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Simplex Method for Solving Maximum Problems in Linear Programming

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Abstract: In this paper, the simplex method in linear programming is discussed for solving maximum problems with constraints. The simplex method is a general mathematical solution technique for solving linear programming problems. In the simplex method, the model is put into the form of a table, and then a number of mathematical steps are performed on the table. This simplex method is an algebraic procedure in which a series of repetitive operations are used to reach the optimal solution.

Keywords: simplex method; liner programming; objective function; optimal solution; algebraic procedure

1. INTRODUCTION

Optimization principles are of basic importance in modern Engineering design and systems operation in various areas. Optimization problems have both constrained optimization (Gradient method) and unconstrained optimization (linear programming). Graphical method and simplex method are two methods for solving Linear programming problems. For linear programming problems involving two variables, the graphical solution method is convenient. However, for problems involving more than two variables or problems involving a large number of constraints, it is better to use solution methods that are adaptable to computers. One such method is called the simplex method. A linear program is a method of achieving the best outcome given a maximum or a minimum equation with linear constraints. To solve linear programming problems in three or more variables, we can use the simplex method.

2. METHOD

The simplex method can be applied for solving the maximum problem. The necessary steps are explained in the followings.

Step (1): Set up simplex tableau using slack variables.
Step (2): Locate pivot value
 (i) Look for negative indicator in first row.
 (ii) For the value in this column, divide the far right column by each value to find a "test ratio".
 (iii) The value with the smallest non negative "test ratio" is pivot.
Step (3): Pivot to find a new tableau.
Step (4): Repeat steps 2 & 3 if necessary, Goal: no negative indicators in the first row.
Repeat steps 2 & 3 until all numbers on the first row are positive.
Step (5): Read the solution.

3. PROBLEM SOLVING

A standard maximum problem is discussed in this paper. The following steps are needed to do before solving the problem.
(a).z is to be maximized
(b). All variables, $x_1, x_2, x_{3,} \ldots, \geq 0$
(c).All constraints are "less than or equal to (i.e. $\leq$)

$$\text{Maximize,} \quad z = 40x_1 + 88x_2$$
$$\text{subject to the constraints,} \quad 2x_1 + 8x_2 \leq 60$$
$$5x_1 + 2x_2 \leq 60$$
$$x_1 \geq 0, x_2 \geq 0$$

Next, the first two inequalities are converted to linear equations by introducing two slack variables .Together with the objective function, written as an equation,
z - 40x1- 88x2 = 0.
The normal form is

$$z - 40x_1 - 88x_2 = 0$$
$$2x_1 + 8x_2 + x_3 = 60$$
$$5x_1 + 2x_2 + x_4 = 60$$
$$x_1 \geq 0, x_2 \geq 0, x_3 \geq 0, x_4 \geq 0.$$

3.1 Simplex Tableau

To find an optimal solution of it, its augmented matrix must be considered. This is called the "simplex tableau".

$$T_0 = \begin{array}{c} \\ \end{array}\begin{array}{cccccc} z & x_1 & x_2 & x_3 & x_4 & b \end{array}$$
$$T_0 = \begin{bmatrix} 1 & -40 & -88 & 0 & 0 & 0 \\ 0 & 2 & 8 & 1 & 0 & 60 \\ 0 & \boxed{5} & 2 & 0 & 1 & 60 \end{bmatrix}$$

3.2 Selection of Pivot

Most negative indicator is found in first row, and then the value in this column divide the far right column of each value to find a test ratio. The value with the smallest non negative "test ratio" is pivot. So, the values are shown in below.

$$\frac{60}{2} = 30, \frac{60}{5} = 12$$

Among them, the smallest value is 12. Thus, pivot is 5.

3.3 Elimination by Row Operation

Matrix is altered by using some restricted row operations. One of the entries in the tableau is used as a pivot. The aim is to make all of other elements in the column with the pivot equal to zero. The elements in a row are multiplied by a nonzero constant and added a multiple of one row to the elements of a multiple of any other row.

$$T_2 = \begin{array}{c} \\ \end{array}\begin{array}{cccccc} z & x_1 & x_2 & x_3 & x_4 & b \\ \end{array}$$

$$T_2 = \begin{bmatrix} 1 & 0 & -72 & 0 & 8 & 480 \\ 0 & 0 & 7.2 & 1 & -0.4 & 36 \\ 0 & 5 & 2 & 0 & 1 & 60 \end{bmatrix} R_1 + 8R_3 \text{ and } R_2 - 0.4R_3$$

When a simplex tableau is considered, it may be able to spot basic variables. A basic variable is a variable that only has all zeros expect one number in its column in the tableau. One of basic feasible solution can be found by finding the value of any basic variables and then setting all remaining variables equal to zero.

Unfortunately, solutions read off of the initial simplex tableau are seldom optimal.

It can be seen that basic variables are now x_1, x_2 and non-basic variables are x_3, x_4. The basic feasible solution is given by $T_{1.}$

$$x_1 = \frac{60}{5} = 12, \quad x_2 = 0, \quad x_3 = \frac{36}{1} = 36, \quad x_4 = 0, \quad z = 480.$$

Elimination is applied only to get non negative entries in row one but the other rows aren't needed to eliminate. So, the basic feasible solution given by T_1 is not yet optimal because the non-negative entry -72 in row 1.

Accordingly, the operations are performed again to choose pivot in the column of -72. The test ratios $\frac{36}{7.2} = 5, \frac{60}{2} = 30$ are got. Select 7.2 as the pivot because it gave the smallest quotient $\frac{36}{7.2} = 5$.

By elimination of row operation gives,

$$\begin{array}{cccccc} z & x_1 & x_2 & x_3 & x_4 & b \end{array}$$

$$T_2 = \begin{bmatrix} 1 & 0 & 0 & 10 & 4 & 840 \\ 0 & 0 & 7.2 & 1 & -0.4 & 36 \\ 0 & 5 & 0 & \frac{-1}{3.6} & \frac{1}{0.9} & 50 \end{bmatrix} R_1 + 10R_2 \text{ and } R_3 - \frac{2}{7.2}R_2$$

It can be seen that basic variables are now x_1, x_3 and non-basic variables are x_2, x_4. The basic feasible solution is given by $T_{2.}$

$$x_1 = \frac{50}{5} = 10, \quad x_2 = \frac{36}{7.2} = 5 \quad x_3 = 0, \quad x_4 = 0, \quad z = 840.$$

4. RESULT

The optimum solution is found out from the above calculation. This is $z = f(10,5) = 40 \times 10 + 88 \times 5 = 840$. Since T_2 contains no more non negative entries in row 1, this is maximum possible value. This is the solution of our maximum problem by using the simplex method.

5. CONCLUSION

In this study, simplex method is applied to solve the maximum problem. The simplex method is an approach for determining the optimal value of the maximum problems. This method produces an optimal solution to satisfy the given constraints and a maximum value. To use the Simplex method, a given maximum problem needs to be in standard form. By applying the steps in this paper, an optimal solution can be obtained.

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Investigation in Human Health, Environment and Safety Aspects of Additive Manufacturing (AM) Processes

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Abstract: Environmental impacts of every manufacturing procedure are a major consideration in every industry. These impacts include human health and safety and environmental burdens which are known as vital concerns in the industrial world. Before accepting any new process as a part of manufacturing procedure, a clear landscape from every aspect of that process should be provided. Additive manufacturing (AM) is growing from a prototyping method to the level of manufacturing functional products which require specific and accurate characterization information about every step of the whole production line. In this paper, attempts are made to address environmental impacts and safety considerations of metallic AM-based processes as well as their applicable solutions. AM processes are compared to conventional manufacturing methods from environmental aspects. Moreover, the benefits of metal AM as a fabricating and repairing method are presented. In conclusion, AM potential as a substitution or even complement for conventional manufacturing methods are discussed, where safety is considered vital.

Keywords: Additive manufacturing (AM), hybrid manufacturing, life cycle inventory (LCI), human safety, environmental impacts.

1. INTRODUCTION

Every manufacturing activity has specific impact on the environment and manufacturers have attempted to lower their environmental burdens. Conventional manufacturing methods, including all types of subtractive manufacturing methods cause a lot of material and energy waste. According to International Energy Agency (IEA) [1], the electricity usage of industries are about 42% of the world electricity consumption which means any applicable method to reduce the energy consumption would be highly considered.

Additive manufacturing (AM) is defined as the process of joining materials to make objects from 3D model data, usually layer by layer, as opposed to subtractive manufacturing methodologies [2]. Metal additive manufacturing processes such as selective laser melting (SLM), electron beam melting (EBM), direct metal deposition (DMD), etc., have been accepted by many major industries such as aerospace and automotive. AM-based processes present more efficient mean to fabricate parts in low production volume such as prototypes, tools and complex parts. Also AM enable the ability to fabricate lighter parts with the same mechanical properties. This approach could also improve human safety. Another use for AM-based processes could be the utilization of AM in repairing and remanufacturing applications. This approach could reduce the volume of material and energy used for manufacturing.

In this paper, attempts are made to assess a number of AM-based processes advantages, potentials and environmental efficiencies in comparison with conventional manufacturing processes through several case studies. Furthermore, utilization of AM as a fabricating and repairing process is discussed in detail. Environmental impacts of AM are identified and some solutions and guides are proposed in order to make AM processes more efficient and green.

2. AM ENVIRONMENTAL EFFECTS

Manufacturing processes have major impact on environment and human health; therefore, they should be environmentally characterized and identified the effects. Three main manufacturing processing types are (1) Bulk-forming, (2) subtractive manufacturing and (3) additive manufacturing. In bulk-forming usually a die or mold is required. Bulk-forming is an economical way to fabricate parts with high volume rate. Subtractive processes such as all types of machining processes are building parts from a material block. These types of processes are used for medium volume rate of production of parts with medium complexity. In contrast, additive manufacturing processes build parts near-net-shape from powder or wire. AM-based processes are mostly used for complex and low volume rate of production such as tools. The main process of each method is shown in figure 1. Thanks to the new production methods, decision making for the most efficient fabrication method gets much harder. Therefore, the environmental impacts of each production method such as energy consumption of every step of manufacturing including material and equipment preparation should be taken into consideration to obtain accurate understanding about process costs. Such model is called life cycle inventory (LCI). This helps manufacturers to decide which procedure is more efficient for their production purpose. To this end, a wide LCI database for every material and process is required. Collected database would be developed as a built-in software for every AM machine in order to pick the best manufacturing strategy.

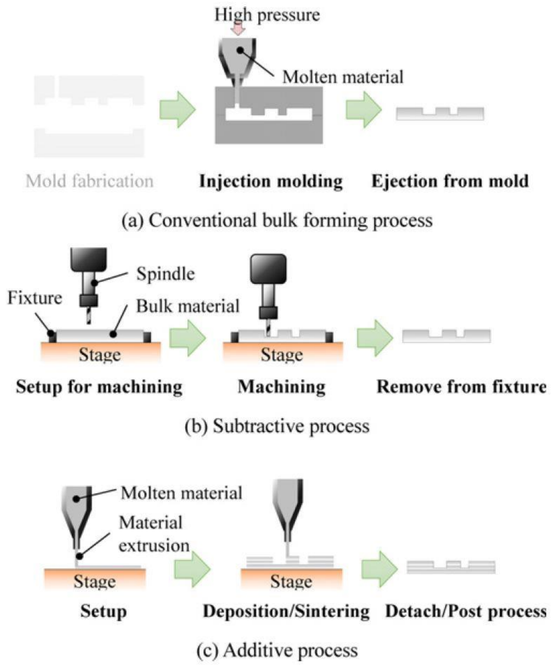

Figure. 1 Schematic diagram of the three manufacturing processes considered in this study; only the main processes were considered [3].

Several studies are dedicated to compare conventional manufacturing with AM-based manufacturing methods from environmental aspects [3, 4]. As a conclusion, fabricating parts with complex geometry which take excessive time or different processes to build and parts in low volume of production are economically and environmentally feasible to be done by AM processes. Moreover, it is forecasted that air transport will increase by 45% from 2014 to 2035 [5]. Consequently, the use of lightweight parts could cover some of the greenhouse gases produced by aircraft. One study is revealed that if weight reduction is higher than 50% and the part is used in aircraft, AM processes would be preferable [6]. The number of parts required for a module could be reduced with AM products as well as weight reduction. AM provide the ability of designing according to functionality over possibility. For example, the new fuel nozzle of jet engine made by Airbus is 50% lighter and also more efficient. It is made via AM as a single part except 20 parts in prior versions. Another study investigates efficiency of LBM process in gear fabrication and finds it energy efficient for low volume production [7].

A typical AM process procedure is shown in figure 2. Environmental effects are considered as determinant key factors in the way of part fabrication. Every step of AM processes has its own environmental impact. For example, powder production is done by several methods which mainly depend on material type and the required particle size. Also the scenario chosen for powder production is one of the most energy consuming parts of the LCI. Lutter-Guenther et al. [7] suggested choosing an efficient procedure to atomize powder for LBM process.

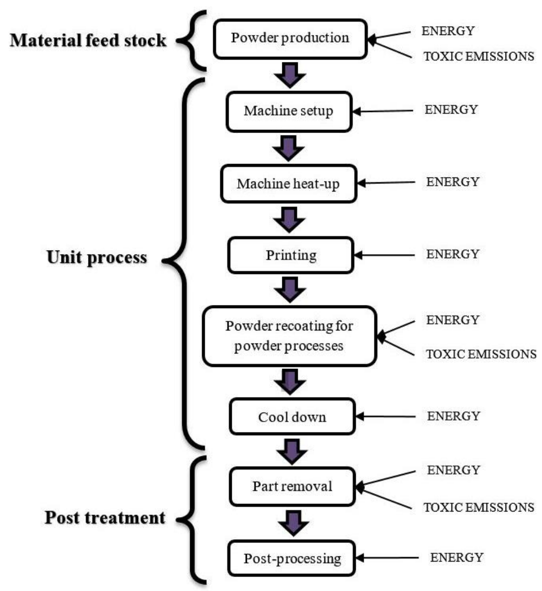

Figure. 2 A typical AM process procedure [8].

Environmental effects could be investigated from several aspects: (1) energy usage, (2) material and fluids (e.g. protective gases) usage, (3) human health and (4) harmful emissions. Every aspect should be taken into consideration in order to accurately model each one. The only way to assess these key factors is to compare them with conventional part manufacturing methods such as machining and forming. There are few studies that investigated metallic AM processes such as SLM from environmental aspects. A recent study is dedicated to compare SLM process with machining and forming process through a part fabrication case study from environmental aspects [6]. This study reveals that if weight reduction is higher than 50%, additive manufacturing approach seems to be environmentally superior. This substitution is much highlighted when the part is used in transportation systems especially in aircraft. Another study by Kafara et al. [9] showed that AM-based processes have the lowest environmental impact among other candidate processes in CFRP mold core fabrication.

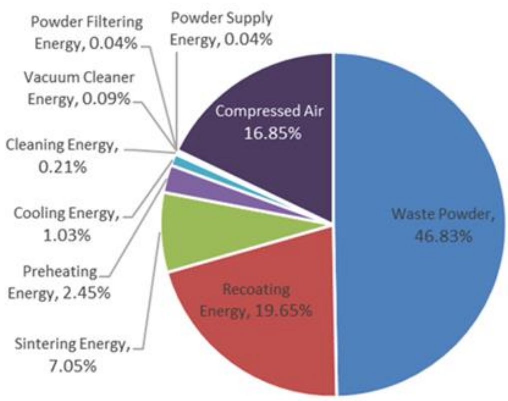

Figure. 3 Environmental impact distribution of 1 hour of SLS of PA2200 with a layer thickness of 120 μm [10].

Environmental effects of AM processes are highly related to selected process, process parameters and process equipment such as laser, building chamber volume, etc. [11]. For example, environmental impact distribution of one hour part fabrication with PA2200 setup through selective laser sintering (SLS) method with a layer thickness of 120 μm showed that up to 50% of power is wasted (see figure 3) [10]. Such model is required for other metal AM processes like SLM, DMD, etc.

As mentioned above, an accurate model is required to evaluate consuming energy and material for fabrication to decide whether AM is environmentally and economically beneficial or not [12]. It is also important to provide clear documented information about environmental effects of AM feedstock production [10]. Besides, AM processes could be used for in-house fabrication or spare parts fabrication which is effectively reduced the environmental effects by eliminating unnecessary transports [13]. As shown in figure 4 every step in conventional production methods require a transport step which is avoidable by AM methods.

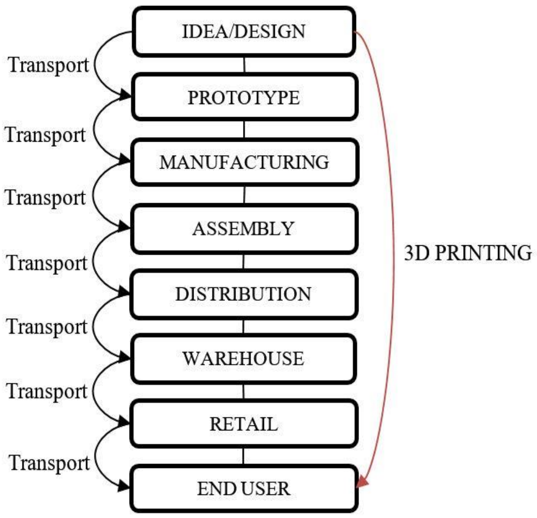

Figure. 4 Traditional versus 3D printing supply chain [13].

There are several studies developed predictive models for AM-based processes to evaluate the amount of energy and material consumed during the fabrication procedure. Kellens et al. [10] assess available LCI data and compare them for SLM and other processes as well as the impacts during material production and post-processing. Post-treatments such as detachment of part from the building plate is a part of process that neglected or underestimated during the environmental assessments most of the time. Faludi et al. [14] showed removing parts by electron discharge machining (EDM) will add more energy consumption than conventional processes. They also determined that the use of SLM machine for a single part production would not be an excellent choice. However, using of whole building plate will significantly reduce the building energy consumption. Bourhis et al. [15] developed such model for DMD process as well as powder atomization process to assess energy, fluid and material consumption used for part fabrication. A predictive model for each factor's consumption is proposed.

2.1 Electrical Consumption

Electric use of machine is divided into two main categories: (1) constant energy consumption referred to hydraulics components and electrical cabinet, (2) referred to electrical consumption due to part geometry and machine setup. The model proposed by bourhis et al. [15] is:

$$E.I._{electricity} = \left\{ \begin{matrix} g(P_l) \times t_{laser} + Pc_{standby} \times t_{man} + (Pc_{on} - Pc_{standby})t_{on} \\ + \left(\sum_{i=1}^{5} \int_0^{t_{man}} Pe_{axei}(t) \times dt) + Pe_{constant} \right) \end{matrix} \right\} \times fc_{elec} \quad (1)$$

2.2 Material Consumption

Material use during the process is highly depended on nozzle efficiency. An analytical model for this factor is developed by previous authors [15]:

$$E.I._{material} = [e_n + k \times (1 - e_n)] \times d_p \times t_{man} \times fc_{material} \quad (2)$$

Powder recycling could significantly reduce this load, however, unfused powder require treatments such as drying and sieving before reuse due to possible damages to the machine [15]. This require deeper study and experiments to find out if the recycled powder have the same characteristics of brand new powder. One study investigated in properties of Inconel 718 parts which built with recycled powder by means of SLM process [16]. The metallographic and mechanical properties of Inconel 718 remain the same as brand new powder, however, further studies are needed to confirm other mechanical properties such as fatigue.

2.3 Fluids Consumption

As mentioned previously, fluids include inert gases that add to building atmosphere to protect melting pool from oxides. Inert gas which mainly use in AM processes is argon due to its safety and price. Environmental impact of gases assess by the Eco-Indicator 99 (fc) which multiply to the proposed model below [15].

$$E.I._{fluids} = [d_c + d_f] \times t_{man} \times fc_{argon} \quad (3)$$

As indicated above, the highest environmental impact in utilization of AM is the energy consumption during the process. One solution is the combination of AM-based processes with conventional processes to obtain more efficient way to fabricate parts. A study by Paris et al. [17] developed an innovative strategy based on combination of EBM and CNC milling to reduce environmental impacts which is mainly considered as electricity consumption. In their work, existing parts are recycled to build new parts. It is believed that such combinations could be more environmentally friendly. Such combinations are known as "hybrid process". Kaplan and Samarjy [18] employed a laser-driven drop jet to build parts from waste metallic materials such as scrap plates. This procedure seems to be feasible to recycle old parts but environmental aspects of this procedure are not identified yet. Another solution could be the combination of DMD process with CNC machining or casting process. For example, simple sections of a part could fabricate through CNC machining, casting or even forging and after that DMD process would be employed to take care of complex sections of the previous part. This method has similarities to the welding process with computer-aided three-dimensional building capabilities. Therefore, this method benefits both conventional and modern manufacturing processes as the simple sections of the part which are time-consuming to fabricate by AM-based processes could be done by conventional methods and fabricating of the complex sections which is known as limitation of conventional methods done by AM processes. This innovative method has an obstacle which is the distortion of base material caused by the heat added to the part during DMD process [19]. This problem is not fully investigated;

however, one solution proposed by [19] is to use machining after metal deposition in order to obtain more geometrical accuracy. Another solution may be hot isostatic pressing (HIP). In some cases, this approach prevents post-treatment by avoiding part removal stage. Besides, building plate should be replaced after specific number of building cycles because of detachment damages which is added extra cost. Figure 5 shows an example of this innovative method for turbine blade fabrication. In such cases, ceramics with high life cycle could be replaced with metallic building plates.

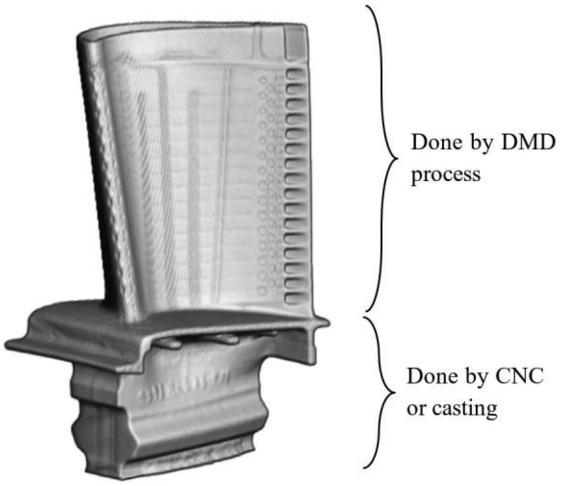

Figure. 5 An innovative combination of AM and conventional manufacturing processes to achieve more efficiency.

3. AM AS A REPAIRING METHOD

Metal AM-based processes could be used as a repairing tool for both parts and tools repair. This revolutionary solution provides longer lifespan for mechanical parts which lead to a lot of energy and material saving as shown in figure 6. Applicable strategies should be developed in every industry with respect to their criteria to employ optimum procedure for repair and remanufacturing purpose.

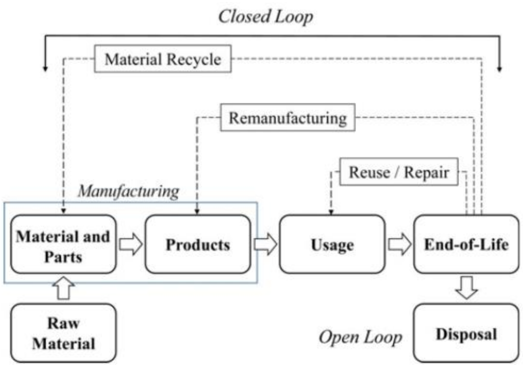

Figure. 6 Conceptual diagram of resource circulation [20].

Another positive point about repairing parts in order to back them to their life cycle is the reduction of transferring key parts such as tools [21]. This approach could also be seen in spare parts production [22]. Spare parts usually are stored far from the workshop where they are needed which means it takes a lot of time to transfer. With the aid of in-house key-part production, the production lead time could be avoided [23]. Repairing procedures are mainly used for key-parts like tools but it could be used for scrap parts as well. This approach eliminates material and energy waste. There are several studies investigated possibilities of tooling by means of metal AM [24, 25]. AM have several exclusive features that make it even more efficient than conventional tooling processes. These features including conformal cooling channels (CCC) in order to enhance cooling rate, porous structures for lighter products, complex geometries such as custom molds, etc., not only increase production rate but also decrease the environmental impacts and costs. Part repairing and coating increase product lifespan which improves safety in some cases. Figure 7 show overall benefits of repairing by means of AM processes.

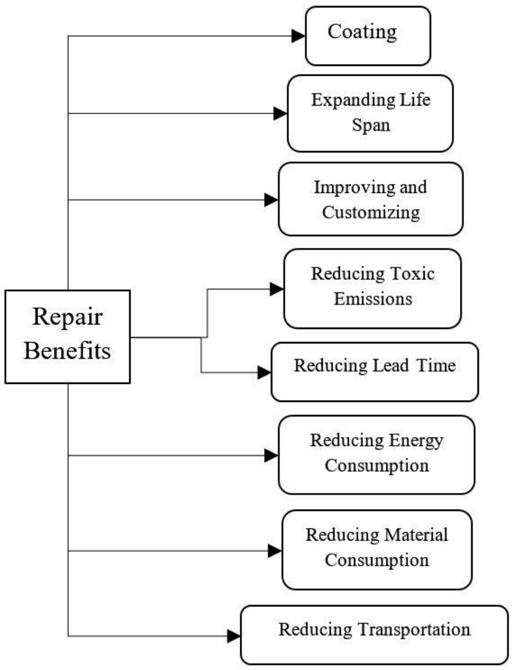

Figure. 7 Overall benefits of repairing by means of AM processes.

4. HUMAN HEALTH AND SAFETY

Human health safety and exposing to process emissions are also very important during the building phase. However, there is no referable information about human-related harms for metal AM methods yet. Metal AM processes are kind of welding processes; therefore, the danger of emitted toxic heavy metal vapor require consideration. Besides, floating metal powder particles could cause respiratory problems in both powder production and AM procedure. Therefore, every step of manufacturing including powder transport, powder storage, powder recycle, etc., should be carefully considered. Existing standards have not addressed all the safety concerns and it is mainly up to operators and manufacturing conditions (e.g. product rate, workshop conditions, ventilation, etc.) [26]. Feedstock should be supplied from reliable sources with specified composition to avoid toxic emissions as much as possible. This issue may be related to process parameters; however, further studies are required to understand the relationship between feedstock/process parameters and emissions. Besides that, optimum process parameters would lead to perfect product which eliminate post-processing and scrap parts. Another consideration is exhaust gases that should be managed very carefully as well as floating nanoparticles.

Metal AM processes are mainly done by laser power or electron beam which bring the risk of danger for human eyes [27]. Process safety management could be achieve through the use of data collecting methods such as cyber-physical systems and Internet of Things by avoiding hazards and accidents by identifying and controlling potential sources of failure [28].

From another point of view, safety may be considered as human life. This approach could be widely found in aerospace industry which deals with human life. The European Aviation Safety Agency (EASA) is responsible for certifying civil aircraft parts. They have begun to evaluate AM products for flying and critical parts, yet AM products had been used in cabin equipment. However, safety standards of AM products are still under development for critical use [29]. From the safety aspect, repaired parts which would be used in safety-critical industries such as aerospace should be tested and verified by professionals. In case of spare parts, in-situ inspection systems should be employed to evaluate part quality and integrity to avoid unpredictable failure. Moreover, nondestructive evaluation techniques play a crucial role in certifying key-parts. However, destructive tests such as tensile and fatigue tests are suited for determining material properties and behavior in different situations. To achieve higher mechanical properties, post-processing treatments such as hot isostatic pressing (HIP) are required [30].

In case of human implants, there are three class parts which could be fabricated by means of additive manufacturing processes. Class I is associated with low-risk parts such as dental implants and class II is related to higher risk parts with more safety concern and functionality (e.g. woven polylactic acid scaffolds), while class III products responsible for parts like artificial heart valves with the highest level of safety consideration. Therefore, for class III products premarket approval from FDA is required [31].

5. RESULTS AND DISCUSSION

With respect to all the studies done to address several aspects of environmental impacts and safety aspects of AM-based processes, still there are many questions about the accurate environmental impacts of additively manufactured part production as well as safety considerations. This problem is mainly because of the wide range of parameters and their effects on process sustainability. However, it seems feasible to reduce environmental impacts of AM by using more efficient laser source, adjusting optimum process parameters and machine setup, reduce weight as much as possible, filtering toxic gases, reducing energy waste by using it for heating purposes such as powder pre-heating or other usages or combination of AM with conventional manufacturing processes. It is found out that powder production play an important role in total manufacturing energy consumption and still have unknown environmental impacts.

Some models are developed recently; however, further studies are required to fully identify all aspects of powder production environmental impacts. AM minimize transport by centralizing production line and reduce unnecessary costs and environmental burden. Moreover, the utilization of AM products in industries such as aerospace which related to human life safety is a major concern and require more investigation.

AM enable several features that make products much lighter and functionally more efficient such as conformal cooling channels (CCC) in molds and casting equipment and porous structures for higher strength-to-weight property. Hybrid processes take the benefits of both AM and conventional processes to fabricate more efficient parts. Repair strategies by means of AM seem feasible and environmentally friendly; however, further studies are required to observe this capability in action. Spare parts and tools could be built by the aid of AM to reduce lead time and following costs.

6. CONCLUSION

Metal additive manufacturing is highly promising method for fabricating and repairing parts with lower environmental burden than conventional methods. Hybrid processes make AM even more beneficial, especially for complex parts. Powder related issues including production, usage and recycling require more attention. Energy consumption of part detachment from building plate is a post-treatment which is neglected in many studies should be considered as well as other production steps. More efficient equipment (e.g. laser, electron beam, smaller building room, etc.) should be used. Safety considerations and risk factors should investigate in detail and documented instructions should be developed to avoid injuries. All these risk factors are undefined at this time and require more assessment.

In this paper, Environmental and safety aspects of AM processes are presented. Several benefits of repairing parts and spare part fabrication by means of AM, especially environmental benefits are addressed. Further studies are needed for all types of metal AM processes and powder production methods to fully characterize environmental impacts of each process. Accurate LCI models should be developed for other AM methods.

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Review of the Proppant Selection for Hydraulic Fracturing

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Abstract: Hydraulic fracturing is not a new technology and has become an essential part of petroleum industry to produce oil and gas. The goal of hydraulic fracturing is to create a highly conductive fracture system that will allow flow of fluid and/or gases through the formation to production well. A proppant is a solid material, typically sand, treated sand or man-made ceramic materials, designed to keep an induced hydraulic fracture open. Many proppants and mesh sizes are available for the design of a fracture stimulation treatment. Proppant types and sizes are effected on the fracture conductivity. This paper describes the factors which are critical to proper proppant selection and ultimately, proppant performance. Proppant fines, Proppant pack cyclic stress, Effective Vs Reference conductivity, Proppant flowback, Proppant pack rearrangement, Proppant embedment and Downhole proppant scaling are explained in relation to proppant selection.

Keywords: Proppant, hydraulic fracturing, sand, man-made, synthetic proppant

1. INTRODUCTION

A proppant is a solid material, typically sand, treated sand, or a manufacture ceramic material that is designed to prevent and keep an induced hydraulic fracture open during and after a fracturing treatment. Proppants are used to hold the walls of the fracture apart to create a conductive path to the wellbore after pumping has stopped and the fracturing fluid has leaked off. Placing the appropriate concentration and type of proppant in the fracture is critical to the success of hydraulic fracturing treatment. Proppants types and grain sizes selection are the key of hydraulic fracturing design, because natural sand or synthetic proppants are the only material left in place downhole after termination of the operation and are the critical agents whose performance decides on success or failure of the job.

2. HISTORY OF PROPPANT

For the first propped fracture treatments in the late 1940s and early 1950s, proppant consisted of sand dredged from riverbeds. Stronger and better processed sand became available in the mid-1950s from the St.Peter sandstone (Fast, 1961; Montgomery and Steanson, 1985). This formation, mined near Ottawa, Illinois, produced a high quality proppant that become known as Ottawa frac sand. Later more angular sand became available from the Hickory Sandstone formation, mined from the Heart of Texas mines near Bardy, Texas, and science that time many supplier for natural sand proppant have come into the market. In the 1960s, a variety of manufactured proppants were introduced including walnut hulls, aluminum pellets, glass beads, iron shot, and plastic beads. As deeper wells were drilled in the 1970s, the shortcomings of sand for high-stress environments became apparent. Other high-strength proppants were also introduced in the 1970s and 1980s including resin-coated sand (curable and procured), zirconia (no longer used), lightweight ceramics, and intermediate density/ intermediate strength proppant(ISP). Currently, the major proppants used for propped fracture stimulations include ISO quality sand, procured resin-coated sand, lightweight ceramics, ISP, sintered bauxite.

3. PROPPANT TYPES AND GRAIN SIZES

3.1 Normal or Body Text

There are basically divided into two group of proppants used for hydraulic fracturing applications: either naturally occurring silica sands or made-made ceramic proppants. In the hydrocarbon stimulation market, presently, five different types for hydraulic fracturing are available in various grain sizes and for different prices from several manufactures:

(1) Natural quartz sand

(2)Synthetic intermediate-strength low-density alumina silicate (ceramic) proppant

(3)Intermediate-strength high-density alumina oxide and silicate proppant

(4)High-strength high-density bauxiteproppant

(5)High-strength low-density zirconia-silicate proppant.

Proppant with larger grain sizes provide a more permeable pack because permeability increases the square of the grain diameter, however, their use must be evaluated in relation to the formation that is propped and the increased difficulties that occur in proppant transport and placement. Larger grain sizes can be less effectives in deeper well because of greater susceptibility to crushing resulting from higher closure stresses (as grain size increases, strength decreases.

The following general guidelines may be used to select proppant based on strength and cost:

Sand ----- closure stresses less than 6000 psi

Resin-coated proppant (RCP) ---- closure stresses less than 8000 psi

Intermediate-strength proppant (ISP) ---- closure stresses greater than 5000 psi, but less than 10000psi

High strength Proppant ---- closure stresses at or greater than 10000 psi

Table I. Mechanical Properties of Proppants for Hydraulic Fracturing

Mechanical Properties of Proppants for Hydraulic Fracturing			Mechanical Properties			
Proppant Type						
Provenance	Strength	Type	Specific Gravity (g/cm^3)	Bulk Density (lb/ft^3)	API Crush Test: %fines at 10000 psi (20/40) Grain Sizes	Closure Stress Resistivity and Field Application Boundary (psi)
Natural	Low-strength	quart sand	2.65	96.03 - 103.0	40.8 - 59.0	3000 - 5000
Synthetic	Intermediate-strength	Low-density alumina silicate Proppants	2.70 - 2.75	99.0 - 102.4	4.3 - 9.5	8000
Synthetic	Intermediate-strength	High-density alumina oxide and silicate proppants	3.15 - 3.27	112.5 - 116.8	3.5 - 6.1	10000 - 12000
Synthetic	High-strength	Alumina oxide proppants	3.60 - 3.80	130.0 - 144.0	1.5 - 5.0	15000
Synthetic	High-strength	Zirconia-silicate proppants	3.15 - 3.17	106.0 - 120.0	0.3 - 4.6	15000

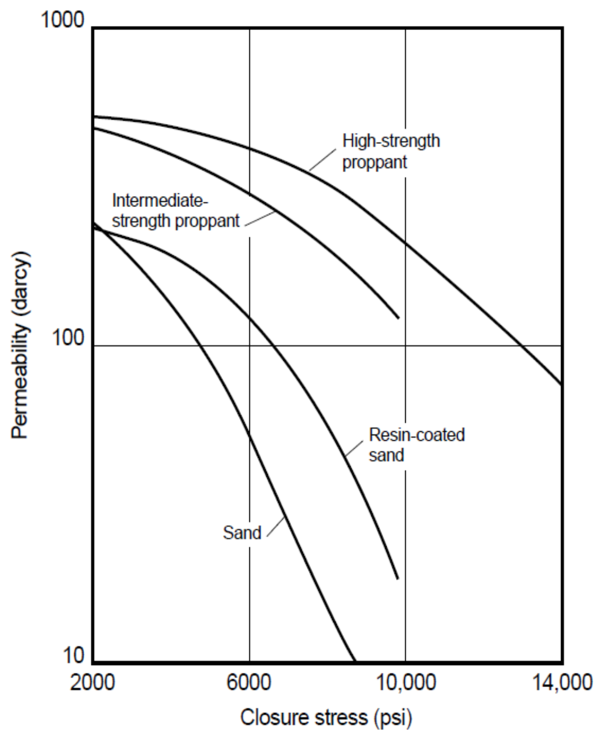

Fig1. Strength comparison of various types of proppants (Reservoir Stimulation, Third Edition, 2010, Michael J. Economides)

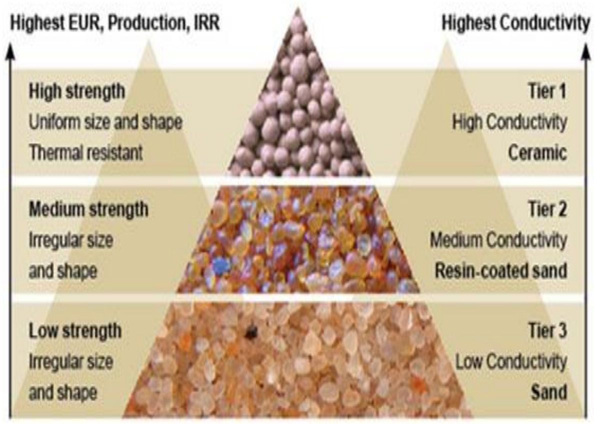

Fig2. Different types of proppant (Retsch Technology, 2012-11)

Proppants are specified in grain diameter sizes of less than 1/16 of an inches. Some common mesh sizes are 16/20, 20/40, 30/50, 40/70, and 100. Treatments may use one size or a multitude of sizes during pumping. The smaller sizes are intended to reach closer to the fracture trip. Proppant size is an important consideration for design and depends on the degree of stress target conductivity, and achievable fracture width. Large-mesh proppants have greater permeability than small-mash proppants at low closure stresses but will mechanically fail and produce very fine particulates at high closure stresses such that smaller-mesh proppants overtake large-mesh proppants in permeability after a certain threshold stress. Proppant mesh size also affects fracture length: proppants can be bridged out if the fracture width decreases to less than twice the size of the diameter of the proppants.

Table II. Typical proppant sizes

Tylar Mesh Size	Particle Size Range (μm)
10/40	1400-2000
12/18	1000-1700
16/20	850-1180
16/30	600-1180
20/40	420-850
30-50	300-600
40/70	212-420
70/140	212-106

4. CRITICAL PROPPANT SELECTION FACTORS

Fracturing proppant selection is crucial to optimizing well productivity. Besides the traditional proppant selection factors of size, strength, and density, there are many other important factors to be consider such as:(1) Proppant fines, (2) Proppant pack cyclic stress, (3) Effective Vs Reference conductivity, (4) Proppant flowback, (5) Proppant pack rearrangement, (6) Proppant embedment and (7) Downhole proppant scaling.

4.1 Proppant Fines

Proppant fines generation and the resulting migration in the fracture are considered to be one of the major contributors to poor treatment results and well performance. It has been noted by Coulter & Wells that just 5% fines can decrease fracture flow capacity by as much as 60%. Hexion's advanced grain-to-grain bounding technology reduces proppant fines generation and migration through the proppant pack. The fines generated by the light-weight ceramic (8.2%) and uncoated frac sand (23.9%) greatly decrease well production.

4.2 Proppant pack cyclic stress

During the life of a well, numerous events such as well shut-in during workovers, connections to a pipeline or possible shut-in due to pipeline capacity lead to cyclic changes in fracture closure stress. Curable resin coated proppnts resist these cyclic stress changes by forming a flexible lattice network that redistributes the stresses through the proppant pack, reducing individual point loads on each proppant grain. This feature leads to improved proppant pack integrity and well production.

4.3 Effective Vs. Reference conductivity

The fracture conductivity is a measusre of proppant performance, and proppant selection is deemed successful only with can achieve substantial fracture conductivity. It depends on the fracture width proppant distribution, and proppant concentration. Traditionally, proppant performance has been measured using baseline or reference conductivity testing. Effective conductivity is a much more accurate measurement of downhole proppant performance. Unfortunately, the low flow rats during the baseline conductivity test do not simulate downhole flow rates. High flow rates downhole can cause proppant fines to migrate and severely decrease fracture conductivity.

4.4 Proppant Flowback

Proppant flowback is the movement of proppants back to the wellbore and the higher the pump velocity, the more the change of flowback occurring. Futhermore, proppant flowback and pack rearrangement is the main cause of well production decline, equipment damage, as well as lockdown of the well for repair. Thus flowback reduces conductivity at the wellbore and decrease connectivity to the reservoir. Proppant flowback can be prevented by the use of resin-coated proppant. Resin-coated proppants that have grain-to-grain bounding can eliminate proppant backflow, if applied properly, by forming a consolidated proppant pack in the fracture. Post treatment proppant flowback is a leading cause of production decline, equipment damage, and well shut-in for repair. Proppant flowbackcan also cause loss of near wellbore conductivity and reduced connectivity the reservoir. Curable resin-coated proppant eliminate proppant flowback by forming a consolidated proppant pack in the fracture. This grain-to-grain bonding occurs under a combination of reservoir temperature and closure stress.

Fig3. Proppant Flowback (Critical Proppant Selection Factors, HexionFracline)

4.5 Proppant pack rearrangement

Proppant pack rearrangement in the fracture can cause a significant reduction in propped width, which can also lead to reduce fracture flow capacity and connectivity to the wellbore. As a well is produced, high flow velocities in propped microfractures may cause uncoated or procured proppant packs to shift or rearrange, causing the microfractures to narrow or possibly closed completely. Curable resign-coated proppants will prevent the proppant grains from shifting, keeping the microfractures propped open. This unique bonding technology provides additional proppant pack integrity, enhance fracture flow capacity, and increase productionduing the life of the well.

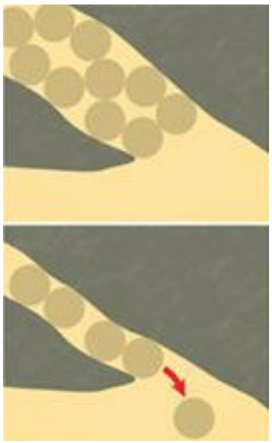

Fig4. Proppant pack rearrangement. (Critical Proppant Selection Factors, HexionFracline)

4.6 Proppant embedment

Proppant embedment occurs as a result of the proppant embedding into the fracture face, especially in soft shale formation, leading to reduced fracture width and lower fracture flow capacity. In the embedment process the proppant partially or completely sinks into the formation through displacement of the formation around the grain. Proppant embedment is caused by an interaction between the formation and the proppant at the face of the fracture, which cause a loss in conductivity. Uncoated proppant and precuredresin coated sand often deeply embed into softer formation due to the increased single point loading between the proppant grain and the soft fracture face. Light weight ceramic proppants embed deeply into soft shale formation, and an additional issue with proppant embedment is the spalling of formation fines, which can migrate and cause additional loss of fracture conductivity. When curable resin-coated proppants are used, there are multiple grains bonded together instead of just single-grain point loading.

Fig5. Proppant embedment. (Critical Proppant Selection Factors, HexionFracline)

4.7 Down-hole proppant scaling

Down-hole proppant scaling is the result of a geochemical reaction, which can occur downhole in the fracture in high-pressure/high-temperature wells, especially in a wet, hot downhole fracture environment. The result of proppant scaling is a serve loss of proppant pack porosity and permeability with the creation of fines and debris in the proppant pack. Uncoated light weight ceramics can lose up to 90% of the permeability of the proppant pack, often in a matter of days. However, Resin-coated proppants can drastically reduce the impact of downholeproppant scaling, which result in improved fracture flow capacity and significantly higher long-term productivity.

5. PROPPANT SELECTION

Some general guide line of rule-of-thumb character can be given as a summary for proppant selection for the application in oil and gas well stimulation in hydrocarbon industry. The most important characteristics of natural sand, intermediate-strength low-density alumina silicate proppants, intermediate-strength high-density alumina silicate proppants, high-strength high-density alumina oxide proppants, and high-strength low-density zirconia-silicate proppants are briefly sketch as follows;

Natural sand is the cheapest of all proppant types and has always been available in nearly unlimited quantities due to widespread occurrences, uncomplicated accessibility and easy processing. However, its application is restricted to shallow wells due to its low closure stress resistivity which is the reason for classifying natural sand as low-strength proppant. Nowadays, natural sand is more and more replaced by synthetic high conductivityproppants in all the cases where no extreme cost containment is necessary, and also that give better permeability contrast between fracture and formation can be selected.

Intermediate-strength low density alumina silicate proppants have the best pumping characteristics of all synthetic proppants due to their low specific gravity which is compare to that of sand. The higher closure stress resistivity allows the application of this material in shallow to intermediate depth reservoirs beyond the pressure boundary of natural sand. Effects of proppant settling are still insignificant for a wide variety of carrier fluids and a broad spectrum of proppant concentrations. Thus proppants are the economically most feasible proppant type in any respect if the boundary of closure stress resistivity is not exceeded.

Intermediate-strength high-density alumina oxide and silicate proppants are mainly applied for hydraulic fracturing of gas reservoirs in moderate to high depth. Being cheaper, lighter and less abrasive than sintered bauxite, they are chosen in all the cases where lightweight synthetic proppants are no longer resisting to the closure stress properly, but high strength alumina oxide proppants are not yet necessary, and thus both cost premium and disadvantage of even higher particle density can be avoided. The specific gravity is still low enough to allow good pumping behaviour with little risk of screenout, but depending on carrier fluid composition and weight, effects of proppant settling may already become significant.

High-strength high-density alumina oxide proppants or sintered bauxite have been the first synthetic proppants that were introduced to the oil and gas industry. The high specific gravity of sintered bauxite does not only leads to problems of proppants settling in lighter carier fluids, but also increase the risk of premature screenout termination of the fracture operation when using heavier transport media in order to minimize or to avoid settling. The major disadvantage of sintered bauxite is its considerable abrasiveness to the treatment equipment which further deteriorates its economical feasibility.

High-strength low density zirconia-silicate proppants are an almost idea material for wide range of applications as a consequence of their properties. There are excellent characteristics for usage in shallow to deeps wells without any problem of placement and settling, and the very good conductivity provides in almost all the cases the necessary contrast between formation and fracture in order to allow hydrocarbon flow at economically feasible rates. The major technical disadvantage are the sudden catastrophical failure of the brittle glassy material into powder-like crushing remnants when the boundary closure stress is exceeded, and the low frication angle which does not only guarantee a better entry of the material into the crack, but also an easier subsequent escape from the fracture by flowback.

6. CONCLUSION

Successful hydraulic fracturing requires the integration of technical proppant data with economics to allow the development and implementation of an optimum fracture design. The critical factors affecting fracture conductivity, described in the previous section, such as closure stress, proppant size, proppant concentration, strength, embedment can each be reviewed both from a technical and economic. The major consideration in proppant selection is optimizing permeability or conductivity versus the associated cost and benefit. The cost of propping agents offering enhanced conductivity and well performance in the fractuing operation can be considerably higher, so it is essential to calculate the desired production rate during the life of the well. If a substantial increase in production is expected, it may justify the use of more expensive proppants.

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Utilization of New Definitions to Calculate Overall Equipment Effectiveness (OEE) for Air Compressors: A Case Study

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Abstract: In recent Decade, utilization of management and engineering indicators has become a common task. Among these indicators, Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR) and Overall Equipment Effectiveness (OEE) are more popular. Iran Khodro as the largest car manufacturer company in Iran and in the Middle East to optimize its production lines, electricity has been substituted by compressed air power. To achieve this target, this company launched compressed air department that has 50 air compressors including centrifugal and screw types and this number was reached gradually through the years. In this paper, to investigate the status of the equipment and report to department managers OEE index has been used. Since this indicator is more commonly used for systems and equipment that has a specific production schedule, this paper by proposing new definitions and changes in OEE parameters, calculation of this index for one compressor has become possible. By having this index for each compressor, one can analyze the performance of each compressor alone or in comparison with the others and as a case study the OEE of ten compressors belonged to the compressed air department since march to august of 2017 have been calculated and analysis has been reported.

Keywords: Overall Equipment Effectiveness (OEE), Air Compressor, Effective Maintenance, Equipment Status Report.

1. INTRODUCTION

Equipment analysis due to the variety in the operation of air compressors, such as centrifugal or screw type with different working pressure, and also the study of their operation since march to august of 2017 in terms of the number, timing and impact of downtime and efficiency of each Compressor Brigade for Iran Khodro Company will be performed in terms of the amount of compressed air produced in proportion to the energy consumption of a specific compressor using the calculation of the relevant indices.

Maintenance indexes have definite descriptions in all international references that will be used to compute them in this paper, but what matters is that for equipment with different definitions, the overall equipment efficiency (OEE) index can have different computational methods that can be found in This paper and have been computed for air compressors. Also, the technical information of the equipment that have been examined are discussed in detail.

In this paper, the analysis of the compressors used by Tehran Iran Khodro Company in terms of efficiency and calculation of maintenance indicators, as well as management indicators such as OEE index have been introduced, as well as compressors have been rejected in terms of quality.

2. INTRODUCTION OF COMPRESSED AIR DEPARTMENT

Iran Khodro Company as the largest car manufacturer in Iran and Middle East for the provision of compressed air for car production lines employs 50 air compressors in 7 and 10 bar pressure range which 10 compressors have been chosen as a case study. Since Iran Khodro is active in three working shifts and 24 hours a day, it is necessary that the working pressure of the production lines has been supplied constantly by the company's compressed air department at all working hours. The compressors of this department based on the requirements of production lines are divided into two groups, compressors to generate 7 and 10 bar pressure. These compressors are from popular companies such as Samsung, Ingersoll rand, Atlas Copco, CompAir and Pars which produce compressed air in standard and oil free (high) quality. Standard quality air is used in body shops, assembly shops and rims shops where a little oil in the compressed air will not cause problem or fault. Oil free or high quality air is used in paint shop to power robots which are painting the body of the car.

3.METHODOLOGY

Effect of the efficiency of each compressor for the compressed air department of Iran Khodro in terms of the amount of compressed air and its energy consumption, as well as analysis based on the failure rates and their repairs and overhauls costs based on the calculation of relevant indicators such as PM rate, range rate, mean time to repair (MTTR), mean time between failure (MTBF), mean time to failure (MTTF), availability (AV), and finally the OEE which is a Management Indicator [1-3].

how to calculate the OEE index according to equation (1), rate of quality (Q) and performance rate (P) for the compressors of this company have been calculated.

$$OEE = Av * P * Q \qquad (1)$$

Since the technical information, operating conditions and performance of the equipment under investigation are monitored, they are used for use in the formulas of the introduced indicators.

As shown in Equation 1, OEE index is calculated from the product of the three factors. If we want to calculate the total OEE for the compressed air department, then we can assume that the values of the parameters except p have the value of 1.

The value of p is reduced to 92 percent of its value due to the leakage measurement of the system, so for p, the value is 0.92, and according to equation (1), OEE with a value of 0.92 can be calculated, which according to the system conditions is reasonable.

Since in this paper, the computation and expression of compressors effectiveness are considered, we assume the system boundary as compressor itself. In this method, the calculation of the factor Q will have a value of 1. Because the point of measurement of the volumetric flow of air is just at the outlet of the compressor, which is located on the boundary and there is no rejected air at this point. On the other hand, various factors have to be considered in order to calculate the effectiveness of compressors.

It should be noted that in Iran Khodro's site, almost all of its production lines are operating 24 hours a day in three shifts. On the other hand, based on the market demand, it is necessary for production management to declare shifts in a number of production halls of the company at a number of scheduled holidays. Also, due to the fact that the distribution network of compressed air in Iran Khodro's site is continuous and there is no possibility of separating compressed air consumption of a hall, the process of producing and distributing compressed air is an uninterrupted process throughout the year. In the event of momentarily interruption of compressed air, some processes or equipment for production and support will be experiencing serious disturbance and damage. According to the above, in the calculations of the indices we have to consider the scheduled time as 365 days a year and 24 hour a day. In fig. (1) the suggested approach to define factors has been demonstrated.

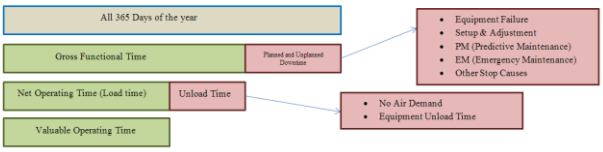

Figure 1. Suggested Approach.

In case of availability calculation equation (2) is suggested to use for air compressors.

$$Av = \frac{(\text{365 Days of year} - \text{Downtimes})}{(\text{356 days of year})} \quad (2)$$

As shown in equation (3), the parameter P is result of the production time of a net output of equipment to its entire availability time. In this paper, the net output of a compressor consists of the amount of compressed air produced by the compressor in a given time period in real working conditions. In other words, increasing the parameter P depends on the maximum production of compressed air of equipment during the entire time of its availability.

$$P = \frac{(Load\ Time)}{(365\ Days\ of\ year\ - Downtimes)} \quad (3)$$

The important thing to note here is that all references that are related to total productive maintenance have focused on taking the planned net time into consideration. This is because the Av index increases dramatically by eliminating unplanned times for the production of an equipment (production planned time which is in the denominator of the Av index). While by the explanation given in this article is inevitably limited to consider the maximum possible time for working hours of equipment. It is natural that in this situation, any operation of the device despite its availability, due to internal or external factors, will all negatively affect the parameter P. Since one of the purpose of this paper is to calculate OEE as close as possible to its real value. To do so it has been recommended to multiply it by capacity coefficient (equation (4)).

$$Capacity\ Coefficient = \frac{(Actual\ Capacity)}{(Nominal\ Capacity)} \quad (4)$$

And by using equation (4), equation (5) can be achieved.

$$P = (Equation\ (3)) * (Equation\ (4)) \quad (5)$$

Therefore by the explanations above, the suggested OEE equation to calculate for air compressors can be demonstrated as following equation (6) after simplification.

$$OEE = \frac{(\text{Load Time}) * (\text{Capacity coefficient})}{(\text{365 Days of year})} \quad (6)$$

Equation (6) has been resulted from putting equation (2), (3) and (5) and the value of quality which is one due to the mentioned reasons, into equation (1).

4.RESULT AND DISCUSSION

In this section all the data that are needed to investigate the status of equipment. The information of compressors that has been studied including manufacturing date, working pressure and quality of demanded compressed air are available in table (1). In this table demanded quality shows the criticality of compressed air quality produced by compressors in case of existence of oil in the compressed air. That actually is the reason of using oil free compressors to satisfy these demands. In the figure (2), a pie chart of compressors percentage by manufacturing date that is belonging to the compressed air department has been shown. In the fig.(2), it is demonstrated that most of the compressors have the age of at least 12 years. This figure includes all 50 compressors of the compressed air department.

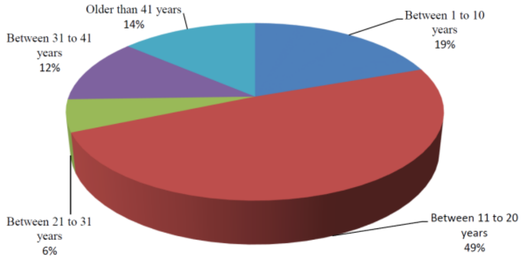

Figure 2. Pie chart of compressors percentage based on age.

Table 1. Information of Compressors

Compressor Number	Manufacturing date	Demanded quality	Working pressure
1	2015	Standard	7 bar
2	2015	Standard	7 bar
3	2002	High	7 bar
4	1996	Standard	7 bar
5	1998	High	10 bar
6	2000	High	7 bar
7	1971	High	7 bar
8	2009	Standard	7 bar
9	2015	Standard	7 bar
10	1983	High	7 bar

As it is shown in table (1), the age of the compressors is between 3 to 47 years. Type of the first three is centrifugal and the rest are screw. In the table (2), data for calculating OEE index including planned working time of compressors which is six months, total downtimes, load time have been shown.

Table 2. Required data

Compressor Number	Planned time(hr)	Total downtime(hr)	Load time(hr)
1	4464	55	3588
2	4464	55	3744
3	4464	65	3059
4	4464	2389	789
5	4464	60.75	1496
6	4464	1264.75	1686
7	4464	55	2015
8	4464	45.5	2002
9	4464	55	1821
10	4464	55	2542

Since the calculation of P factor needs computing capacity coefficient and to do so must extract nominal and actual capacity from table (3).

Table 3. Nominal and actual capacity

Compressor Number	Nominal capacity(m^3/min)	Actual capacity(m^3/min)
1	83	79
2	83	79
3	55	51
4	43	35
5	30	26
6	32	28
7	32	28
8	44	38
9	70	68
10	32	28

Finally by using equations (2) to (6) and tables (1) to (3), OEE index and its factor can be achieved for mentioned equipment as following table (table (4)).

Table 4. Final results

Compressor Number	Av	P	OEE
1	0.99	0.77	0.76
2	0.99	0.81	0.8
3	0.99	0.64	0.64
4	0.46	0.31	0.14
5	0.99	0.29	0.29
6	0.72	0.46	0.33
7	0.99	0.4	0.39
8	0.99	0.39	0.39
9	0.99	0.4	0.4
10	0.99	0.5	0.5

As it is shown in table (4), some of the OEE indexes are very low which to analyze and explain the reasons must compute other indicators such as MTTF and MTBF. Results have been shown in table (5). These indicators have been calculated by using equation (7) and (8).

$$MTTF = \frac{(Planned\ time)-(Repair\ time)}{Number\ of\ failures} \quad (7)$$

$$MTBF = \frac{(Planned\ time)}{Number\ of\ failures} \quad (8)$$

Table 5. Analysis required data

Compressor Number	MTTF	MTBF	Number of failures
1	∞	∞	0
2	∞	∞	0
3	2229.5	2232	2
4	1060	2232	2
5	2230.63	2232	2
6	1085.75	1488	3
7	∞	∞	0
8	4463.5	4464	1
9	∞	∞	0
10	∞	∞	0

During the investigations and data collection, the number of failures and repair time of the compressors from March to august of 2017 have been showed in table 5.

In this paper, compressors that have been studied have different OEE index that can be analyzed more accurately according to the MTTF and MTBF index. MTTF and MTBF indices are infinite when there is no failure during the time interval. When at least one breakdown leads to a stop, the most ideal condition is to fix the failure at the shortest possible time, in which case the MTTF will be close to the planned time, which can be equal to the MTBF index.

For example, Compressor number 1 and 2 have a planned working time of 4464 hours between march to agaust of 2017, but their run times were about 3,600 hours, considering that during this period they did not stop because of breakdowns or PMs. Therefore, they have a high AV index, and during this time compressors have been almost always on and on load. it must be taken into account that these equipment as shown in table 1 are not old, so their capacity coefficient has a high value. As a result, the OEE index is desirable. For compressor number 1, the only reason for the OEE index deviation can be related to the time that no air was demanded.

The other examples are compressors number 7, 9 and 10 which their operating times do not have stops because of CMs and EMs but the time to use the equipment was much less than the planned time Which means the most ideal MTTF and MTBF index and a lower value in OEE index. as it has been said earlier the low OEE is directly related to the low usage of the equipment.

Another example in compressor number 6 as it can be seen in the table 2, the load time of the equipment is 1686 which is less than the planned time. it must be taken into account that during this time it has done approximately 2000 hours of run. The equipment has failed and its operation has stopped 3 times in the assumed time interval. Downtime of the equipment includes more than 1200 hours of repair time which has a very effective influence in MTBF and MTTF indices. it can be concluded that this equipment has low effectiveness and low performance.

By the discussion above, it has been proven that proposed approach can be used to calculate and compare compressor conditions which lead to a great index to help managers make better decisions.

5.CONCLUSION

Unlike most maintenance and repair engineering indicators that cannot be investigated alone, the OEE index is an analytical and management evaluation indicator that, as stated, the product of the multiplier is the factor of accessibility, the rate of quality and the rate of performance. To make since the performance of the device is considered in this analysis, we consider the system boundary as the device itself. In this calculation, there is no Q factor because the point of measurement of the volumetric flow is exactly at the outlet of the compressor and there is no rejection air. Therefore, in the calculations for the OEE index instead of having three components, only have two which are AV and P. Reviews have also been made to find the best performance rates. The results in separate tables describe the performance of all compressors according to the type of application and their working conditions, which will allow the respective managers to take care of the equipment and personnel involved in the maintenance planning and Have a clearer vision on this matter. As mentioned in methodology section, OEE of compressed air department is 0.92 which is good but about the OEE of the equipment, different values have been resulted. These low values can be explained by using other indicators such as MTTF and MTBF. For example compressor 1 has a run time of 3588 hours but its planned working time is 4464 hours in 24 hours and 3 shifts. Since it had no failure in the assumed time interval, the cause of this difference is mostly no air demands which by looking at the MTBF and MTTF , it is obvious that this equipment has no failure .It does need to be considered that these calculations are done for the first time at compressed air department in Iran Khodro Company.

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Utilization of Metal Additive Manufacturing (AM) in Precision Oriented Mechanical Part Production

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Abstract: Metal additive manufacturing (AM) is an innovative technology that opens up new visions in any industrial field. This technology is growing rapidly, entering various industries every day. After over 30 years from the introduction of metal additive manufacturing into the industrial world, the today's demand is to make mechanical parts with high precision by metal additive manufacturing. Until now, methods like high precision grinding or micro-machining processes are used to make more precise dimensions in parts. Those methods have their own limits and deficiencies that could be eliminated with additive manufacturing. In this paper, attempts are made to compare conventional precise processes with metal additive manufacturing from different aspects. Surface finish in these two categories is discussed and some advice for improving the surface quality of metal additive manufacturing parts is proposed. Applicability and utilization of metal additive manufacturing as a precise metal fabrication method in various industries with examples are also discussed.

Keywords: Additive manufacturing, precision manufacturing, inkjet, benchmark, micro fabrication.

1. INTRODUCTION

According to ASTM, additive manufacturing (AM) is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [1]. With the arrival of revolutionary metal AM, every industry is now looking for new applications of this technology in their field. AM has shown great potential in almost every high-tech industry such as aerospace, electronics, biomechanics, MEMS, etc., and has provided a strong tool to build near net shape parts with any level of complexity.

Fabrication of smaller parts with higher precision has determined as a new demand in serious industries. Precision manufacturing refers to any process that leads to fabricate micro and nano-scale parts and features with high accuracy. Precision manufacturing is one of those interesting fields that could be applied to a wide range of industries such as porous structures in medical implants, micro-scale heat exchangers, parts with embedded structures, reference blocks, etc. Precision manufacturing processes capability depends on several parameters. To fabricate precision parts by means of AM, effective process parameters should be identified. Level of part accuracy depends on process planning and parameters involved. In the following sections, a comparison between AM and other precision methods are discussed. Then, some solutions for AM process deficiencies are presented. Last, a brief review on micro fabrication by means of AM is presented.

2. COMPARISON BETWEEN ADDITIVE AND SUBTRACTIVE PRECISION MANUFACTURING

Subtractive precision manufacturing processes are divided into two categories: (1) conventional methods (i.e. micro-machining, micro-scale abrasive processes, etc.) and (2) non-conventional (i.e. micro-electrical discharge machining (μEDM) and micro-electrochemical machining (μECM), laser micro-machining, etc.) processes [2]. Although each of these processes has its own limitations; nevertheless, most of them are not capable of producing complex parts. Moreover, processes such as micro milling need precise tools and equipment which are expensive and hard to manufacture.

In contrast to other precision manufacturing processes, AM has the capability of building high level complex parts but its surface quality and tolerance is not satisfying [3]. Figure 1 shows poor resolution of boundaries due to layer by layer deposition. Subsequently, parts fabricated by AM are required post-processing treatments to enhance micro structural and surface properties. By combination of AM and conventional or non-conventional machining processes, high precision and accuracy and fine surface finish could be achieved. Wang et al. [4] combined directed energy deposition (DED) process with CNC machining to attain better accuracy. Such combinations are known as hybrid manufacturing. This could improve mechanical behaviors such as fatigue life [5] and help fabricate more efficient parts. However, it may lead to some difficulties like part distortion observed during fused deposition modeling (FDM) of the second part on a pre-manufactured machined part due to thermal gradient [6]. Part distortion is severely occur in metallic parts. For example, Afazov et al. [7] reported a turbine blade which is manufactured by powder-bed AM processes had approximately ±300μm distortion. This number could be reduced through a compensation methodology during designing procedure [7].

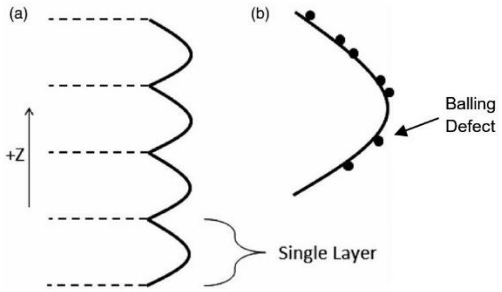


Figure. 1 AM deposited layers representing (a) poor resolution in boundaries and (b) balling defect on a single layer.

Manufacturing processes could be managed in a way that minimizes waste of material and time as much as desirable accuracy and precision [3]. However, AM has high potential to be combined with other manufacturing processes such as electron discharge machining (EDM), electrochemical machining, grinding, etc., to obtain better surface finish and higher accuracy. By this means, AM could be employed just for complex features of a part which are impossible or hard to be made by other processes. An attempt done by Butzhammer et al. [8]. They employed laser beam melting (LBM) to build some functional features on sheet metals. According to their comparison between hybrid manufacturing and purely additive and subtractive manufacturing, it is concluded that hybrid manufactured parts could reach almost 90% of mechanical properties of subtractive manufactured part, while it could also save raw material and manufacturing time as well as better surface finish.

Precision manufacturing may refer to micro-scale part fabrication. These parts have used in micro-electro-mechanical systems (MEMS), micro-opto-electro-mechanical systems (MOEMS), microelectronic products, micro-optical electronics systems (MOES) and any applicable combination [9]. New AM methods have this capability to facilitate micro-scale part production. Many related works are done in this field and could be found in the literature [10-12]. For example, in [11], authors have believed that no single AM process is able to satisfy high resolution, high purity and intricate geometry and current methods still struggle to guarantee high quality products. They reviewed recent trends and latest micro-scale fabrication processes by means of AM. As shown in figure 2, every AM-based process has its precision scale depend on process characteristics, material type, physical state of the material, etc. These boundaries are not rigid and could change as technology grows. Two key methods in this diagram are inkjet and laser-induced forward transfer (LIFT) which are very promising and flourishing.

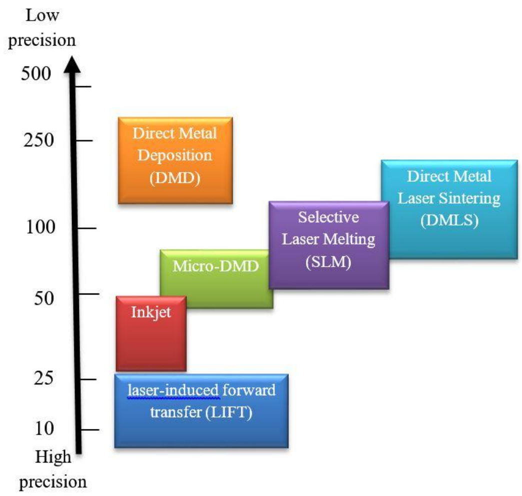
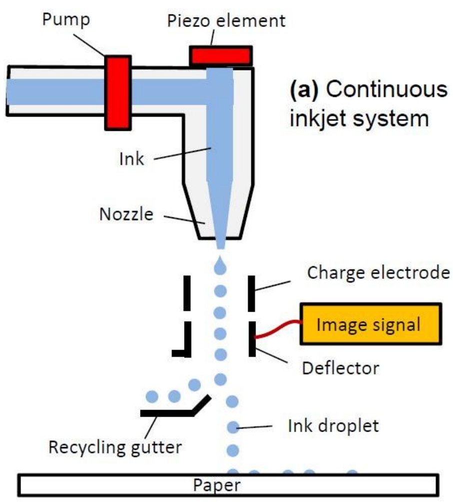


Figure. 2 Least dimensional accuracy achieved by metal-based AM processes until now (highly depend on material and process parameters).

2.1 INKJET

One of the new AM methods which has the capability of micro-scale production is droplet printing better known as inkjet. In this method molten metal droplets are dropped from specific location above the substrate and cool down during free fall before solidifying in a few nanosecond as soon as touching the substrate. This strategy provides a situation which eliminate melt pool problems and spreading melts [13]. However, positioning where droplets land, jet height, temperature and other parameters require accurate control to achieve precise shape. Figure 3 demonstrates schematic of two different types of inkjet system. Drop on-demand (DOD) process type has better controllability and accuracy due to singularity and independency of each droplet, however, it is more time consuming in comparison to continuous system. Researchers in this field have mainly focused on droplet geometry and its heat transfer and control to achieve higher precision as well as higher production rate. It should be noted that inkjet processes have almost no material waste, therefore, high value metals like gold could be widely used. MEMS technology have significantly benefited from this production method.



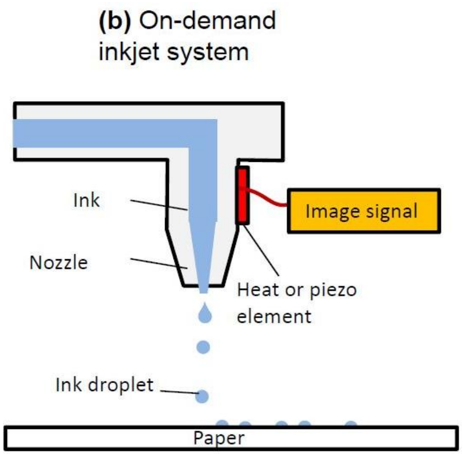


Figure. 3 Schematics demonstrating: (a) a continuous inkjet printer; (b) an on-demand inkjet printer [14].

From a closer look at the droplet head in figure 4, many functions such as heating source, orifice, electrode charger, etc. could be seen. From the top, depends on type of feed, wire or powder are fed to the melting chamber. Melting chamber is built of ceramics or high melting point metals to withstand high temperature. Heating source melt the metal inside and then molten metal pour though control orifice. Charging electrode mainly used in continuous systems and cut the stream into single droplets and make it possible to change landing position of droplets by changing the charge voltage [15].

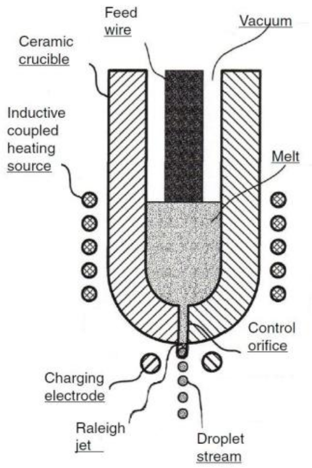


Figure. 4 Metal droplet generator head design using wire feed system [16].

2.2 LASER-INDUCED FORWARD TRANSFER (LIFT)

LIFT process is a high precision direct-write additive manufacturing process which has the ability of fabricating 3D micro-parts from thin metal plate. Figure 5 shows the schematic of this process. During the process, a ultra-violet laser pulse in a few picosecond causes ablation through a thin metallic plate which is coated on a carrier substrate (usually glass slide) [10]. This means oxidation and phase changes minimized due to elimination of melting pool and heat affected zone (HAZ) [10]. Accurate positioning of droplets is highly depending on gap distances, therefore, all gap distances must control with the highest precision via distance meter [11].

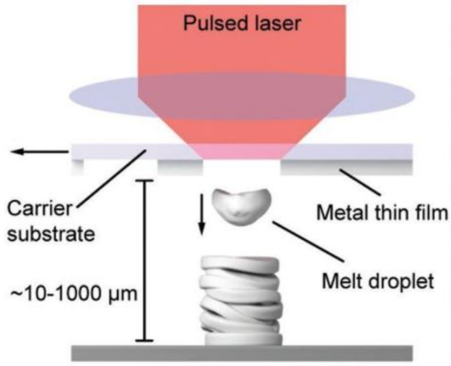


Figure. 5 LITF process schematic [10].

LIFT process has uncountable applications in MEMS and other related industries. One of the examples of utilization of LIFT is in manufacturing of thermal managers in electronic devices. Figure 6 shows a micro heat exchanger that could being manufactured by means of LIFT process [17]. Its innovative structure provides channels with 3 fold surface which gives better and more efficient heat transfer.

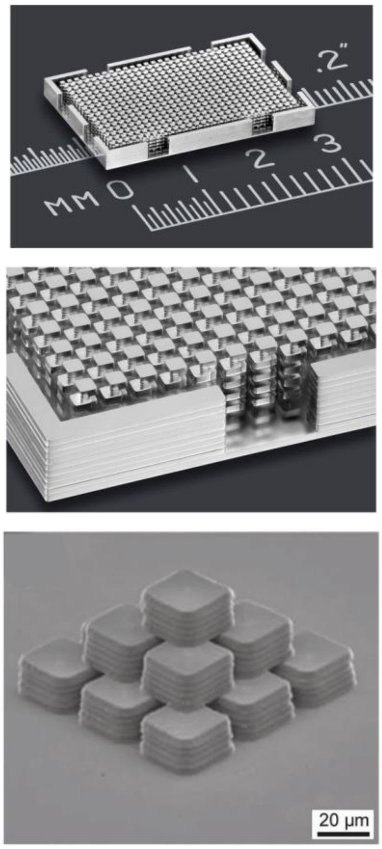


Figure. 6 (Top) thermal heat management system (dimensions: 2×3×0.25 mm, with total surface of 43.6 mm2), (bottom) closer look at pillars [17, 11].

There are wide variety of fabricating processes by means of AM and these are only a small fraction of existing methods. Some other methods are laser-assisted electrophoretic deposition, electrohydrodynamic printing, laser-induced photoreduction and so on.

3. BENCHMARK (TEST PIECE ARTIFACT)

One of the most important prerequisites of utilization of AM as precision manufacturing method is to evaluate process and equipment integrity. This could be achieved via two major methodologies: (1) through a series of direct measurements of machine and process characteristics and (2) through measurements of manufactured test artifacts [18] by methods like X-ray computed tomography (XCT) [19] or CMM [20]. Prior methodology is associated with condition monitoring (CM) methods such as acoustic emission (AE), closed loop control systems, high speed cameras, etc. Later methodology is related to build a part with various features such as holes, notches, bosses, tubes, angles, etc., in different shapes to evaluate capabilities and limitations of an AM system as well as to apply system improvements by linking specific errors measured in the test artifact to specific sources in the AM system [18]. An example of such test pieces is shown in figure 7. Such benchmark includes several features like flat base, tubes, cones, cylindrical holes, angled surfaces, spheres, hollow cube and cylinders. Several researchers work on optimum structure of benchmarks [21, 22]. However, there is no standardized artifact to detect all the faults that could occur during the AM processes. According to [18] the smallest features could be achieved by selective laser melting (SLM) process is 0.2 mm thin wall and 0.25 mm cylindrical section diameter. As shown in figure 8, SLM machine fails to build top side of the lateral cylindrical hole and hollow cube.

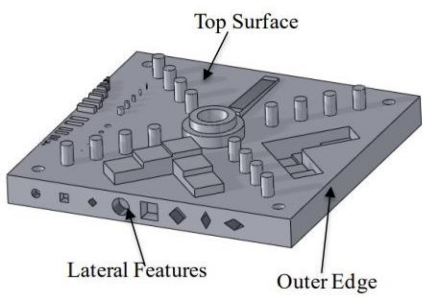


Figure. 7 An example of test artifact with different features [18].

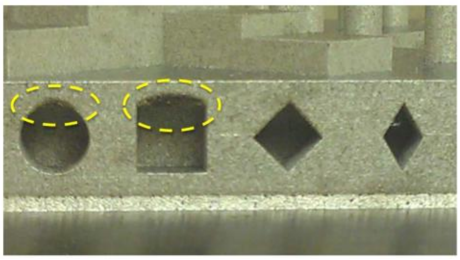


Figure. 8 SLM deficiencies in manufacturing highlighted features [18].

4. OPTIMIZATION FOR PRESICION ADDITIVE MANUFACTURING

To utilize AM as a precision manufacturing process, effective parameters should be identified and optimized for lower porosity and surface roughness, better dimensional accuracy, lower thermal gradient, cooling rate, etc. These parameters include: process type, laser diameter, scan strategy, type and size of powder particles, size of melting pool, etc. Attempts are made to achieve optimum process and parameters setup [23, 24], however, there is no reliable standard yet. For example, in [23], authors develop a neural network based geometry compensation to predict part deformation after solidification which is lowering the part geometrical accuracy and limit that by the use of optimum build orientation. Another solution is to shorten laser beam to avoid large HAZ and melting pool. Authors in [24] used ultra-short laser pulses to fabricate micro-scale parts by means of stereolitography. This requires very close control on process parameters. Another solution for more precision and integrity could be achieved by hot isostatic pressing (HIP) process [25]. That leads to higher density and accuracy by lowering the porosity inside the part. To predict process output, more accurate models are needed. In some cases, part boundaries could be fabricated with more conservative parameters. For example, laser power could be decreased to create smaller melting pool or lower layer thickness. This strategy may also lead to better tensile and fatigue properties.

5. PROCESS MONITORING AND NON-DESTRUCTIVE TESTING

Monitoring and qualification are two important factors in fabricating precision parts. There are several monitoring and evaluating systems such as high-speed digital camera systems, scanning electron micrographs (SEM), micro-computed tomography (μCT), laser CMM, etc. For example, Khademzadeh et al. [26] used both μCT and SEM to evaluate micro porosity and micro-scale dimensional accuracy of parts produced by μDMD process. One of the important factor in the use of CT is the effect of surface roughness on dimensional measurements. This leads to a systematic error, however, CT scan seems to be the only way to evaluate both dimensional accuracy and internal defects level. According to [27], internal diameters are larger than CMM reference while external dimensions are smaller. In case of processes such as inkjet or LIFT, the need of close process monitoring is major concern. In most cases, high-speed cameras take care of process monitoring and parameters control.

6. DISCUSSION

Conventional additive manufacturing processes such as SLM have some deficiencies which make them inappropriate in case of micro-scale fabrication. However, new process developments provide micro-scale part fabrication by means of AM and such processes have found their position among conventional processes in high-tech industries. Nowadays, term “micro-AM” become common in micro-scale industry, however, more studies are needed to improve micro-AM systems and their production quality. Processes such as inkjet or LIFT have major potential and capability for even nano-scale fabrication. The rate of production are getting higher and new processes are created for different applications. These methods produce no waste and are more flexible and functional than prior methods. There are some limitations such as disability in fabricating overhang and hollow structures which require additional post-processing.

Neural network and finite element methods provide process optimization means and thanks to them, part distortion and residual stress are now predictable. In-situ monitoring are usually done by means of high-speed camera and provide very useful information about melting pool, geometry of droplets, possible defects formation and many other major factors. Moreover, µCT and laser CMM are powerful tools to evaluate dimensional accuracy and precision of the produced parts.

7. CONCLUSION

In this paper, the applicability of AM as a precision manufacturing process is discussed. Inkjet and LIFT process are described in detail. According to presented evidences, lots of studies are needed to characterize effect of each parameter by itself as well as in combination together to achieve optimum result. Benchmarks are powerful tool to identify process capabilities, but they should be more general. Finer powders should be produced for better dimensional accuracy. Advanced monitoring systems are a major requirement and more investigations should be done on the use of high speed cameras. Combining AM with subtractive processes might be a good idea in order to achieve higher accuracy and surface finish. It is concluded that AM could be an ideal solution in case of manufacturing precision parts. AM has bright future as a micro-fabrication process, however, there are some deficiencies that should be overcome.

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Design and Feasibility Analysis of a Solar PV System for Street Lighting in a University Campus

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Abstract: Due to global concern on climate change, renewable energy is also attracting both public and private investments to supply energy in Bangladesh as a developing country. Increasing the percent share of total energy produced from renewable energy is vital for achieving a sustainable energy growth. In this research paper, a PV(photovoltaics) solar system has been designed for the purpose of street lighting at Shahjalal University of Science and Technology (SUST), Sylhet, Bangladesh. The analyses for economic feasibility and greenhouse gas emission of the proposed solar street lighting system have been conducted using a clean energy management software namely 'RETScreen'. For a project lifetime of 25 years, the equity payback period for the solar PV system is found to be as low as 13.6 years. The internal rate of return (IRR), net present value (NPV), benefit cost ratio (BCR) and annual life cycle savings are found to be about 7%, BDT 35690, 2.6 and BDT 1430, respectively. As a result, it can be concluded that the implementation of the solar PV systems is economically viable. Moreover, a total reduction of 11.42 tons of CO_2 emission per year is expected from replacing fossil fuel based electric energy which indicates a great environmental impact for the better world.

Keywords: Solar energy, photovoltaics (PV), street lighting, financial analysis, emission analysis.

1. INTRODUCTION

Bangladesh is a developing country of South-Asia with a large population. For maintaining the lifestyle of its citizens, it has a huge energy demand. Mitigating the existing energy crisis is a great concern for its government. Throughout the world fossil fuel is the main source of energy with a contribution of 79.68% of total energy consumed whereas Bangladesh consumes 73.8% of total energy [1]. Energy from electricity is the most vital form of energy in Bangladesh. It gets most of its electric energy from fossil fuel where the largest share is from natural gas about 46.96% of total energy and the share of electricity from heavy fuel oil (HFO), captive power plants, high speed diesel (HSD), imported electricity, coal and renewable energy are 22.43%, 10.71%, 10.61%, 5.64% and 2.16%, respectively [2]. However, the fossil fuel is not inexhaustible. Wadud et al. [3] reported that in the year of 2030, the forecasted gas consumption in Bangladesh will be double of its present demand. The energy sector will have to face this growing demand of energy. Supplying the whole energy from fossil fuels will be devastating for the earth. Renewable energy sources such as solar, wind, biomass and hydro power can be the probable alternatives to offset the energy crisis not only for Bangladesh but also for the world.

Energy obtained from sunlight striking the earth in one hour is more than the energy consumed by human in one year [4]. In Bangladesh the present share of renewable energy to the total energy generation is only 1.49% where the major portion of total renewable energy (61.1%) is from solar energy [2]. Solar energy is the most abundant sources of renewable energy. It's one of the most potential renewable energy attracting significant drive to be harvested across the world. Due to the geographical location of Bangladesh, between 20.30-26.380 north latitude and between 88.04-92.440 east longitude, it has a great potential to harvest solar energy [5]. With an increasing attention towards carbon-neutral energy production, solar electricity using photovoltaic (PV) technology is receiving heightened attention as a promising approach towards sustainable energy production. Energy requirement for a university sourced from renewable energy will obviously play a vital role for reducing fossil fuels consumption.

Shahjalal University of Science and Technology (SUST) located at a city, namely, Sylhet in Bangladesh is a green campus having a green panorama and hills with a number of tourist attractions. Solar PV systems for street lighting is expected increase its tourist attraction. system can play a vital role in this issue. Average global solar insolation in Sylhet during 1988-98 considering the whole year was reported as 4.54 kW/m2 /day [6]. Sustainable solution using solar have been explored for a variety of application such as solar boat, solar-powered wheel chair, solar powered base station of mobile networks, etc. [7,8]. Sowe et al. [9] investigated on the economic viability of a c-Si module based power plant and found it as an economically feasible alternative. In their work, they also found that the IRR, PBP, BCR were 9%, 8.35 years and 1.82, respectively. Mondal [10] argued that only financial analysis is not sufficient to appreciate the investment on energy sectors, environmental impacts should be assessed as well. In a research, Aung and Myint [11] investigates a solar PV system for the purpose of street lighting.

So far, the literature survey reveals that there is a scarcity of research work done investigating on the economic feasibility of solar PV systems for street lightings. The present work aims at designing a PV(photovoltaics) for the purpose of street lighting at Shahjalal University of Science and Technology (SUST), Sylhet, Bangladesh. The economic feasibility and CO_2 emission savings by implementing the proposed solar street lighting system have been conducted using a clean energy management software namely 'RETScreen'.

2. METHODOLOGY

At first, the relevant data were collected from the existing street lighting system to calculate the required energy for an electric poll. After a market survey, the suitable models for solar panels, storage batteries, charge regulators and the LED lamps were selected. The sizing of the solar PV system has been conducted on the basis of previous research works [12, 13] that is detailed at the results and discussion section. For the analysis of the economic viability and estimation of the greenhouse gas emission, a clean energy management software namely 'RETScreen' and the well-known Microsoft Excel are used.

The net present value (NPV), internal rate of return (IRR), benefit cost ratio (BCR) and payback period (PBP) methods are determined using the RETScreen software to check the economic viability of the proposed solar project. The NPV for the life cycle cost of the solar project is also calculated using the Microsoft Excel.

Net Present Value (NPV) shows the difference between the present value benefit and present value cost, which can be calculated as below [9]:

$$NPV = \sum_{n=0}^{N} \frac{\mathrm{P_n}}{(1+\mathrm{i})^{\mathrm{n}}} - \sum_{\mathrm{n}=0}^{\mathrm{N}} \frac{\mathrm{Q_n}}{(1+\mathrm{i})^{\mathrm{n}}} = PVB - PVC$$

where, P_n is expected benefit at the end of year n, Q_n is expected cost at the end of year n, i is discount rate, n is project duration in years, N is total project period, PVB is present value benefit and PVC is present value cost.

The interest rate which can be earned on the unrecovered project balance of the investment, is known as the internal rate of return (IRR). The internal rate of return (IRR) can be determined while the discount rate, i equals to IRR and NPV=0 using the following equation [9]:

$$\sum_{n=0}^{N} \frac{\mathrm{P_n}}{(1+\mathrm{i})^{\mathrm{n}}} - \sum_{\mathrm{n}=0}^{\mathrm{N}} \frac{\mathrm{Q_n}}{(1+\mathrm{i})^{\mathrm{n}}} = 0$$

The benefit cost ratio (BCT) is estimated from the ratio of the total present value benefit (PVB) with the total present value cost (PVC) as below [9].

$$BCR = \frac{PVB}{PVC}$$

Payback period (PBP), N is calculated as the period in years while the following equation is satisfied [9]:

$$\sum_{n=1}^{N} (P_n - Q_n) = 0$$

If the net present value(NPV) is greater than zero, it means that the project will add value to the farm or investor and create wealth for shareholders [14]. If the IRR is greater than the discount rate, the PV project is considered as the acceptable and viable project. The BCR value greater than one indicates the profitable PV project. Life-Cycle Costing (LCC) is the sum of all significant costs incurred for a product or a project over its lifetime and is determined by adding all relevant major costs [15].

3. RESULTS AND DISCUSSION

In order to assess the existing grid-connected lighting system established at different roads in the studied university campus, the existing number of electric polls were counted and found to be about 126. The details of different sorts of electric lighting systems currently available in the campus including the peak energy consumption are given in Table 1. The total energy consumption is calculated assuming the lighting system runs for an average of 11 hours from evening to morning in a day. It is seen that most of the existing lamps are fluorescent tubes and flashlights having relatively higher electric consumption. The total daily energy consumption is calculated to be 61.78 kWh per day which is substantial energy consumption. For maintaining similar illumination, two existing lamps can be replaced by two (light emitting diode) LED lamps having 20 watts each. As a result, total daily energy consumption from 126 pairs of LED lamps (126 electric poles) for same period of operation (11 hours) is calculated to be 55.44 kWh/day which is lower than the existing system.

Table 1. Details of existing electric appliances at SUST.

Electric appliances	Quantity	Unit power (in watts)	Daily energy consumption (in kWh/day)
Energy savings bulb	32	23	8.10
Fluorescent tube	112	40	49.28
Flashlight bulb	8	50	4.40
		Total	61.78

3.1 Design of the Solar PV System

An off-grid system as a stand-alone PV system is considered in this research work. A simple schematic diagram for the solar PV street lighting system with its components is shown in the Figure 1. The has mainly five components, namely, a solar panel, charge regulator, battery and two LED lamps. In the present work, at first, a grid electricity based electric pole is designed as a solar PV based one and economic feasibility analysis is performed for the single electric pole. Finally, total financial analysis is carried out for the solar PV system for all 126 electric poles in the university campus. The total costings and benefits are simply the multiple of those associated with of a single electric pole.

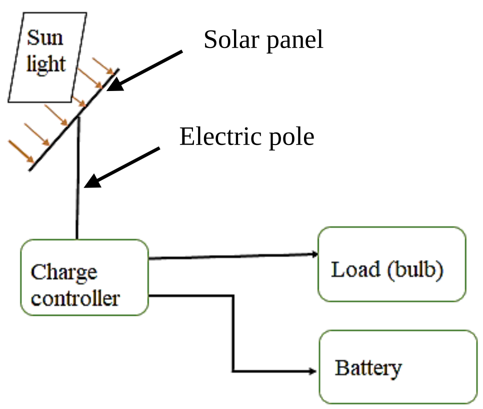

Figure 1. A simple schematic diagram for the solar PV street lighting system.

Energy consumption and sizing of a PV panel

The energy consumption of one electric poll for SUST solar street lighting project is shown in Table 2.

Table 2. Daily energy consumption for an electric pole based on solar energy.

Particulars	Quantity
LED bulb (load)	2
Unit power	20 watts
Duration of running per day	11 hours
Daily energy consumption	0.44 kWh

The required energy to supply from the solar system, R_e is calculated from the ratio of the total energy consumption per day and the overall efficiency of different system components as below. In this work, the overall efficiency is considered 80%.

$$R_e = \frac{Daily\ energy\ consumption}{overall\ efficiency}$$

$$R_e = \frac{R}{\eta_{comp}} = \frac{0.44\ kWh}{.8} = 0.55\ kWh$$

The peak power, P_e can be determined by the ratio of R_e and average sunshine hours in that location. The average sunshine hours in Sylhet region is reported to be about 6.6 hours/day[17].

$$P_e = \frac{R_e}{average\ sunshine\ hours}$$

$$P_e = \frac{0.55\ kWh}{6.6} = 0.84\ kWh$$

The total current for the solar PV system needed can be found by dividing the peak power with the system voltage as follows. For the low energy required, the system voltage is considered as 12 V for the present work.

$$I_{dc} = \frac{Peak\ power, P_e}{system\ DC\ voltage} = \frac{0.84}{12} = 7\ A\ (amperes)$$

As the solar PV system for street lighting is designed to work at night only, it is basically based on the storage battery. A cost-effective solar panel having a higher power (>>40 watts) and a short circuit current (>7 A) can be chosen. In this research, the solar panel was selected with Model Name: GOPV150Wp 156P 36 SERIES and the details are given in Table 3.

Sizing of the DC battery and charge controller

Total daily energy requirement for the street lighting is 550 Wh and two days are considered as the days of autonomy with one day without sun. Rough energy required is defined as the product of total energy and the days of autonomy, so it is 1100 Wh. For the safe storage of energy in battery, depth of discharge should be considered as 80%. It means that 80 percent of the available energy will be delivered while 20 percent remains in reserve.

$$Actual\ energy\ required = \frac{Rough\ energy\ required}{Depth\ of\ discharge}$$

$$= \frac{1100}{0.8} \cong 1375\ Wh$$

So, the capacity of the battery can be determined by the ratio of the actual energy required and the DC voltage of the battery. In this research work, a 12V battery is considered complying with the system voltage adopted.

$$Capacity\ of\ the\ battery = \frac{energy\ required}{battery\ voltage} = \frac{1375}{12}$$

$$= 115\ Ah\ (Ampere.hour)$$

Therefore, a storage battery with good reliability and lifetime having higher capacity than 115 Ah. In this research, the model selected for storage battery having a capacity of 120Ah is also shown in Table 3. Depending on the system voltage and current, a charge controller is selected with a rated current and voltage of 10 A and 12 V, respectively. The detail specifications of all components for the solar PV project for street lighting at SUST are given in the table and it also includes the approximate procurement costs for each components.

Table 3. Detail specifications and price of different components of the solar PV project [16].

Items	Quantity	Model name	Specifications	Price (in BDT)
Solar panels	1	GOPV150Wp 156P 36 SERIES	Capacity: 150 W Type: Polycrystalline-Si Efficiency: 15.6% Lifetime: 25 years Size:1470mm×680mm×35mm Weight: 12 kg	6478
Charge controller	1	Tracer1305LPLI	Rated current: 10 A Rated voltage: 12V	3944
Battery	1	Eagle DC 120-12	Type: Sealed rechargeable battery Capacity: 120 Ah Voltage: 12 V DC Weight: 34 kg Life cycle: 5 years	9467
LED Bulb	2	THL-20	Power ratings: 20 W Voltage:12v DC	852

Life cycle: 50000 hrs

3.2 Cost Analysis

The costs involved in the project lifetime include components' costs, operating and maintenance (O&M) costs, installation costs and replacement costs. To find the replacement costs, it is necessary to find the lifetime of all components. As the selected LED bulbs have life hours about 50000 hrs. So, the light should be replaced after a certain period. Life time of LED bulb can be calculated assuming that it runs 11 hours per day and is given below:

$$Lifetime\ of\ \ an\ LED\ bulb = \frac{Working\ life\ time}{working\ hours\ per\ night}$$
$$= \frac{50000}{11} hours = \frac{4546}{365} = 12.45\ years$$

So, every 12.5 years the LED lamps should be replaced and it is clearly observed that during the project life time of 25 years, they should be replaced once only. The installation cost is considered as 10% costs of solar panels. The operation and maintenance (O&M) cost is assumed about 3% of PV cost. The costs for the solar PV street lighting project have been illustrated in Table 4.

The total development cost for the SUST street light system considers a single electric pole that is the sum of first four costs given in Table 4. And it is found to be BDT 22241. Battery warranty is one year, though its lifecycle is claimed as 5 years whereas the LED bulb has 12.5 years of working life time. The charge controller has warranty of three years and the solar panel has warranty of twenty-five years. Considering the warranty and their price, it is assumed that about 25% of the total cost of battery, panel and charge controller as replacement cost after each four years. So, the replacement cost is found to be about BDT 5000 after each four years.

Table 4. Costs for the SUST solar street lighting project consindering an electric pole.

Items	Quantity	Unit cost (in BDT)	Total cost (in BDT)
Solar panel	1	6478	6478
Battery	1	9467	9467
Charge controller	1	3944	3944
LED lamp	2	852	1704
Installation cost		10% of PV cost	648
Operation and maintenance cost per year		3% of PV cost	195
		Total cost	22436

3.3 Economic Analysis and Emission Impact

Financial analysis is the process of determining the finance related activities for a certain project to check whether the project is producing substantial profit or not. It mainly deals with the income statement, balance sheet and the cash flow statement. RETscreen which is a renowned renewable energy technology software has been selected for the financial analysis. In this section financial analysis of the developed solar model has been analyzed. Several factors are considered for this analysis. According to Bangladesh bank, the inflation rate and the discount rate or minimum interest rate in Bangladesh are found to be 5.5% and 5%, respectively [18]. The fuel cost escalation rate is considered about 7%. The electricity bill rate for the street lighting system for Bangladesh was considered as 7.17 BDT/kWh [19].

After considering all types of costs, required energy and present energy prices, the RETscreen software provided the project costs or saving income summary. On the basis of the fuel cost, the annual savings per year is about BDT 1430. From the financial viability, the equity payback period (PBP) is found 13.6 years. The internal rate of return (IRR) is found to be 7% which is more than the discount rate 5% as considered. For verifying the results, the IRR and PBP values are also calculated using the Microsoft Excel and are found to be in a good agreement. The benefit cost ratio (BCR) is also found to be 2.6 which indicates the project as an economically viable one. The summary report of the financial viability using 'RETScreen' software is given in the Table 5.

Table 5. Financial viability of the solar PV project for street lighting.

Items	Unit	Rate/Amount
Pre-tax IRR – equity		7%
Pre-tax IRR – assets		7%
After-tax IRR – equity		7%
After-tax IRR – assets		7%
Equity payback	Year	13.6
Annual life cycle savings	BDT/year	1427
Benefit-Cost (B-C) ratio		2.60
Net present value	BDT	35685

The yearly cumulative cash flow using the RETscreen software is shown in Figure 2. When the income is higher than the expenses, the cash flow is positive. Again, when the income is lower than the expenses, the cash flow is found to be negative. In the break-even point, the total income equals to the total expenses is equal. The number of years required to reach break-even point is the payback period which is observed to be 13.6 years. As shown in the figure, the project investor is supposed to get profit after 13.6 years in a project life span of 25 years

Using the Microsoft Excel, the net present value of life cycle costing (LCC) is estimated to be about BDT 52850. The NPV for the proposed solar street lighting system is much more than zero. If the net present value(NPV) is greater than zero, it means that the project will add value to the farm or investor and create wealth for shareholders [14]. Therefore, it can be said that the solar PV project is going to create wealth for the shareholders. The above results in the present work is found to be in good agreement with the work by Sowe et al. [9]. In their work, they investigated on the economic viability of a c-Si module based power plant and found that the IRR, PBP, BCR are 9%, 8.35 years, 1.82 respectively. On the basis of the savings on electricity bills, the annual savings per year by implementing a solar system for an electric pole only is about BDT 1430 as mentioned earlier. A complete solar PV system for street lighting in SUST campus is expected to give a total annual savings of BDT 180,180.

The emission analysis is performed to determine annual reduction of CO_2 gas emission by implementing the proposed PV system. In Bangladesh, grid electricity is produced from natural gas, petroleum, coals and hydroelectricity. Hossain et al. [20] reported in their thesis, an off-grid solar PV system is capable of reducing 506.3 g of CO_2 by replacing 1 kWh of grid electricity. From the data in Table 1, the total electricity consumption for all 126 electric poles in a day is estimated to be about 22550 kWh annually. In this present work, replacing 22550 kWh grid electricity by implementing the whole solar project is expected to reduce 11.42 tons of CO_2 emission in a year. It is undoubtedly going to be a vital contribution to mitigate the global warming.

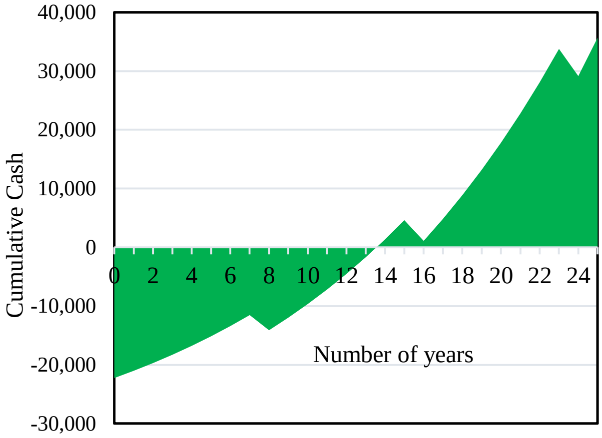

Figure 2. Cumulative cash flow graph for the solar PV project for the street lighting at SUST.

4. CONCLUSIONS

Increasing the share of renewable energy for the total energy consumption is a crying need for a developing country like Bangladesh. Financing a project based on renewable energy needs to be attractive and economically viable to prospective entrepreneurs. Solar irradiance in Bangladesh promises a better perspective of utilizing solar energy technologies. The present paper aims at investigating a current street lighting system for a university campus and designing a solar street lighting system to replace the existing system. It also evaluates financial and environmental benefits of the proposed solar street lighting system. A clean energy management software 'RETScreen' and Microsoft Excel were used for various analysis in the paper. With the project lifetime of 25 years, the equity payback period for the solar PV system is found to be 13.6 years. The net present value of life cycle costing (LCC) is estimated to be about BDT 52850 using the Microsoft Excel that is larger than that found using RETScreen (BDT 35690). The internal rate of return (IRR), and benefit cost ratio (BCR) are found to be 7% and 2.6, respectively. A complete solar PV system for street lighting in SUST campus is expected to give a total annual savings of BDT 180,180. As a result, it can be concluded that the implementation of the solar PV systems is economically viable. Moreover, a total reduction of 11.42 tons of CO_2 emission per year is expected from replacing fossil fuel based generation which indicates a great environmental impact for the better world.

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