee replacement was numbered at 19205 while the demand for hip replacement was numbered 14043 (7). This data was collected by CHIA from 52 hospitals in Massachusetts. The individual demand for each of these hospitals is presented in Appendix A. A total of 10 hospitals were selected for the scope of this project.

ii. <u>Cost Parameters (Setup, Production, Operation, Transport, Emission)</u>

<u>Setup Cost</u>.

Equipment list for a job as sensitive as 3D printing of knee and hip replacement implants involves several individual units, the foremost of which is a suitable 3D printer. For the project the 3D printer, which would be setup at AM center, was assumed as DMP Flex 350 (8) from 3D Systems. DMP Flex 350 is a high performance industrial metal 3D Printer. It has a larger build volume, as compared to most available 3D printers, which helps reduce waste and improves production time by building the model at a higher speed than other available printers. It also has a low setup time (8). The total cost setup for this equipment was estimated at $575,000 (9).

There were other cost components which were also considered while building the setup cost. These individual contributors to the AM process included, but were not limited to, a computer system, to process and store data and design the implants and design software (Solidworks or Autodesk Inventor). It was assumed that the cost of the computer system would be $3500 (10). For the design software, it was decided to choose the cheaper out of the available choices. Hence the cost of design software chosen (Solidworks) was assumed to be $3995/year (11).

Operational Cost.

The process of 3D printing a prosthetic starts with designing the model on modeling software. This warrants the services of an expert CAD designer. The average wage of a designer in Massachusetts was estimated as $26.44/hour (12).

The designer would work in conjunction with an operator, who is trained on the equipment for feedback and production. The hourly wage of an AM printer operator in Massachusetts was assumed as $14.35 (13) .

The energy cost for the operation was also calculated within the operation cost. The average commercial energy cost in MA is $0.216/kWh (14). For this project, it was considered that the energy consumed by the computer is 0.6kWh (15) and the energy consumed by the 3D printer to print one implant was 1.65kWh (15).

Transport Distances and Cost.

As mentioned earlier, list of 10 hospitals was finalized for the scope of this project. These hospitals were chosen from in and around the cities of Boston, Massachusetts. The hospitals included and the individual distances between each hospital is presented in Appendix B. These distances were estimated by using Google Maps (16).

According to the American Transport Research Institute (ATRI), the average transportation cost in 2016 was $1.59/mile (17). This included the costs of driver's wages, fuel, equipment, insurance, repair and other truck operating costs (17). This was calculated for a vehicle carrying a minimum load of 100 pounds (17).

However, considering the weight of prosthetics and the short distances between the selected hospitals, the transportation cost for this project was assumed to be $0.5/pound/mile.

Production Cost.

The production cost for the process was calculated using the raw material cost and the average weight of a 3D printed knee and hip implant. Certain post processing tool costs and overhead costs were also included in the estimation of production cost.

The standard material used for printing implants is an alloy of Cobalt Chromium (CoCr) (4). This raw material assumed to be used for the production of implants for this project would be provided by the manufacturers of the printer. The cost of 1 kilogram of CoCr powder was estimated at $35 (9).

It was assumed that the average weight of a knee implant and a hip implant is 1.5 pounds and 4 pounds respectively (18). Taking this into consideration, the cost of raw material for the production was estimated:

Cost rate of CoCr alloy powder = $35 per kg or $15.88 per pound

Cost of raw material for knee implant = Rate × Weight of knee implant = $23.82

Estimated overhead cost (15) = $51

Total cost of producing a knee implant = Cost of raw material + Overhead cost ≈ $75

Cost of raw material for hip implant = Rate × Weight of hip implant = $63.5

Estimated overhead cost (15) = $136

Total cost of producing a knee implant = Cost of raw material + Overhead cost ≈ $200

iii. <u>Methodology</u>

Figure shows the methodology which was adopted to build the mathematical model.

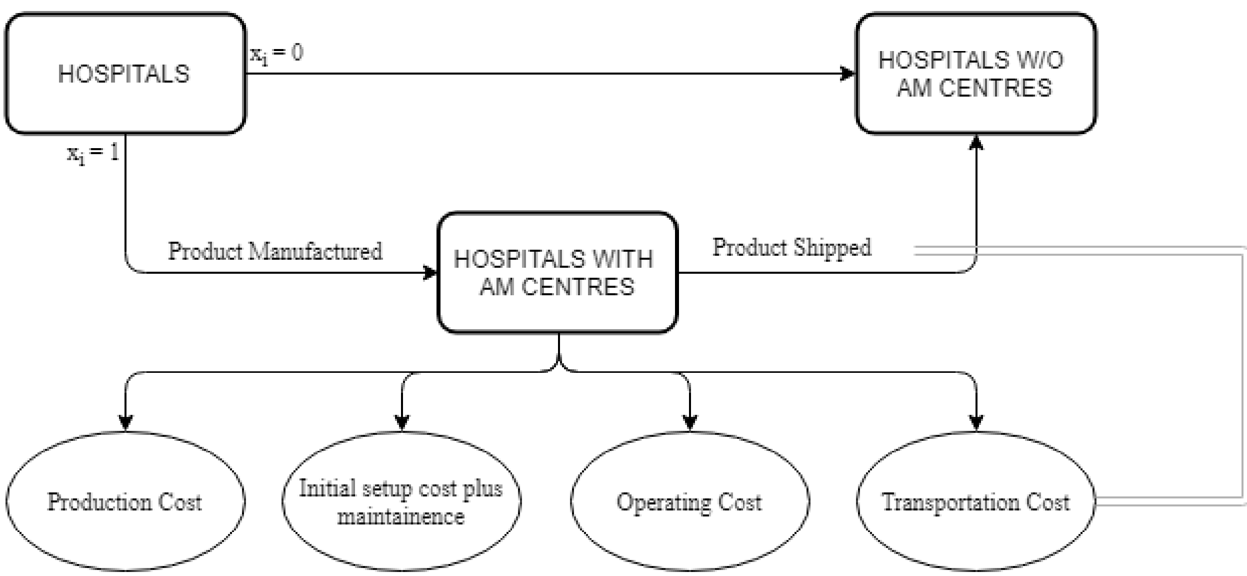

Figure 1: Methodology

III. MATHEMATICAL MODEL

As mentioned earlier, the project aimed at determining the minimum number of additive manufacturing centers, to manufacture customized knee and hip implants, which could be setup at hospitals in Massachusetts, while minimizing the cost of setup.

The problem was formulated around this aim. The total cost included the cost of setup, the cost of operations, the cost of production and the cost of transportation. Each of these costs are explained further in this section.

The cost model included the cost of the opening the AM facility with the number and the cost of equipment along with the maintenance cost, the production volume, the available production times, the production rate of the equipment, the energy consumption rate, location of the hospitals with AM centers from the hospitals without AM centers, transport cost per unit mass and unit distance for the raw material and the final product, the products shipped from hospitals with AM centers to hospitals without AM centers, the demands of hip and knee implants for all the selected hospitals, and the operating costs.

The following notations and parameters were used to develop the model.

INDEX SETS

H	Set of Hospitals	{H = 1,2,3,4,5,6,7,8,9,10}; indexed by i and j
P	Set of Products	{P=1,2}; indexed by p

PARAMETERS

D_{ip} or D_{jp}	Demand in Hospital ‘i’ of Product ‘p’
d_{ij}	Distance between Hospital ‘i’ and Hospital ‘j’
T_i	Total Production time available at Hospital ‘i’
PT_p	Total processing time for Product ‘p’
W_p	Weight of Product ‘p’
EA_i	Maximum equipment allowed in Hospital ‘i’
C_{ip}	Production cost in Hospital ‘i’ per Product ‘p’
OC_{ip}	Operating Cost in Hospital ‘i’ per Product ‘p’

SC	Setup cost for AM center
TC	Transportation cost in Massachusetts
MC_p	Maximum capacity of the equipment for Product 'p'

DECISION VARIABLES

PV_{ip}	Production volume in Hospital 'i' of Product 'p'
PS_{ijp}	Product shipped from Hospital 'i' to Hospital 'j' of Product 'p'
NE_i	Number of equipment in Hospital 'i'

BINARY VARIABLES

x_i	= 1 if hospital is an AM center = 0 otherwise
y_i	= 1 if hospital is **not** an AM center = 0 otherwise

Table 1 below shows the cost factors considered in this model

COST FACTORS	**FORMULA**
Setup Cost	$\sum_{i \in H} SC \times NE_i$
Operational Cost	$\sum_{i \in H} \sum_{p \in P} OC_{ip} \times PV_{ip} \times PT_p$
Production Cost	$\sum_{i \in H} \sum_{p \in P} PV_{ip} \times C_{ip}$
Transportation Cost	$\sum_{i \in H} \sum_{j \in H} \sum_{p \in P} TC \times d_{ij} \times W_p \times PS_{ijp}$

Table 1: Cost Factors

The objective function was to minimize the total cost where

$$\text{Total Cost (Z)} = \text{Setup Cost } + \text{ Operational Cost } + \text{ Production Cost } + \text{Transportation Cost}$$

$$Min\ Z = \sum_{i \in H} SC \times NE_i + \sum_{i \in H} \sum_{p \in P} OC_{ip} \times PV_{ip} \times PT_p + \sum_{i \in H} \sum_{p \in P} PV_{ip} \times C_{ip} + \sum_{i \in H} \sum_{j \in H} \sum_{p \in P} TC \times d_{ij} \times W_p \times PS_{ijp}$$

This objective function was subject to many constraints. These constraints are discussed below.

Constraint 1: Ensures that the defined binary variables are contraries of each other

$$x_i + y_i = 1 \qquad \forall i \in H \tag{1}$$

Constraint 2: This constraint indicated the maximum capacity of the equipment/s which could be setup at AM center.

$$PV_{ip} \leq MC_p \times NE_i \qquad \forall i \in H, \forall p \in P \tag{2}$$

Constraint 3: This constraint accounts for the total available production time and ensures that the implant is built within this limit.

$$\sum_{p \in P} PV_{ip} \times PT_p \leq T_i \times NE_i \qquad \forall i \in H \tag{3}$$

Constraint 4: This constraint ensures that the total demand of all hospitals is met by the supply from the hospital/s with AM center.

$$\sum_{i \in H} D_{ip} - \sum_{i \in H} PV_{ip} \leq 0 \qquad \forall p \in P \tag{4}$$

Constraint 5: This constraint confirms that the volume of production of each AM center in each period should be greater than or equal to the summation of the demand of that facility and the volume of products shipped to demand hospitals which are connected to that AM center.

$$D_{ip} \times x_i + \sum_{j \in H} PS_{ijp} \leq PV_{ip} \qquad \forall i \in H, \forall p \in P \tag{5}$$

Constraint 6: This constraint ensures that the implants shipped from hospital/s with AM center are greater than or equal to the demands of the hospitals without AM centers.

$$\sum_{i \in H} PS_{ijp} \geq D_{jp} \times y_j \qquad \forall j \in H, \forall p \in P \tag{6}$$

Constraint 7: This constraint ensures that the number of equipment setup at AM center is less than or equal to the maximum allowable number of equipment.

$$NE_i \leq EA_i \times x_i \qquad \forall i \in H \tag{7}$$

Constraint 8: Non-negativity constraint for decision variables and binary variables

$$PV_{ip} \geq 0, integer \tag{8}$$

$$PS_{ijp} \geq 0, integer \tag{9}$$

$$NE_i \geq 0, integer \tag{10}$$

$$x_i = 0 \ or \ 1 \tag{11}$$

$$y_i = 0 \ or \ 1 \tag{12}$$

IV. AMPL Model

AMPL is an algebraic modelling language which is used to solve highly complex problems for large scale mathematical computing. Considering the aim of the project, a model file (.mod) was developed on AMPL. This file would represent the standard formulation of the integer linear programming model which is discussed in the above section.

Furthermore, a data file (.dat) was created on AMPL. This file would contain the data which was collected through a through quantitative research. Initially, the model was tested on a sample data consisting of 5 hospitals. Various scenarios were considered for demands from the hospital. The model file was then analyzed on each scenario and checked for its robustness. After completing this phase of analysis, the model was tested on the actual assumed set of data which is presented in Section II of this report.

The figures below show the model file, data file and run file which were built on AMPL.

```
#Model file

#Sets
set PRODUCTS;                                          #Set of products
set HOSPITALS;                                         #Set of hospitals

#Parameters
param demand_hosp {HOSPITALS,PRODUCTS} >= 0;           #Annual Demand of knee and hip implants in each hospital

param dist_betwn_hosp {HOSPITALS,HOSPITALS} >= 0;      #Distance between Hospitals

param total_prod_time {HOSPITALS} >= 0;                #Total Available Production Time in a year

param processing_time {PRODUCTS} >=0;                  #Processing Time of a Product

param weight {PRODUCTS} >=0;                           #Average weight of a Product

param max_equip_allowed {HOSPITALS} >=0;               #Maximum equipment allowed to setup in a hospital which is an AM center

param prod_emission >=0;                               #Maximum Production emission allowed

param prod_cost {HOSPITALS, PRODUCTS} >=0;             #Production Cost per product

param operating_cost {HOSPITALS, PRODUCTS} >=0;        #Operational Cost per product

param setup_cost >=0;                                  #Initial Setup Cost plus maintainance cost

param transportation_cost >=0;                         #Transportation Cost per mile per weight of the product

param max_equip_capacity {PRODUCTS} >=0;               #Maximum production capacity of an equipment for a product
```

Figure 2: Model file from AMPL

```
#Decision Variables
var production_volume {HOSPITALS,PRODUCTS} integer >= 0;          #Production volume of a product in an AM center

var prod_shipped {HOSPITALS,HOSPITALS,PRODUCTS} integer >=0;      #Product shipped from AM center to non AM center

var num_equip {HOSPITALS} integer >=0;                            #Number of equipments to be setup in a hospital which is an AM center

var x {HOSPITALS} binary;                                         #If hospital is an AM center then 1 , otherwise 0

var y {HOSPITALS} binary;                                         #If hospital is a non AM center then 1 , otherwise 0


#Objective Function
minimize Total_Cost:
   sum {i in HOSPITALS}
      setup_cost * num_equip[i]                                                        #Setup Cost
 + sum {i in HOSPITALS, j in HOSPITALS, p in PRODUCTS}
     transportation_cost * dist_betwn_hosp[i,j] * weight[p] * prod_shipped[i,j,p]    #Transportation Cost
 + sum {i in HOSPITALS, p in PRODUCTS}
      production_volume[i,p] *  prod_cost[i,p]                                         #Production Cost
 + sum {i in HOSPITALS, p in PRODUCTS}
      operating_cost[i,p] * production_volume[i,p] * processing_time[p];               #Operational cost

#Constraints

#This constraint ensures that the value of variables x and y are contradictory to each other.
subject to connect_am_with_non_am {i in HOSPITALS}:
   x[i] + y[i] = 1;

#Maximum equipment capacity constraint
subject to max_cap_equip {p in PRODUCTS, i in HOSPITALS}:
    production_volume[i,p]  <= max_equip_capacity[p] * num_equip[i];

#Total production time availability constraint
subject to prod_time_constraint {i in HOSPITALS}:
   sum {p in PRODUCTS}  production_volume[i,p] * processing_time[p] <= total_prod_time[i] * num_equip[i] ;

#Total demand must be less than or equal to total production volume
subject to total_Demand_hosp {p in PRODUCTS}:
 sum {i in HOSPITALS} demand_hosp[i,p] - sum {i in HOSPITALS} production_volume[i,p] <=0;

#This constraint ensures that the demand of the AM center is met first before its surplus is shipped
subject to total_Demand {p in PRODUCTS, i in HOSPITALS}:
   demand_hosp[i,p] * x[i] + sum {j in HOSPITALS} prod_shipped[i,j,p] <= production_volume[i,p];

#Demand constraints for implants from hospitals that don't have their own AM centres
subject to non_am_demand {p in PRODUCTS, j in HOSPITALS}:
    sum{i in HOSPITALS} prod_shipped[i,j,p] >=  demand_hosp[j,p] * y[j];

#Equipment constraints in the AM centre
subject to security_constraint {i in HOSPITALS}:
    num_equip[i] <= max_equip_allowed[i] * x[i];
```

Figure 3: Figure 2 Contd.

```
#Data file

set PRODUCTS := KNEE_IMPLANT HIP_IMPLANT;                    #Set of products

#Set of all the hospitals considered
set HOSPITALS := Brigham_and_Womens_Faulkner_Hospital   Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospital
Beth_Israel_Deaconess_Medical_Center    Boston_Medical_Center  Mount_Auburn_Hospital  Lahey_Hospital_and_Medical_Center  Tufts_Medical_Center    Carney_Hospital;

#Demand of each product at the hospitals
param demand_hosp (tr): Brigham_and_Womens_Faulkner_Hospital    Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospital
Beth_Israel_Deaconess_Medical_Center Boston_Medical_Center Mount_Auburn_Hospital Lahey_Hospital_and_Medical_Center  Tufts_Medical_Center    Carney_Hospital:=
            KNEE_IMPLANT    538 737 820 3197    470 297 236 594 261 76
            HIP_IMPLANT 251 666 857 2836    317 214 182 561 252 18;

#Distance between the hospitals
param dist_betwn_hosp (tr): Brigham_and_Womens_Faulkner_Hospital    Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospital
Beth_Israel_Deaconess_Medical_Center Boston_Medical_Center Mount_Auburn_Hospital    Lahey_Hospital_and_Medical_Center    Tufts_Medical_Center    Carney_Hospital:=
            Brigham_and_Womens_Faulkner_Hospital    0   3.3 7   3.3 3.1 5.2 7.5 22.1    6   5.1
            Brigham_and_Womens_Hospital 3.3 0   3.3 3.4 0.7 2.4 4   22.9    2.7 6.7
            Massachusetts_General_Hospital  7   3.3 0   3.9 5.4 4.2 5.9 16.4    1.4 9
            New_England_Baptist_Hospital    3.3 3.4 3.9 0   3.9 2.6 21.2    23.1    2.8 6.7
            Beth_Israel_Deaconess_Medical_Center    3.1 0.7 5.4 3.9 0   2.9 4.7 21.2    3   6.6
            Boston_Medical_Center   5.2 2.4 4.2 2.6 2.9 0   7.4 18.8    1.3 6.5
            Mount_Auburn_Hospital   7.5 4   5.9 21.2    4.7 7.4 0   16.2    5.5 12
            Lahey_Hospital_and_Medical_Center   22.1    22.9    16.4    23.1    21.2    18.8    16.2    0   25  35
            Tufts_Medical_Center    6   2.7 1.4 2.8 3   1.3 5.5 25  0   6.6
            Carney_Hospital 5.1 6.7 9   6.7 6.6 6.5 12  35  6.6 0;

#Maximum production time per product in hours and maximum permissible number of equipments at each hospital
param : total_prod_time max_equip_allowed :=
            Brigham_and_Womens_Faulkner_Hospital    7200    2
            Brigham_and_Womens_Hospital 7200    2
            Massachusetts_General_Hospital  7200    2
            New_England_Baptist_Hospital    7200    5
            Beth_Israel_Deaconess_Medical_Center    7200    2
            Boston_Medical_Center 7200  1
            Mount_Auburn_Hospital 7200  1
            Lahey_Hospital_and_Medical_Center   7200    1
            Tufts_Medical_Center    7200    1
            Carney_Hospital 7200    1;

#Processing time, the weight and the maximum capacity of the equipment
param : processing_time weight max_equip_capacity :=
    KNEE_IMPLANT 3  1.5 2400
    HIP_IMPLANT 8   4 900;


#Production cost of each product at the hospitals
param prod_cost (tr): Brigham_and_Womens_Faulkner_Hospital  Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospital
Beth_Israel_Deaconess_Medical_Center Boston_Medical_Center  Mount_Auburn_Hospital    Lahey_Hospital_and_Medical_Center    Tufts_Medical_Center    Carney_Hospital:=
        KNEE_IMPLANT    75  75  75  75  75  75  75  75  75  75
        HIP_IMPLANT 200 200 200 200 200 200 200 200 200 200;

#Operating cost of each product at the hospitals
param operating_cost (tr): Brigham_and_Womens_Faulkner_Hospital Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospital
Beth_Israel_Deaconess_Medical_Center Boston_Medical_Center  Mount_Auburn_Hospital    Lahey_Hospital_and_Medical_Center    Tufts_Medical_Center    Carney_Hospital:=
        KNEE_IMPLANT    41  43  45  42  43  42  45  47  41  39
        HIP_IMPLANT 41  43  45 42    43 42  45  47  41  39;

param setup_cost default 579845;                    #Setup cost of the AM centre

param transportation_cost default 0.5;              #Trasportation cost per mile per pound
```

Figure 4: Data file from AMPL

```
model ORProject.mod;
data OR_Project.dat;
option solver cplex;

solve;

printf   'Demand at all hospitals:  \n' ;
display demand_hosp;

printf 'Production Volume at AM center: \n';
display production_volume;

printf 'Products Shipped from AM center to other hospitals: \n';
display prod_shipped;

var Transportation_Cost = sum {i in HOSPITALS, j in HOSPITALS, p in PRODUCTS} transportation_cost * dist_betwn_hosp[i,j] * weight[p] * prod_shipped[i,j,p];

var Setup_Cost = sum {i in HOSPITALS} setup_cost * num_equip[i];

var Production_Cost = sum {i in HOSPITALS, p in PRODUCTS} production_volume[i,p] *  prod_cost[i,p];

var Operating_Cost = sum {i in HOSPITALS, p in PRODUCTS} operating_cost[i,p] * production_volume[i,p] * processing_time[p];


display Total_Cost;

display Setup_Cost;

display Production_Cost;

display Transportation_Cost;

display Operating_Cost;

display num_equip;
```

Figure 5: Run file from AMPL

V. Sensitivity Analysis

As mentioned earlier, it has been assumed that the entire demand of each hospital is met by AM centers. However, in a more realistic scenario, due to space, security and regulatory constraints, one or more hospitals may not be able to add more than one AM equipment at its premises. Moreover, due to the competition from already existing players in this market, the entire requirement of implants may not be procured from these AM centers alone. A sensitivity analysis of the objective was carried out by assuming that 30% of the demand is met by AM centers, as shown in Table 2. In addition to this, it was also assumed the number of maximum permissible equipment in a hospital as 1.

		Actual		**Revised**	
	Hospital	**Knee Implant Demand**	**Hip Implant Demand**	**Knee Implant Demand**	**Hip Implant Demand**
1.	New England Baptist	3197	2836	959	851
2.	Brigham and Women's	737	666	221	200
3.	Beth Israel Deaconess	470	317	135	97
4.	Boston Medical Center	297	214	89	64
5.	Brigham and Women's Faulkner	538	251	162	75
6.	Steward Carney	76	18	23	5
7.	Lahey Hospital	594	561	178	168
8.	Massachusetts General Hospital	820	857	246	257
9.	Mount Auburn	236	182	71	55
10.	Tufts Medical Center	261	252	78	76

Table 2 : Actual Demand vs Revised Demand

These aforementioned changes were made in the AMPL data file, and the corresponding setup cost, operational cost, transportation cost, as well as the number of shipments, and production at each AM center were calculated by its help. Figure 6 shows the new data file from AMPL.

```
#Data file

#Set of products
set PRODUCTS := KNEE_IMPLANT HIP_IMPLANT    ;

#Set of hospitals
set HOSPITALS := Brigham_and_Womens_Faulkner_Hospital   Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospital    Beth_Is

#Demand of each product at the hospitals
param demand_hosp (tr): Brigham_and_Womens_Faulkner_Hospital    Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospital
        KNEE_IMPLANT    162 221 246 959 135 89  71  178 78  23
        HIP_IMPLANT 75  200 257 851 97 64   55  168 76  5;

#Distance between the hospitals
param dist_betwn_hosp (tr): Brigham_and_Womens_Faulkner_Hospital    Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospita
        Brigham_and_Womens_Faulkner_Hospital    0   3.3 7   3.3 3.1 5.2 7.5 22.1    6   5.1
        Brigham_and_Womens_Hospital 3.3 0   3.3 3.4 0.7 2.4 4   22.9    2.7 6.7
        Massachusetts_General_Hospital  7   3.3 0   3.9 5.4 4.2 5.9 16.4    1.4 9
        New_England_Baptist_Hospital    3.3 3.4 3.9 0   3.9 2.6 21.2    23.1    2.8 6.7
        Beth_Israel_Deaconess_Medical_Center    3.1 0.7 5.4 3.9 0   2.9 4.7 21.2    3   6.6
        Boston_Medical_Center   5.2 2.4 4.2 2.6 2.9 0   7.4 18.8    1.3 6.5
        Mount_Auburn_Hospital   7.5 4   5.9 21.2    4.7 7.4 0   16.2    5.5 12
        Lahey_Hospital_and_Medical_Center   22.1    22.9    16.4    23.1    21.2    18.8    16.2    0   25  35
        Tufts_Medical_Center    6   2.7 1.4 2.8 3   1.3 5.5 25  0   6.6
        Carney_Hospital 5.1 6.7 9   6.7 6.6 6.5 12  35  6.6 0;

#Total time available for production annually, Maximum number of permissible equipments at each hospital
param : total_prod_time max_equip_allowed :=
        Brigham_and_Womens_Faulkner_Hospital    7200    1
        Brigham_and_Womens_Hospital 7200    1
        Massachusetts_General_Hospital  7200    1
        New_England_Baptist_Hospital    7200    1
        Beth_Israel_Deaconess_Medical_Center    7200    1
        Boston_Medical_Center 7200  1
        Mount_Auburn_Hospital 7200  1
        Lahey_Hospital_and_Medical_Center   7200    1
        Tufts_Medical_Center    7200    1
        Carney_Hospital 7200    1;

#Processing time of each product, Weight of each product, Total capacity of equipment for each product
param : processing_time weight max_equip_capacity :=
    KNEE_IMPLANT 3  1.5 2400
    HIP_IMPLANT 8   4 900;

#Cost of production of each product
param prod_cost (tr): Brigham_and_Womens_Faulkner_Hospital  Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospital    Bet
      KNEE_IMPLANT    75  75  75  75  75  75  75  75  75  75
      HIP_IMPLANT 200 200 200 200 200 200 200 200 200 200;

#Operating cost of each product at the hospitals
param operating_cost (tr): Brigham_and_Womens_Faulkner_Hospital Brigham_and_Womens_Hospital Massachusetts_General_Hospital  New_England_Baptist_Hospital
      KNEE_IMPLANT    41  43  45  42  43  42  45  47  41  39
      HIP_IMPLANT 41  43  45 42    43 42  45  47  41  39;

#Setup cost
param setup_cost default 579845;

#Transportation cost per pound per mile
param transportation_cost default 0.5;
```

Figure 6: Data file for sensitivity analysis from AMPL

VI. Transportation Problem

Once the AM centers were assigned by the model, a balanced transportation problem was formed with the origin as the hospitals with AM center and destination as the demand hospitals (Non - AM center). The AM centers would fulfill their own demands and ship the surplus to the demand hospitals by solving the above balanced transportation model. Tables 3 and 4 shows the transportation problem for the data used the second scenario.

Index	Hospitals
H1	Brigham and Women's Faulkner Hospital
H2	Brigham and Women's Hospital
H3	Massachusetts General Hospital
H4	New England Baptist Hospital
H5	Beth Israel Deaconess Medical Center
H6	Boston Medical Center
H7	Mount Auburn Hospital
H8	Lahey Hospital and Medical Center
H9	Tufts Medical Center
H10	Carney Hospital

Table 3: Hospital Index

KNEE IMPLANT

Hospital	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	SUPPLY
Brigham and Women's Faulkner Hospital	M	2.5	5.25	2.48	2.33	3.9	5.625	17	4.5	3.83	1384
Tufts Medical Center	4.5	2	1.05	2.1	2.25	0.98	4.125	19	M	4.95	706
Carney Hospital	3.83	5	6.75	5.03	4.95	4.88	9	26	4.95	M	72
DEMAND	162	221	246	959	135	89	71	178	78	23	

HIP IMPLANT

Hospital	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	SUPPLY
Brigham and Women's Faulkner Hospital	M	6.6	14	6.6	6.2	10.4	15	44	12	10.2	340
Tufts Medical Center	12	5.4	2.8	5.6	6	2.6	11	50	M	13.2	635
Carney Hospital	10.2	13	18	13.4	13.2	13	24	70	13.2	M	873
DEMAND	75	200	257	851	97	64	55	168	76	5	

Table 4: Balanced Transportation Problem for Knee and Hip Implants

VII. RESULTS

In the first scenario, the actual demand, as shown in Appendix A, was considered. The optimal cost obtained using this data was $10,563,511.93. The setup cost, production cost, operating cost and transportation cost calculated in the model were $5,798,450, $1,772,750, $2,935,020 and $57,291.9 respectively. A total of 5 AM centers were formed, and 10 equipment were setup in these 5 AM centers. Figures 7, 8 and 9 show the AMPL Console with displayed results.

```
ampl: include 'F:\PhD\OR6205\AMPL BB Files\AMPL-FALL2018\ORProject.run';
CPLEX 12.8.0.0: optimal integer solution within mipgap or absmipgap; objective 10563511.93
19913 MIP simplex iterations
3573 branch-and-bound nodes
absmipgap = 1033.14, relmipgap = 9.78027e-05
Demand at all hospitals:
demand_hosp :=
Beth_Israel_Deaconess_Medical_Center HIP_IMPLANT     317
Beth_Israel_Deaconess_Medical_Center KNEE_IMPLANT    470
Boston_Medical_Center                HIP_IMPLANT     214
Boston_Medical_Center                KNEE_IMPLANT    297
Brigham_and_Womens_Faulkner_Hospital HIP_IMPLANT     251
Brigham_and_Womens_Faulkner_Hospital KNEE_IMPLANT    538
Brigham_and_Womens_Hospital          HIP_IMPLANT     666
Brigham_and_Womens_Hospital          KNEE_IMPLANT    737
Carney_Hospital                      HIP_IMPLANT      18
Carney_Hospital                      KNEE_IMPLANT     76
Lahey_Hospital_and_Medical_Center    HIP_IMPLANT     561
Lahey_Hospital_and_Medical_Center    KNEE_IMPLANT    594
Massachusetts_General_Hospital       HIP_IMPLANT     857
Massachusetts_General_Hospital       KNEE_IMPLANT    820
Mount_Auburn_Hospital                HIP_IMPLANT     182
Mount_Auburn_Hospital                KNEE_IMPLANT    236
New_England_Baptist_Hospital         HIP_IMPLANT    2836
New_England_Baptist_Hospital         KNEE_IMPLANT   3197
Tufts_Medical_Center                 HIP_IMPLANT     252
Tufts_Medical_Center                 KNEE_IMPLANT    261
;
Production Volume at AM center:
production_volume :=
Beth_Israel_Deaconess_Medical_Center HIP_IMPLANT       0
Beth_Israel_Deaconess_Medical_Center KNEE_IMPLANT      0
Boston_Medical_Center                HIP_IMPLANT     568
Boston_Medical_Center                KNEE_IMPLANT    885
Brigham_and_Womens_Faulkner_Hospital HIP_IMPLANT    1056
Brigham_and_Womens_Faulkner_Hospital KNEE_IMPLANT   1984
Brigham_and_Womens_Hospital          HIP_IMPLANT       0
Brigham_and_Womens_Hospital          KNEE_IMPLANT      0
Carney_Hospital                      HIP_IMPLANT     870
Carney_Hospital                      KNEE_IMPLANT     80
Lahey_Hospital_and_Medical_Center    HIP_IMPLANT       0
Lahey_Hospital_and_Medical_Center    KNEE_IMPLANT      0
Massachusetts_General_Hospital       HIP_IMPLANT       0
Massachusetts_General_Hospital       KNEE_IMPLANT      0
Mount_Auburn_Hospital                HIP_IMPLANT       0
Mount_Auburn_Hospital                KNEE_IMPLANT      0
New_England_Baptist_Hospital         HIP_IMPLANT    3165
New_England_Baptist_Hospital         KNEE_IMPLANT   3197
Tufts_Medical_Center                 HIP_IMPLANT     495
Tufts_Medical_Center                 KNEE_IMPLANT   1080
;
```

Figure 7: AMPL Result for first Scenario

```
Products Shipped from AM center to other hospitals:
prod_shipped [*,*,HIP_IMPLANT]
# $1 = Beth_Israel_Deaconess_Medical_Center
# $2 = Boston_Medical_Center
# $3 = Brigham_and_Womens_Faulkner_Hospital
# $4 = Brigham_and_Womens_Hospital
# $5 = Carney_Hospital
# $6 = Lahey_Hospital_and_Medical_Center
# $7 = Massachusetts_General_Hospital
# $8 = Mount_Auburn_Hospital
:                                     $1   $2  $3   $4   $5   $6    $7    $8 :=
Beth_Israel_Deaconess_Medical_Center    0    0   0    0    0    0     0     0
Boston_Medical_Center                   0    0   0    0    0  354     0     0
Brigham_and_Womens_Faulkner_Hospital  317    0   0   99    0  207     0   182
Brigham_and_Womens_Hospital             0    0   0    0    0    0     0     0
Carney_Hospital                         0    0   0  567    0    0   285     0
Lahey_Hospital_and_Medical_Center       0    0   0    0    0    0     0     0
Massachusetts_General_Hospital          0    0   0    0    0    0     0     0
Mount_Auburn_Hospital                   0    0   0    0    0    0     0     0
New_England_Baptist_Hospital            0    0   0    0    0    0   329     0
Tufts_Medical_Center                    0    0   0    0    0    0   243     0

# $1 = New_England_Baptist_Hospital
:                                     $1 Tufts_Medical_Center    :=
Beth_Israel_Deaconess_Medical_Center   0           0
Boston_Medical_Center                  0           0
Brigham_and_Womens_Faulkner_Hospital   0           0
Brigham_and_Womens_Hospital            0           0
Carney_Hospital                        0           0
Lahey_Hospital_and_Medical_Center      0           0
Massachusetts_General_Hospital         0           0
Mount_Auburn_Hospital                  0           0
New_England_Baptist_Hospital           0           0
Tufts_Medical_Center                   0           0

 [*,*,KNEE_IMPLANT]
# $1 = Beth_Israel_Deaconess_Medical_Center
# $2 = Boston_Medical_Center
# $3 = Brigham_and_Womens_Faulkner_Hospital
# $4 = Brigham_and_Womens_Hospital
# $5 = Carney_Hospital
# $6 = Lahey_Hospital_and_Medical_Center
# $7 = Massachusetts_General_Hospital
# $8 = Mount_Auburn_Hospital
:                                     $1   $2  $3   $4   $5   $6    $7    $8 :=
Beth_Israel_Deaconess_Medical_Center    0    0   0    0    0    0     0     0
Boston_Medical_Center                   0    0   0    0    0  588     0     0
Brigham_and_Womens_Faulkner_Hospital  470    0   0  734    0    6     0   236
Brigham_and_Womens_Hospital             0    0   0    0    0    0     0     0
Carney_Hospital                         0    0   0    3    0    0     1     0
Lahey_Hospital_and_Medical_Center       0    0   0    0    0    0     0     0
Massachusetts_General_Hospital          0    0   0    0    0    0     0     0
Mount_Auburn_Hospital                   0    0   0    0    0    0     0     0
New_England_Baptist_Hospital            0    0   0    0    0    0     0     0
Tufts_Medical_Center                    0    0   0    0    0    0   819     0
```

Figure 8: AMPL Result for first Scenario(Contd.)

```
# $1 = New_England_Baptist_Hospital
:                                      $1 Tufts_Medical_Center    :=
Beth_Israel_Deaconess_Medical_Center   0          0
Boston_Medical_Center                  0          0
Brigham_and_Womens_Faulkner_Hospital   0          0
Brigham_and_Womens_Hospital            0          0
Carney_Hospital                        0          0
Lahey_Hospital_and_Medical_Center      0          0
Massachusetts_General_Hospital         0          0
Mount_Auburn_Hospital                  0          0
New_England_Baptist_Hospital           0          0
Tufts_Medical_Center                   0          0
;

Total_Cost = 10563500

Setup_Cost = 5798450

Production_Cost = 1772750

Transportation_Cost = 57291.9

Operating_Cost = 2935020

num_equip [*] :=
Beth_Israel_Deaconess_Medical_Center  0
               Boston_Medical_Center  1
Brigham_and_Womens_Faulkner_Hospital  2
         Brigham_and_Womens_Hospital  0
                     Carney_Hospital  1
   Lahey_Hospital_and_Medical_Center  0
      Massachusetts_General_Hospital  0
               Mount_Auburn_Hospital  0
        New_England_Baptist_Hospital  5
                Tufts_Medical_Center  1
;
```

Figure 9: AMPL Result for first Scenario(Contd.)

The demand considered in the second scenario was approximately 30% of the actual demand, as explained in Section V of this report. The optimal cost obtained using this data was $3,157,940. The setup cost, production cost, operating cost and transportation cost calculated in the model were $1,739,540, $531,750, $857,670 and $28,985.2 respectively. A total of 3 AM centers were selected, and 3 equipment were setup in these 3 AM centers. Figures 10,11 and 12 show the AMPL Console with displayed results.

```
ampl: include 'C:\Users\ankit\Introduction to AMPL\AMPL-FALL2018\ORProject.run';
CPLEX 12.8.0.0: optimal integer solution within mipgap or absmipgap; objective 3157940.2
73 MIP simplex iterations
0 branch-and-bound nodes
absmipgap = 0.375, relmipgap = 1.18748e-07
Demand at all hospitals:
demand_hosp :=
Beth_Israel_Deaconess_Medical_Center HIP_IMPLANT     97
Beth_Israel_Deaconess_Medical_Center KNEE_IMPLANT   135
Boston_Medical_Center                HIP_IMPLANT     64
Boston_Medical_Center                KNEE_IMPLANT    89
Brigham_and_Womens_Faulkner_Hospital HIP_IMPLANT     75
Brigham_and_Womens_Faulkner_Hospital KNEE_IMPLANT   162
Brigham_and_Womens_Hospital          HIP_IMPLANT    200
Brigham_and_Womens_Hospital          KNEE_IMPLANT   221
Carney_Hospital                      HIP_IMPLANT      5
Carney_Hospital                      KNEE_IMPLANT    23
Lahey_Hospital_and_Medical_Center    HIP_IMPLANT    168
Lahey_Hospital_and_Medical_Center    KNEE_IMPLANT   178
Massachusetts_General_Hospital       HIP_IMPLANT    257
Massachusetts_General_Hospital       KNEE_IMPLANT   246
Mount_Auburn_Hospital                HIP_IMPLANT     55
Mount_Auburn_Hospital                KNEE_IMPLANT    71
New_England_Baptist_Hospital         HIP_IMPLANT    851
New_England_Baptist_Hospital         KNEE_IMPLANT   959
Tufts_Medical_Center                 HIP_IMPLANT     76
Tufts_Medical_Center                 KNEE_IMPLANT    78
;
```

```
Production Volume at AM center:
production_volume :=
Beth_Israel_Deaconess_Medical_Center HIP_IMPLANT       0
Beth_Israel_Deaconess_Medical_Center KNEE_IMPLANT      0
Boston_Medical_Center                HIP_IMPLANT       0
Boston_Medical_Center                KNEE_IMPLANT      0
Brigham_and_Womens_Faulkner_Hospital HIP_IMPLANT     340
Brigham_and_Womens_Faulkner_Hospital KNEE_IMPLANT   1384
Brigham_and_Womens_Hospital          HIP_IMPLANT       0
Brigham_and_Womens_Hospital          KNEE_IMPLANT      0
Carney_Hospital                      HIP_IMPLANT     873
Carney_Hospital                      KNEE_IMPLANT     72
Lahey_Hospital_and_Medical_Center    HIP_IMPLANT       0
Lahey_Hospital_and_Medical_Center    KNEE_IMPLANT      0
Massachusetts_General_Hospital       HIP_IMPLANT       0
Massachusetts_General_Hospital       KNEE_IMPLANT      0
Mount_Auburn_Hospital                HIP_IMPLANT       0
Mount_Auburn_Hospital                KNEE_IMPLANT      0
New_England_Baptist_Hospital         HIP_IMPLANT       0
New_England_Baptist_Hospital         KNEE_IMPLANT      0
Tufts_Medical_Center                 HIP_IMPLANT     635
Tufts_Medical_Center                 KNEE_IMPLANT    706
;
```

Figure 10: AMPL Result for second Scenario

```
Products Shipped from AM center to other hospitals:
prod_shipped [*,*,HIP_IMPLANT]
# $1 = Beth_Israel_Deaconess_Medical_Center
# $2 = Boston_Medical_Center
# $3 = Brigham_and_Womens_Faulkner_Hospital
# $4 = Brigham_and_Womens_Hospital
# $5 = Carney_Hospital
# $6 = Lahey_Hospital_and_Medical_Center
# $7 = Massachusetts_General_Hospital
# $8 = Mount_Auburn_Hospital
:                                     $1   $2  $3    $4   $5   $6    $7    $8 :=
Beth_Israel_Deaconess_Medical_Center   0    0   0     0    0    0     0     0
Boston_Medical_Center                  0    0   0     0    0    0     0     0
Brigham_and_Womens_Faulkner_Hospital  97    0   0     0    0  168     0     0
Brigham_and_Womens_Hospital            0    0   0     0    0    0     0     0
Carney_Hospital                        0    0   0    17    0    0     0     0
Lahey_Hospital_and_Medical_Center      0    0   0     0    0    0     0     0
Massachusetts_General_Hospital         0    0   0     0    0    0     0     0
Mount_Auburn_Hospital                  0    0   0     0    0    0     0     0
New_England_Baptist_Hospital           0    0   0     0    0    0     0     0
Tufts_Medical_Center                   0   64   0   183    0    0   257    55

# $1 = New_England_Baptist_Hospital
:                                     $1  Tufts_Medical_Center    :=
Beth_Israel_Deaconess_Medical_Center    0           0
Boston_Medical_Center                   0           0
Brigham_and_Womens_Faulkner_Hospital    0           0
Brigham_and_Womens_Hospital             0           0
Carney_Hospital                       851           0
Lahey_Hospital_and_Medical_Center       0           0
Massachusetts_General_Hospital          0           0
Mount_Auburn_Hospital                   0           0
New_England_Baptist_Hospital            0           0
Tufts_Medical_Center                    0           0
```


```
Products Shipped from AM center to other hospitals:
prod_shipped [*,*,HIP_IMPLANT]
# $1 = Beth_Israel_Deaconess_Medical_Center
# $2 = Boston_Medical_Center
# $3 = Brigham_and_Womens_Faulkner_Hospital
# $4 = Brigham_and_Womens_Hospital
# $5 = Carney_Hospital
# $6 = Lahey_Hospital_and_Medical_Center
# $7 = Massachusetts_General_Hospital
# $8 = Mount_Auburn_Hospital
:                                     $1   $2  $3    $4   $5   $6    $7    $8 :=
Beth_Israel_Deaconess_Medical_Center   0    0   0     0    0    0     0     0
Boston_Medical_Center                  0    0   0     0    0    0     0     0
Brigham_and_Womens_Faulkner_Hospital  97    0   0     0    0  168     0     0
Brigham_and_Womens_Hospital            0    0   0     0    0    0     0     0
Carney_Hospital                        0    0   0    17    0    0     0     0
Lahey_Hospital_and_Medical_Center      0    0   0     0    0    0     0     0
Massachusetts_General_Hospital         0    0   0     0    0    0     0     0
Mount_Auburn_Hospital                  0    0   0     0    0    0     0     0
New_England_Baptist_Hospital           0    0   0     0    0    0     0     0
Tufts_Medical_Center                   0   64   0   183    0    0   257    55

# $1 = New_England_Baptist_Hospital
:                                     $1  Tufts_Medical_Center    :=
Beth_Israel_Deaconess_Medical_Center    0           0
Boston_Medical_Center                   0           0
Brigham_and_Womens_Faulkner_Hospital    0           0
Brigham_and_Womens_Hospital             0           0
Carney_Hospital                       851           0
Lahey_Hospital_and_Medical_Center       0           0
Massachusetts_General_Hospital          0           0
Mount_Auburn_Hospital                   0           0
New_England_Baptist_Hospital            0           0
Tufts_Medical_Center                    0           0
```


Figure 11: AMPL Result for second Scenario (Contd.)

```
Total_Cost = 3157940

Setup_Cost = 1739540

Production_Cost = 531750

Transportation_Cost = 28985.2

Operating_Cost = 857670

num_equip [*] :=
Beth_Israel_Deaconess_Medical_Center  0
              Boston_Medical_Center  0
  Brigham_and_Womens_Faulkner_Hospital  1
          Brigham_and_Womens_Hospital  0
                      Carney_Hospital  1
    Lahey_Hospital_and_Medical_Center  0
        Massachusetts_General_Hospital  0
                Mount_Auburn_Hospital  0
          New_England_Baptist_Hospital  0
                 Tufts_Medical_Center  1
;

ampl: |
```

Figure 12: AMPL Result for second Scenario(Contd.)

The result for the transportation problem is shown in Table 5.

Own Demand (blue) Product Shipped (yellow)

KNEE IMPLANT

Hospital	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	SUPPLY
Brigham and Women's Faulkner Hospital	162			909	135			178			1384
Tufts Medical Center		221	246	1		89	71		78		706
Carney Hospital				49						23	72
DEMAND	162	221	246	959	135	89	71	178	78	23	

HIP IMPLANT

Hospital	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	SUPPLY
Brigham and Women's Faulkner Hospital	75				97			168			340
Tufts Medical Center		183	257			64	55		76		635
Carney Hospital		17		851						5	873
DEMAND	75	200	257	851	97	64	55	168	76	5	

Table 5: Solution to Balanced Transportation Problem for Knee and Hip Implant

VIII. DISCUSSION

i. First Scenario

According to the developed algorithm, the model chose the hospitals with highest demands as AM centers. This would essentially reduce the transportation cost, as higher the demand more would be the transportation cost if the product would be shipped to such high demand hospitals. The allocation of AM centers also depended on other factors like operating cost and number of allowable equipment.

The operating costs for hospitals depended on the processing time and production volume. As shown in Figure 9, Massachusetts General Hospital (MGH) was not selected as an AM center even though it had a higher demand than most of the hospitals. This was because the operating cost for MGH was higher than most hospitals. Similarly, Carney hospital, with a comparatively small demand, was selected as an AM center because it had the lowest operating cost of all the hospitals.

The constraint for maximum allowable number of equipment was set to 5. The amount of equipment assigned to the selected AM center/s was estimated based on the demand of that AM center/s. As seen from the results, New England Baptist Hospital (NEBH) with the highest demand was assigned an AM center with 5 equipment. This enabled NEBH to fulfill its own demands for bio-implants. The surplus production was shipped to the other demand hospitals with optimal distances.

ii. Second Scenario

As explained in Section V, the demand for implants in hospitals was reduced by approximately 70%. Also, the number of maximum allowable equipment was set to 1.

Similar to the first scenario, the assignment of AM centers was based on the demand, operating costs and the number of equipment. However, contrary to scenario 1, NEBH was not assigned an AM center, even though it had the highest demand among the selected hospitals. This was because the operating cost at NEBH was comparatively higher than other hospitals.

IX. FUTURE SCOPE AND IMPROVEMENT

One of the limitations of additive manufacturing is the amount of emissions and greenhouse gases produced while operating the 3D printer. Furthermore, transportation also contributes to GHG emissions. These can be controlled by adding a constraint which would enable the model to select the number of equipment/s with respect to the allowable amount of emissions set by Massachusetts authorities. Similarly, a constraint can be added to control the emissions caused by transportation which would factor in the assignment of AM centers.

In this study, it has been considered that the average weight of knee implants is 1.5 pounds and that of hip implants is 4 pounds. But as the parts are custom made, the weight of each individual implant would be different. This would also affect the production time and production cost. Furthermore, the weight of each individual implant could be categorized as total knee/hip replacement implant and partial knee/hip replacement implant. This would assist in using the actual weight data for cost calculation.

Finally, for the scope of this project, the demand for implants was considered for 10 out of 52 hospitals in Massachusetts. This model can be further detailed if the demand data for 52 hospitals is considered.

X. References

1. **ASTM International.** *ASTM F2792-12a - Standard Terminology for Additive Manufacturing Technologies.* 2015.

2. **Angrish, Atin.** 3D Printing In Biomedical Applications: Overview And Opportunities. *Med Device Online.* [Online] November 14, 2013. https://www.meddeviceonline.com/doc/d-printing-in-biomedical-applications-overview-and-opportunities-0001.

3. **Matthew Chin Heng Chua, Chee-Kong Chui.** Optimization of Patient-Specific Design of Medical Implants for Manufacturing. *Science Direct.* 2016, Vol. 40.

4. *Innovations in 3D printing: a 3D overview from optics to organs.* **Carl Schubert, Mark C van Langeveld, Larry A Donoso.** s.l. : British Journal of Ophthalmology, 2014, Vol. 98.

5. **Larson, Lisa M.** New, evidence-based tool to help osteoarthritis patients decide on hip, knee replacement. *UMass Medical School Communications.* [Online] May 23, 2016. [Cited: 11 28, 2018.] https://www.umassmed.edu/news/news-archives/2016/05/new-evidence-based-tool-to-help-osteoarthritis-patients-decide-on-hip-knee-replacement/.

6. **Kurtz S, Ong K, Lau E, Mowat F, Halpern M.** Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. *The Journal of Bone and Joint Surgery-American Volume.* 2007, Vol. 84, 4.

7. **Center for Health Information and Analysis. *Mass.gov.* [Online] https://www.mass.gov/orgs/center-for-health-information-and-analysis.**

8. 3D Systems. DMP Flex 350. *3D Systems.* [Online] 3D Systems. [Cited: 11 30, 2018.] https://www.3dsystems.com/3d-printers/dmp-flex-350.

9. —. 3D Systems Launches DMP Flex 350 and DMP Factory 350 Metal Printers at Formnext 2018 – Platform Approach Serving as Catalyst for Manufacturing Transformation. *3D Systems.* [Online] 3D Systems. [Cited: 11 30, 2018.] https://www.3dsystems.com/press-releases/3d-systems-launches-dmp-flex-350-and-dmp-factory-350-metal-printers-formnext-2018.

10. Cost Helper Inc. Desktop Computer Cost. *Cost Helper Inc.* [Online] Cost Helper Inc. [Cited: 11 30, 2018.] https://electronics.costhelper.com/computers-desktop.html.

11. Dassault Systems. How to Buy. *Solidworks.* [Online] Dassault Systèmes SolidWorks Corporation. [Cited: 11 30, 2018.] https://www.solidworks.com/how-to-buy.

12. Indeed. Mechanical Designer Salaries in Massachusetts. *Indeed* . [Online] Indeed. [Cited: 11 30, 2018.] https://www.indeed.com/salaries/Mechanical-Designer-Salaries,-Massachusetts.

13. —. 3d Printing Technician Salaries in the United States. *Indeed.* [Online] Indeed. [Cited: 11 30, 2018.] https://www.indeed.com/salaries/3d-Printing-Technician-Salaries.

14. Bureau of Labour Statistics. *Average Energy Prices In Boston-Cambridge-Newton – October 2018.* Boston : United States Department of Labour, 2018.

15. *Systematic proposal to calculate price of prototypes manufactured through rapid prototyping an FDM 3D printer in a university lab.* Carlos Henrique Pereira Mello, et.al. 6, s.l. : Emerald Group Publishing Limited, 2010, Vol. 16.

16. Google Corporation. Google Maps. *Google Maps.* [Online] Google Corporation. [Cited: 11 30, 2018.] https://developers.google.com/maps/documentation/ios-sdk/reference/interface_g_m_s_address.

17. Endres, Jim. *Want to Optimize Your Fleet? Know Your Average Trucking Cost Per Mile.* s.l. : Paragon Software Systems, Inc, 2016.

18. Bal, Sonny. Dr.Bal Orthopeadics. *Hip and Knee Implant.* [Online] [Cited: 11 30, 2018.] https://www.hipandknee.com/.

XI. APPENDIX

Appendix A: Demand of Bio-implant at Hospitals in Massachusetts

Hospital	County	City	Knee	Hip
Sturdy Memorial Hospital	Bristol	Attleboro	219	64
Nashoba Valley Medical Center	Middlesex	Ayer	8	8
Fairview Hospital	Berkshire	Barrington	31	2
Northeast Hospital	Essex	Beverly	591	319
New England Baptist	Suffolk	Boston	3197	2836
MGH	Suffolk	Boston	820	857
Beth Israel Deaconess Medical Center (East)	Suffolk	Boston	470	317
Boston Medical Center	Suffolk	Boston	297	214
Brigham and Women's Faulkner Hospital	Suffolk	Boston	538	251
Tufts Medical Center	Suffolk	Boston	261	252
Brigham and Women's Hospital	Suffolk	Boston	737	666
St. Elizabeth's Medical Center	Suffolk	Brighton	208	125
Good Samaritan Medical Center	Plymouth	Brockton	324	241
Signature Healthcare Brockton Hospital	Plymouth	Brockton	183	100
Lahey Hospital & Medical Center	Middlesex	Burlington	594	561
Mount Auburn Hospital	Middlesex	Cambridge	236	182
CHA Cambridge Hospital campus	Middlesex	Cambridge	257	174
Emerson Hospital	Middlesex	Concord	248	46
Steward Carney Hospital	Suffolk	Dorchester	76	18
Southcoast Hospitals Group	Bristol	Fall River	696	613
Saint Anne's Hospital	Bristol	Fall River	424	209
Falmouth Hospital	Branstable	Falmouth	288	224
MetroWest Medical Center	Middlesex	Framingham	193	110
Henry Heywood Memorial Hospital	Worcester	Gardner	76	18
Baystate Franklin Medical Center	Franklin	Greenfield	50	10
Holyoke Medical Center	Hampden	Holyoke	98	30
Cape Cod Hospital	Branstable	Hyannis	392	356
Healthalliance Hospitals	Worcester	Lancaster	128	45
Lawrence General Hospital	Essex	Lawrence	211	128
Lowell General Hospital	Middlesex	Lowell	619	301
Marlborough Hospital	Middlesex	Marlborough	139	11
Hallmark Health System	Middlesex	Medford	208	125
Steward Holy Family Hospital	Essex	Methuen	274	191
Milford Regional Medical Center	Worcester	Milford	122	39
Beth Israel Deaconess Hospital	Norfolk	Milton	449	322
Beth Israel Deaconess Hospital-Needham	Norfolk	Needham	14	56
Anna Jaques Hospital	Essex	Newburyport	227	45
Newton-Wellesley Hospital	Middlesex	Newton	473	636
Cooley Dickinson Hospital	Hamshire	Northampton	236	170
Steward Norwood Hospital	Norfolk	Norwood	183	100
Martha's Vineyard Hospital	Dukes	Oak Bluffs	3	3
Baystate Wing Hospital	Hampden	Palmer	49	11
Berkshire Medical Center	Berkshire	Pittsfield	357	293
Beth Israel Deaconess Hospital- Plymouth	Plymouth	Plymouth	368	101
North Shore Medical Center Salem Hospital	Essex	Salem	535	278
Harrington Hospital	Worcester	Southbridge	65	17
Baystate Medical Center	Hampden	Springfield	647	465
Mercy Medical Center	Hampden	Springfield	322	239
Morton Hospital	Bristol	Taunton	97	29
Baystate Mary Lane Hospital	Hamshire	Ware	2	2
Baystate Noble Hospital	Hampden	Westfield	35	7
South Shore Hospital	Norfolk	Weymouth	491	408
Winchester Hospital	Middlesex	Winchester	423	255
UMass Memorial Medical Center	Worcester	Worcester	490	407
Saint Vincent Hospital	Worcester	Worcester	526	556
		Total	19205	14043

Appendix B: Distances between network of selected Hospitals

Hospital	Brigham and Women's Faulkner Hospital	Brigham and Women's Hospital	Massachusetts General Hospital	New England Baptist Hospital	Beth Israel Deaconess Medical Center	Boston Medical Center	Mount Auburn Hospital	Lahey Hospital and Medical Center	Tufts Medical Center	Carney Hospital
Brigham and Women's Faulkner Hospital	0	3.3	7	3.3	3.1	5.2	7.5	22.1	6	5.1
Brigham and Women's Hospital	3.3	0	3.3	3.4	0.7	2.4	4	22.9	2.7	6.7
Massachusetts General Hospital	7	3.3	0	3.9	5.4	4.2	5.9	16.4	1.4	9
New England Baptist Hospital	3.3	3.4	3.9	0	3.9	2.6	21.2	23.1	2.8	6.7
Beth Israel Deaconess Medical Center	3.1	0.7	5.4	3.9	0	2.9	4.7	23.2	3	6.6
Boston Medical Center	5.2	2.4	4.2	2.6	2.9	0	7.4	18.8	1.3	6.5
Mount Auburn Hospital	7.5	4	5.9	21.2	4.7	7.4	0	16.2	5.5	12
Lahey Hospital and Medical Center	22.1	22.9	16.4	23.1	21.2	18.8	16.2	0	25	35
Tufts Medical Center	6	2.7	1.4	2.8	3	1.3	5.5	25	0	6.6
Carney Hospital	5.1	6.7	9	6.7	6.6	6.5	12	35	6.6	0