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Cost Minimization of Artificial Hip Bone Implantation Surgery by Adopting Additive Manufacturing Technique and Its Feasibility Assessment

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A B S T R A C T

Osteoarthritis (OA) of the hip is the most common joint disease in elderly people and associated with significant physical disability. Pain relief is a primary treatment of hip OA. When the patient with hip OA has failed medical treatment modalities and remains in pain, the patient should be referred for hip replacement surgery in which the damaged surfaces of the joint is removed and replaced with a set of artificial ball-and-socket implants. In this research, a proposition for Additive Manufacturing (AM) is advocated to produce the bone implant to enhance the customer satisfaction along with minimization of costs. AM primarily differs from traditional material removal process because it creates product by successive deposits of material layer by layer. Because of this difference, the cost and operational methodologies are distinct from traditional manufacturing. For this reason, additive manufacturing is adopted for this artificial bone manufacturing and a stochastic optimization model is proposed to help a manufacturer decide when AM is best for them.

Keywords: Biomedical implants, Additive manufacturing, Supply chain, Cost analysis, Stochastic programming model.

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1. Introduction

The burden of musculoskeletal conditions is rising all over the world, Osteoarthritis (OA) is one of them which causes pain in the limb. In a healthy person, the bones joints are cushioned by cartilage, allowing for unconstrained movement of the joint. With OA, the cartilage breaks down and as the cartilage deteriorates, bone rubs on bone, resulting in pain and reduced mobility. Pain relief is a primary goal in treating of these patients. In the critical stage of OA, the medical treatment fails and patients remain in pain with limitations of physical function in daily life. This patients would be helped best with a surgery in which an artificial bone implant is replaced to match their anatomy. For this bone implantation surgery most of the patients of Bangladesh either go to abroad or the manufacturing of the bone implants is held in other country and they are purchased with a high transportation cost. In both cases the whole process of surgery is very costly and time consuming. For this reason we need a convenient process that can be proven as a very supportive way of enhancing customer satisfaction by minimizing the cost of artificial bone implant.

In this case, Additive Manufacturing (AM) can be proposed as an effective way. AM is a collection of modern technologies which creates products by the addition of layers in the third dimension instead of subtracting or forming material, which are used in other manufacturing methods. Huang et al. [2] discussed that additive manufacturing can produce a final product in one build, there is limited exposure to hazardous conditions and there is little hazardous waste. According to Tuck and Hague [3], by being a very strong enabler of product customization, 3D printing can have remarkable impacts on downstream sections of the supply chain, such as production and distribution. A study on 3d printing and its future, Koff and Gustafson [4] said that the most inspiring use of 3D printing is in the healthcare industry, where 3D printing has the potential to save lives or dramatically improve them. It is designed to print bone joint and tissue structures using data from medical scans, such as CT or MRI. Jia et al. [1] showed the difference between two business model for the chocolate industry for both standard and customized product. 3D chocolate printing provides the technology for manufacturing chocolates layer-by-layer, thus offering customers enhanced product value and personalized consumption experience.

This research work discusses the additive manufacturing in perspective of Bangladesh for artificial hip bone implantation surgery. By introducing additive manufacturing this research reveals the possibilities of increasing capacity, reduction of cost and time in hip replacement surgery.

The rest of the paper is organized as follows. Mathematical model is explained in Section 2. Numerical illustrations are presented in Section 3. Concluding remarks are given in the last section.

2. Mathematical Model

2.1. Mathematical Statement

In this section a stochastic cost model is developed to quantify the supply-chain level costs associated with the production of artificial hip implants using both traditional manufacturing and AM technologies and investigated the economic feasibility of using these technologies to fabricate hip implants in Bangladesh. This model mainly focused on modeling system-level costs such as inventory, transportation the effects of product lead time on the overall transportation costs.

2.2. Model Formulation

Let's consider a scenario where a set of customers (C) need a set of products (I) in a set of time periods (T). The products (I) can be manufactured by a set of traditional manufacturing plants (P) and a set of Additive manufacturing plants (A). Both traditional and additive manufacturing plants receive product materials from a group of suppliers (S). There are costs associated with supplier selection, product transportation, facilities opening and operating, inventory management, and production. Our approach here is to design an effective supply chain considering possible use of traditional manufacturing system or additive manufacturing systems. We have developed a MILP model to get optimal configuration of a supply chain variant.

Sets. a: Set of additive manufacturing plants; c: set of customers; i: set of products; p: set of traditional manufacturing plants; s: set of suppliers; t: set of time periods; w: set of warehouse.

General Parameters.

- $demand_{it}$: demand of product.
- $mfg\_capacity_{pit}$: TM plant capacity.
- $mfg\_var\_cost_{pit}$: TM variable cost.
- $mfg\_oper\_cost_{pit}$: TM plant operation cost.
- $mfg\_open\_cost_{p}$: TM opening cost.

Distribution Parameters.

- wh_var_costwit: warehouse variable cost.
- wh_oper_costwit: warehouse operating cost.
- wh_open_costw: warehouse opening cost.

Supply Parameters.

- $supplier\_capacity_{sit}$: supplier capacity.
- $tsupplier\_cost_{sit}$: supplier unit cost for TM plant.
- $amsupplier\_cost_{sit}$: supplier unit cost for AM plant.

Additive Manufacturing Parameters.

- am_mach_hoursat: AM machine capacity.
- am_cap_usageit (w): hours to build 1 product.
- am_oper_costait: AM plants operating cost.
- am_mach_purchcostait: AM machine purchase cost.
- am_mat_costt (w): AM materials cost per KG.
- am_mat_usageit: AM materials usage per product.
- am_open_costa: AM location opening cost.
- am_var_costait: AM variable cost.

Transportation Parameters.

- $am\_trans\_cost_{acit}$: unit transportation cost from AM location to customer.
- $ib\_trans\_cost_{pwit}$: unit transportation cost from TM plant to warehouse.
- $ob\_trans\_cost_{pwit}$: unit transportation cost from warehouse to customer.
- $tsupply\_trans\_cost_{spit}$: unit transportation cost from supplier to TM plant.
- $amsupply\_trans\_cost_{sait}$: unit transportation cost from supplier to AM plant.

Inventory Parameters.

- aii_a: AM plant's starting inventory.
- $inventory\_hold\_cost_i$: holding cost.
- pii_p: TM plant's starting inventory.
- wii_w: warehouse starting inventory.
- M: a sufficiently large number.

Integer Decision Variables.

- aii_{ait}: AM starting inventory.
- aei_{ait}: AM ending inventory.
- pii_{pit}: TM starting inventory.
- pei_{pit}: TM ending inventory.
- wii_{wit}: warehouse starting inventory.
- wei_{wit}: warehouse ending inventory.
- fsp_{spit}: supply of materials for product i from supplier s to manufacturer p at time t.
- fsa_{sait}: supply of materials for product i from supplier s to AM plant a at time t.
- fpw_{pwit}: supply of product i from TM plant p to warehouse w at time t.
- fwc_{wcit}: supply of product i from warehouse w to customer c at time t.
- fac_{acit}: supply of product i from AM plant a to customer c at time t.
- $am\_oper\_machines_{ait}$: number of AM machines operating at time t to produce i.
- $am\_production_{ait}$: no. of product i is produced by AM plant a at time.
- p_production (P, I, T): no. of product i is produced by TM plant p at time t.

Binary Decision Variables.

- y_{wcit} =1 if customer c gets supply of product i from warehouse w at time t.
- z_{acit} =1 if customer c gets supply of product i from Additive manufacturing plant at time t.
- x_{wcit} =1 if warehouse w is open for product i at time t.
- xa_{ait} =1 if Additive manufacturing plant a is open for product i at time t.
- xp_{pit} =1 if traditional manufacturing plant p is open for product i at time t.
- sp_{spit} =1 if supplier s supplies material for product i to plant p at time t.
- sa_{sait} =1 if supplier s supply material for product i to AM plant a at time t.

The formulation is the following:

Minimize

$$\sum_{s \in S} \sum_{p \in P} \sum_{i \in I} \sum_{t \in T} tsupply\_trans\_cost_{spit} * fsp_{spit} + \sum_{p \in P} \sum_{w \in W} \sum_{i \in I} \sum_{t \in T} ib\_trans\_cost_{pwit} * fpw_{pwit} + \sum_{w \in W} \sum_{c \in C} \sum_{i \in I} \sum_{t \in T} ob\_trans\_cost_{wcit} * fwc_{wcit} + \sum_{a \in A} \sum_{c \in C} \sum_{i \in I} \sum_{t \in T} am\_trans\_cost_{acit} * fac_{acit} + \sum_{w \in W} \sum_{i \in I} \sum_{t \in T} wei_{wit} * inventory\_hold\_cost_{i} + \sum_{p \in P} \sum_{i \in I} \sum_{t \in T} pei_{pit} * inventory\_hold\_cost_{i} + \sum_{a \in A} \sum_{i \in I} \sum_{t \in T} aei_{pit} * inventory\_hold\_cost_{i} + \sum_{a \in A} \sum_{i \in I} \sum_{t \in T} am\_var\_cost_{ait} * am\_production_{ait} + \sum_{p \in P} \sum_{i \in I} \sum_{t \in T} mfg\_var\_cost_{pit} * p\_production_{pit} + \sum_{p \in P} \sum_{i \in I} \sum_{t \in T} xp_{pit} * mfg\_open\_cost_{p} + \sum_{a \in A} \sum_{i \in I} \sum_{t \in T} xa_{ait} * am\_open\_cost_{a} + \sum_{w \in W} \sum_{i \in I} \sum_{t \in T} xw_{wit} * wh\_open\_cos_{w} + \sum_{s \in S} \sum_{p \in P} \sum_{i \in I} \sum_{t \in T} tsupplier\_cost_{sit} * sps_{pit} + \sum_{s \in S} \sum_{a \in A} \sum_{i \in I} \sum_{t \in T} amsupply\_cost_{sit} * sa_{sait} + \sum_{p \in P} \sum_{i \in I} \sum_{t \in T} mfg\_oper\_cost_{pit} * xp_{pit} + \sum_{a \in A} \sum_{i \in I} \sum_{t \in T} am\_oper\_cost_{ait} * xa_{ait} + \sum_{w \in W} \sum_{i \in I} \sum_{t \in T} wh\_oper\_cost_{wit} * xw_{wit}. \quad (1)$$

The objective function is to minimize total supply chain cost.

Subject to

$$\sum_{w \in W} \sum_{i \in I} y_{wcit} + \sum_{a \in A} \sum_{i \in I} z_{acit} = 1. \quad (2)$$

Every customer is served by either warehouse or AM plant

$$xw_{wit} \geq y_{wcit}. \quad (3)$$

If a customer is assigned to a warehouse then that warehouse must be up

$$xa_{ait} \geq z_{acit}. \quad (4)$$

If a customer is assigned to a AM plant then that plant must be up

$$fwc_{wcit} = y_{wcit} * demand_{cit}. \quad (5)$$

Amount of flow from warehouse w to customer c for product i at time t

$$fac_{acit} = z_{acit} * demand_{cit}. \quad (6)$$

Amount of flow from Additive manufacturing plant a to customer c for product I at time t

$$wii_{wit} + \sum_{p \in P} fpw_{pwit} = wei_{wit} + \sum_{c \in C} fwc_{wcit}. \quad (7)$$

Flow balance for warehouse

$$wii_{wit} = wii_{w}. \quad (8)$$

At time t = 1 every warehouse has a given inventory

$$wii_{wit} = wei_{wi(t-1)}. \qquad (9)$$

At time t > 1 initial inventory is the ending inventory of t-1 time period

$$pii_{pit} + \sum_{s \epsilon S} fsp_{spit} = pei_{pit} + \sum_{w \epsilon W} fpw_{pwit}. \qquad (10)$$

Flow balance for traditional plant

$$pii_{wit} = pii_{p}. \qquad (11)$$

At time t =1 every manufacturing plant has a given inventory

$$pii_{wit} = pei_{pi(t-1)}. \qquad (12)$$

At time t > 1 initial inventory is equivalent to the ending inventory of t-1 time period

$$aii_{pit} + \sum_{s \epsilon S} fsa_{sait} = aei_{ait} + \sum_{c \epsilon C} fac_{acit}. \qquad (13)$$

Flow balance for Additive manufacturing

$$aii_{ait} = aii_{a}. \qquad (14)$$

at time = 1 AM plant has a given inventory

$$aii_{ait} = aei_{ai(t-1)}. \qquad (15)$$

At time t > 1 initial inventory of AM plant is equivalent to the ending inventory of t-1 time period

$$pii_{pit} + \sum_{w \epsilon W} fpw_{pwit} - pei_{pit} \leq mfg\_capacity_{pit}. \qquad (16)$$

Capacity constraint for traditional factory

$$aii_{pit} + \sum_{c \epsilon C} fac_{acit} - aei_{ait} \leq am\_mach\_hours_{ait} * am\_oper\_machines_{ait}/am\_cap\_usage_{it}. \qquad (17)$$

Capacity constraint for Additive manufacturing plant

$$\sum_{a \epsilon A} fsa_{sait} + \sum_{p \epsilon P} fsa_{spit} \leq supplier\_capacity_{sit}. \qquad (18)$$

Capacity constraint for supplier

$$am\_production_{ait} = aii_{ait} + \sum_{c \epsilon C} fac_{acit} - aei_{ait}. \qquad (19)$$

Total production at AM plant at time t

$$p\_production_{pit} = pii_{ait} + \sum_{w \epsilon W} fpw_{pwit} - pei_{ait}. \quad \textbf{(20)}$$

Total production at traditional plant at time t

$$p\_production_{pit} \leq xp_{pit} * M. \quad \textbf{(21)}$$

If there is a production from a traditional plant than that traditional plant must be up

$$am\_production_{pit} \leq xa_{pit} * M. \quad \textbf{(22)}$$

If there is a production from a AM plant than that AM plant must be up

$$fsa_{sait} \leq sa_{sait} * M. \quad \textbf{(23)}$$

If there is a flow from a supplier to a AM plant then that supplier-plant relation is on

$$fsp_{spit} \leq sp_{spit} * M. \quad \textbf{(24)}$$

If there is a flow from a supplier to a traditional plant then that supplier-plant relation is on

$$am\_oper\_machines_{ait} = am\_production_{ait} / am\_mach\_hours_{ait}. \quad \textbf{(25)}$$

Number of AM machines required to run at time t in AM plant.

3. Numerical Illustration

In this section, data gathered from the professionals and 6Axis technologies are applied to the above model and solved by using the GAMS software to find the best possible solution. The input data and result of the decision variables are given in ***Table 1*** and ***Table 2***. Finally the total supply chain costs of both models are presented in ***Table 3***.

From ***Table 2*** and ***Table 3*** it can be seen that both the starting and ending inventory of AM plant remains zero because this plant anticipates only by the customer demand. On the other hand TM plant maintains the production schedule by forecasting demand based on different specification of hip prosthesis. Another advantage of AM plant is that there is no need of warehouse in this plant, which also reduces the total supply chain cost. Finally the additive manufacturing technology maintains the quicker response with respect to customer demand compared to the TM plant.

So, based on the above analysis it can be said that Additive manufacturing is economically feasible for the production of artificial hip implant as the total supply chain cost of AM plant is lower than that of TM plant.

Table 1. Input parameter.

General Parameters	Unit	AM Parameters	Unit
	238	$am\_mach\_hours_{at}$	2400
$demand_{it}$	364	$am\_cap\_usage_{it(w)}$	1
	201	$am\_oper\_cost_{ait}$	34000 BDT
	169	$am\_mach\_purchcost_{ait}$	35000000 BDT
$mfg\_capacity_{pit}$	1000	$am\_mat\_cost_{t(w}$	37100
$mfg\_var\_cost_{pit}$	63615 BDT	$am\_mat\_usage_{it}$	1.3kg
$mfg\_oper\_cost_{pit}$	354000 BDT	$am\_open\_cost_{a}$	11500 BDT
$mfg\_open\_cost_{p}$	108300000 BDT	$am\_var\_cost_{ait}$	48200 BDT
Distribution Parameters		Supply Parameters	
			12000
			10500
$wh\_var\_cost_{wit}$	2670 BDT	Supplier capacity	10000
			9000
$wh\_oper\_cost_{wit}$	10000 BDT		
			19824
$wh\_open\_cost_{w}$	640000 BDT		15310
		Supplier unit cost for TM plant	
Transportation Parameters			14500
			10450
$am\_trans\_cost_{acit}$	0.00	$ob\_trans\_cost_{pwit}$	40000 BDT
$ib\_trans\_cost_{pwit}$	50 BDT		
$inventory\_hold\_cost_{i}$	100 BDT		

Table 2. Solution of integer decision variables.

Results	Unit		
	Period 1	Period 2	Period 3
aii_{ait}	0	0	0
aei_{ait}	0	0	0
pii_{pit}	1200	1200	0
pei_{pit}	1200	0	0
wii_{wi}	500	219	1074
wei_{wit}	219	1074	727
fsp_{spit}	5400	5675	5400
fsa_{sait}	345	448	451
fpw_{pwit}	0	1200	0
fac_{acit}	69	92	78
	112	127	125
	57	71	73
	43	55	71
$am\_oper\_machines_{ait}$		1	
$am\_production_{ait}$	281	345	347
p_production	0	2400	0

Table 3. MIP solution of total supply chain cost.

TM Plant	AM Plant
283291370.00	88879156.00

4. Conclusion

In conclusions it can be said that, we have developed a stochastic optimization model to quantify the supply-chain level costs associated with the production of artificial hip implants and investigated the economic feasibility. Then we have formulated the programming code using GAMS software and the MIP solution of the two models given the result that additive manufacturing would be economically beneficial for the production of artificial hip bone implants.

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