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Analysis of Energy Utilization in 3D Printing Processes

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Abstract

Manufacturing paradigm is shifting from production-centric to service-oriented to meet emerging requirements, such as highly customized products and public “green” awareness. 3D printing, using a layered production mechanism, becomes a featured technology worldwide. This is attributed directly to its ability to efficiently fabricate complex and on-demand product. In this paper, energy consumption of 3D printing processes is focused and analyzed in the context of environmental impact. A preliminary study is conducted on a 3D printing process, where energy is divided into two parts, primary and secondary energy. Energy models were then proposed for each part, providing a fundamental approach for energy estimation and optimization, and subsequently, improving actual production settings and supporting 3D printing product re-design. The findings reported in this research, form an important knowledge piece, which complements life cycle assessment of 3D printing processes.

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Keywords: 3D printing; energy analysis; fused deposition modeling; energy utilization; sustainability.

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1. Introduction

Manufacturing, a fundamental industry to provide people with daily-use products and services, has been revitalized in recent years. A number of strategic, long-term development programs were launched at the national or international level, such as "Accelerating U.S. Advanced Manufacturing", "Industrie 4.0" in Germany, "Horizon 2020" in European Union, and "China Manufacturing 2025". All these plans target at high-end manufacturing technologies to achieve high intelligence for autonomous production, flexibility for personalized products, and environment-friendly manufacturing. Meanwhile, living a "low-carbon" life has been widely respected and is gradually adopted by the public, thus, energy consumption in corresponding manufacturing processes attracts more attention. Many research works have been reported analyzing, modeling or optimizing energy utilization [1-3]. However, most of them studied the traditional metal-cutting processes. Limited energy-related research is conducted on emerging manufacturing technologies.

3D printing, also referred to as additive manufacturing in many cases, is a global-featured technology. Its emergence and 30-year development promises a more intelligent, sustainable, and cost-effective approach to make highly customized products. The expansion of 3D printing into commercial and industrial production achieved significant scale. According to Wohlers Associates, the market for 3D printers and services was worth $2.2 billion worldwide in 2012, up 29% from 2011 [4]. It is also recognized that the real integration of additive technologies into commercial production is more a matter of complementing traditional subtractive technologies rather than displacing them entirely. On one hand, industrial use of 3D printing shortens product development lead time and manufacturing cycle, for example, a key aero-engine component produced by General Electric (GE) China Technology Centre was printed with 30% reduction in production cost and 40% in lead time. On the other hand, consumer use of 3D printing enables personalized part and rapid sample fabrication, which has even larger application potentials.

Although a more extensive adoption of 3D printing is foreseeable and promising, its accumulated environmental

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impact, particularly energy-efficient performance, would be an important matter if no careful study is conducted. In this paper, energy utilization in 3D printing processes is focused and analyzed. The remainder of the paper is organized as follows. Section 2 presents a brief introduction of 3D printing technology and an up-to-date literature survey of its sustainability research. A detailed energy consumption of a 3D printing, consists of two energy parts, is analyzed in Section 3. Subsequently, it is suggested to include energy consumption in the multi-objective decision-making processes in Section 4, and the findings in this paper are summarized and highlighted in Section 5 with future works in plan.

2. State of the art

A formal definition of additive manufacturing is given by American Society for Testing and Materials (ASTM) Committee F42 as "*a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies*", and 3D printing is defined as "*the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology, often used synonymously with additive manufacturing*" [5]. Various technologies were developed, including Fused Deposition Modeling (FDM), Binder Jetting (BJ), Selective Laser Sintering (SLS), Stereo Lithography Apparatus (SLA), Laminated Object Manufacturing (LOM), and Laser Engineered Net Shaping (LENS) [6].

Take FDM as an example. A printed part is typically built layer upon layer, using plastic filament or metal wire unwound from a coil. Figure 1 depicts a schematic diagram of a 3D printer. The move mechanism used is often an X-Y-Z rectilinear design, resembling 3-axis CNC machine tools, although other mechanical designs are also available, e.g. delta robot 3D printers.

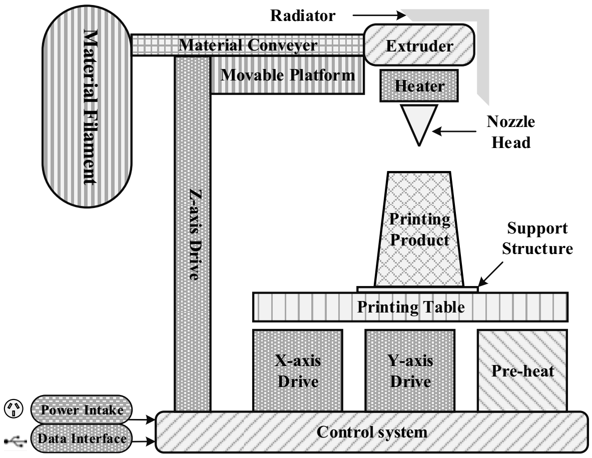

Figure 1 A schematic diagram of a 3D printer

2.1. Sustainability benefits

In general, 3D printing processes possess better environmental characteristics [7]. Since they only utilize the amount of material required to consolidate the final part, and in some cases a small amount of support structure, they are highly resource-efficient and reduce the buy-to-fly ratio drastically [8]. In terms of low-carbon, there are five primary environmental benefits [9] as follows.

1. Reduced amount of raw material required in the supply chain. Hence, mining and primary material ores processing is reduced;
2. Reduced need for energy-intensive manufacturing processes, such as casting, and wasteful/harmful materials, such as cutting fluids in CNC machining;
3. Flexibility to design more efficient components with better operational performance;
4. Reduced the weight of products, contribute to carbon footprint improvement in service on the vehicle into which they are integrated, such as aircraft;
5. Parts could be manufactured closer to the point of consumption, reducing the energy consumption in logistics.

A literature review of societal impact conducted by Huang et al. [6] confirmed many positive impacts of 3D printing processes, including reduced environmental impact, but also identified that more research is needed to accurately evaluate the energy consumption of various processes. Existing research on sustainability performance of 3D printing processes is briefly reviewed in next section.

2.2. Energy-related research

The study by Gutowski et al. [10] showed that emerging processes were capable of working to finer dimensions and smaller batches but at lower rates, which resulted in very large specific energy requirement. They stated that "the seemingly extravagant use of materials and energy resources by many newer manufacturing processes is alarming and needs to be addressed". Drizo and Pegna [11] provided a comprehensive review of environmental impact assessment of existing additive technologies with an emphasis on portable measurement and evaluation methods. They discussed some important unresolved issues, specifically with respect to materials, due to the lack of available data.

An initiative known as Cooperative Effort on Process Emissions in Manufacturing (CO2PE!) coordinates international efforts to analyze and improve the environmental impact for a wide range of emerging manufacturing processes with respect to their direct and indirect emissions [7]. In this framework, Kellen et al. pointed out that quantitative analyses of environmental impact is still limited and proposed a systematic Life Cycle Inventory (LCI) data collection approach [12]. Based on such an approach, they described the development of parametric process model to estimate environmental impact of SLS processes, and found two dominant design features influencing energy consumption, i.e. build height and volume [13]. Sreenivasan and Bourell also presented a sustainability study on SLS processes [14], where four component-based energy segments were calculated. They are energy consumption of chamber heater 36%, stepper motors 26%, roller drives 16%, and laser transmitter 16%. Later, they reported another experimental study with a similar energy proportions, and suggested to develop an improved heat management system, or adopt energy-efficient laser transmitter for less energy utilization [8].

Weissman and Gupta [15] conducted a comparison study of eight different manufacturing processes, including FDM, SLS, CNC machining, injection molding and forming. The results indicated the energy consumption of FDM and SLS heavily relies on the volume of the products. Mognol et al. [16] investigated optimal parameter selection with the purpose of reducing energy consumption. They tested various parameter combinations, part orientations and positions in three representative 3D printing systems, and concluded that minimizing manufacturing time is critical to reduce energy consumption, but there is no general rule for energy optimization for all systems. Santos et al. developed a decision computational tool integrating eco-design principles, and studied energy utilization in three types of interior part fillings in a FDM system [17].

Le Bourhis et al. presents a new methodology where material, fluids and energy flows consumed are all considered. Their research was based on a Direct Laser Solid Forming (DLSF) process, where energy consumption was divided into three parts for laser system, cooling system and motor drives, respectively [18]. A predictive model integrated in the design step was then proposed for environmental impact assessment [19]. Meteyer et al. presented an energy and material consumption model of a BJ process, and verified the model in three different processes, printing, curing and sintering [20]. Xu et al. extended the research and focused on the printing stage of BJ process. The total energy consumption was modelled as a function of part geometry and printing parameters, such as part orientation and layer thickness [21]. In mathematical analysis conducted by Paul and Anand, energy was calculated as a function of the total area of sintering and correlated to the part geometry, layer thickness and build orientation [22]. However, only the laser energy was analyzed in their research while other energy components such as heating energy, platform energy were ignored. Baumers et al. presented a comparative assessment of energy utilization of two laser sintering systems [23]. In their study, energy was divided into four types, job-dependent, time-dependent, geometry-dependent, and Z-height-dependent energy components. Among them, time-dependent component was identified as the main contributor. Strano et al. [24] took product quality, i.e. surface roughness, into consideration, and developed a computational methodology for simultaneous minimization of surface roughness and energy consumption. Franco and Romoli evaluated the effect of the energy density in processing of two polymeric materials by analyzing the geometrical features of linear sintered structures. The volumetric productivity and the energy intensity of the process were calculated [25]. Telenko and Seepersad considered energy consumption in both material refinement and part printing processes, and compared SLS with an injection molding process. The results indicated that the manufacturers may save energy using SLS for small-volume production [26].

Based on abovementioned works, it is evident that research on energy analysis and estimation, as well as environmental impact assessment of 3D printing processes is still lacking. Most research only considers one specific process or even one stage of it. The relationship between energy utilization and design parameters/printing configurations is unclear. Therefore, a close analysis of energy utilization is in demand.

3. Energy analysis

Firstly, the analytical approach proposed by Munoz and Sheng [27] for cutting technologies is borrowed to determine the environmental analysis dimensions of 3D printing processes. Figure 2 illustrates the three analysis dimensions, i.e. energy dimension, material dimension and time dimension. Energy intake is basically attributed to electric energy and material-embedded energy. In printing processes, electric energy is transformed into thermal and mechanical energy, and discharged mainly as heat loss. In material dimension, primary material normally refers to the required material of a printed part, which could be a mix of several materials in printing processes. Support structure or binder material is generally considered as auxiliary material. The “waste” material sometimes can be recycled and re-produced. For instance, the polymer filament can be fabricated from post-consumer plastic waste, besides from virgin resins. The meaning of printing time is straightforward.

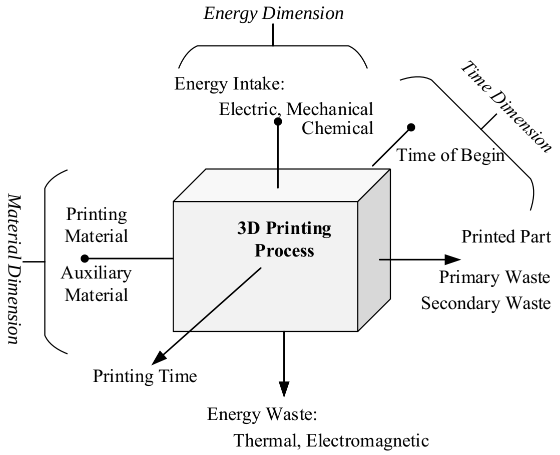

Figure 2 Environmental analysis dimensions of 3D printing processes (modified from [27])

Again, take the FDM printer (Figure 1) as an example, a part is printed by extruding small beads of materials that harden immediately to form layers. A thermoplastic filament or metal wire coil is unreeled to be supplied to a heated extrusion nozzle head. 3-axis drive motors are employed to move the head and adjust the flow. Pre-heating and cooling of the work table is also required in some printing processes. The total energy consumption is decomposed into two parts in this research, primary energy and secondary energy.

3.1. Primary energy

Primary energy represents the energy required to change the material form and properties in a printing process, can also be regarded as intrinsic or direct printing energy. In FDM, it is the essential energy to heat the thermoplastics past their glass transition temperature to melt the material. This is the basic, material-dependent energy component.

For crystalline material or eutectic mixture, which has a fixed temperature in the melting stage (melting point), this part consists of two sub-components, that is heating energy $Q_{heating}$ and melting energy $Q_{melting}$. They can be calculated as,

$$Q_{heating} = 1000 \cdot c \cdot m \cdot \Delta t \quad (1)$$

where $Q_{heating}$ – heating energy (J),

c – specific heat capacity ($kJ / kg \cdot C^{\circ}$),

m – mass of the material (kg),

Δt -temperature difference (C°).

$$Q_{melting} = q \cdot m \, (2)$$

where $Q_{melting}$ – melting energy (J),

q - enthalpy of fusion (J/kg).

For non-crystalline material, such as Acrylonitrile Butadiene Styrene (ABS), the temperature keep rising during the melting process, therefore, only Equation (1) can be applied. Nevertheless, in practices, it can be indirectly calculated by the energy utilization of the nozzle head heater, as expressed in Equation (3).

$$E_{melting} = V \cdot P \cdot v / 250 \cdot \pi \cdot d^2 \, (3)$$

where $E_{melting}$ – energy utilization of the nozzle head heater in the melting stage (J),

V – volume of the printed material (mm^3),

P – power of the heater (W),

v– feed rate of the feed roller (m/s),

d – diameter of the filament (mm).

3.2. Secondary energy

The other part of energy consumption is called secondary energy, which means the energy needed by ancillary components, such as drive motors or table warm-up, to realize and support the printing process. It can be considered as indirect printing energy. This part is process-dependent energy component, which highly influenced by the capability of a 3D printer (consumer components), product design (geometry and dimensions), and printing settings and conditions (layer thickness and part orientation). The energy consumption of necessary environment safety equipment, such as ventilation system, is also included.

Figure 3 depicts an activity-based model, representing different stages of a complete printing process. Energy consumption in each activity shows distinct characteristics. Based on existing research, there are four main activities in a typical 3D printing process (on the left-hand side), that is setup, pre-heating, printing and cooling. Printing process can be further divided into four sub-components, drive axis, heating and melting, material supply and miscellaneous component. Among them, heating and melting is primary energy (darken). State-based approaches, e.g. discrete event modeling, state-transition modeling, can be used to divide total energy consumption into machine-component-based parts, e.g. energy consumption of nozzle heater, drive motors and cooling system. Another five supporting activities (on the right-hand side), product cleaning, material post-processing, re-processing, preparation and inventory, are closely related, and should be included to analyze energy utilization of a 3D printing process from a life cycle perspective.

Product cleaning is different from the necessary cleaning before the printing process happens. It is to remove the support structure, clean the material residue and sometimes perform additional surface processing to meet the quality requirements. The clean-out material can be recycled and prepared for inventory after post-processing and re-processing. However, these five supporting activities are excluded in current research scope.

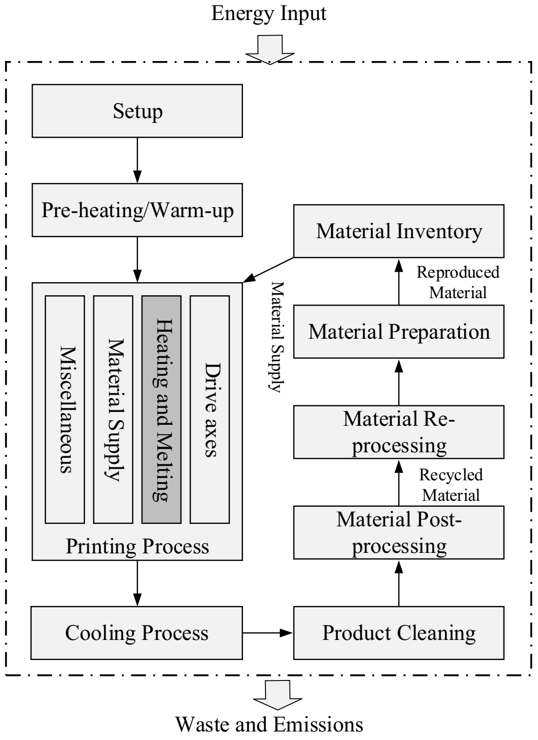

Figure 3 a process model for energy analysis

4. Support decision-making

The layer-based product building mechanism of 3D printing alters the overall manufacturing process, which has an impact on the decision-making in respect of energy utilization. The role of product design becomes even more important in determining the actual energy consumption than that in subtractive manufacturing processes. CAD models can be saved as Standard Tessellation Language (STL) file or be processed into accepted printing format, such as .obj file or .amf file, and directly used as input to a 3D printer. In this way, the connection between product design and manufacturing is shortened. AMF stands for Additive Manufacturing File, which is an XML-based open standard for describing objects for 3D printing. It has native support for color, materials, lattices, and constellations [28]. Optimal energy utilization can be incorporated in CAD model processing, slicing, and printing setup.

Figure 4 demonstrates how energy consumption supports environmental impact assessment. Energy and material consumption evaluation can be performed based a printing program, then their performance indicators are input to environmental assessment for final score calculation. Feedback from optimization processes enables both part design and program modifications.

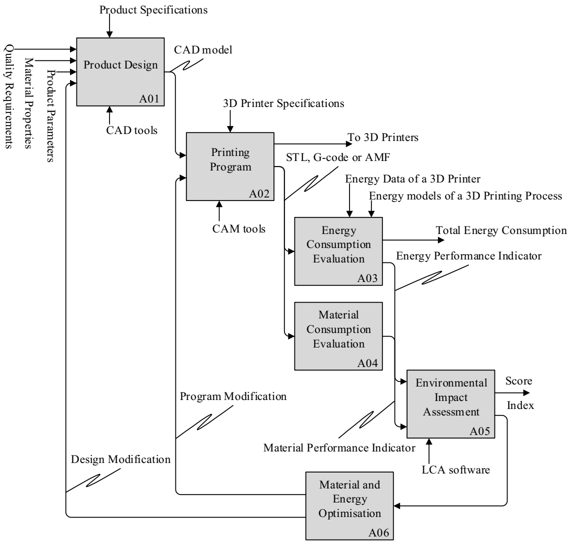

Figure 4 IDEF0 model for environmental impact assessment

Although product quality is ranked the first of importance, a reliable energy prediction is a critical factor in multi-objective decision-making. In other words, good quality of product may determine the survival and existence of a company, but efficient energy utilization will enhance a company's competitiveness. Furthermore, several 3D printing processes can be executed concurrently and interchangeably. Same part (e.g. same .stl file) can always be easily printed on different printers with consistent accuracy, on the contrary, energy consumption using different printers may differ significantly.

Here, the overall objective is to achieve optimized energy efficiency, minimized environmental impact in 3D printing processes, meeting the reasonable quality requirements. Figure 5 presents a generalized methodology for multi-objective optimization, considering product quality, total energy consumption and environmental impact. Unlike a conventional multi-objective optimization process, these objectives are not weighted and combined as one objective, instead, they are evaluated in a serial manner. Parameters are first decided based on initial CAD, and used in model-based energy evaluation. If no optimal energy is achieved, then it is recommended to perform energy optimization. However, the modified settings are only proceeded to the environmental impact assessment stage after they satisfy quality prediction. In some cases, re-design of the product is suggested.

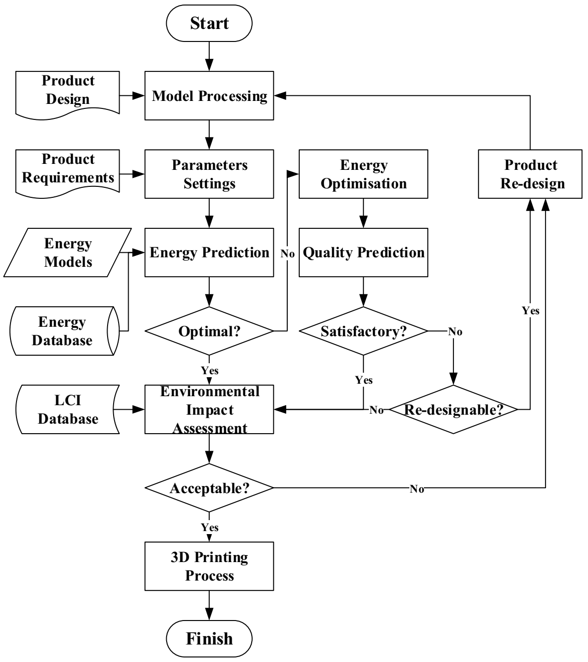

Figure 5 flow chart of an energy-informed decision-making process

It is worth noting that 3D printing is a ubiquitous manufacturing technology much closer to personal users, so full understandings of its energy utilization and environmental impact are crucial, particularly the health- and safety- related issues. For instance, ventilation system is usually a must to discharge ultra-fine particles.

5. Conclusions

With the development of three decades, 3D printing technology shows promising results and huge potentials in real production application. Numerous research has been conducted to improve the process control and product quality, however, the "green" performance is seldom considered. In this paper, a preliminary analysis of energy utilization in 3D printing processes is conducted using an analytical approach. In the energy dimension, the total energy consumption is divided into two parts, primary and secondary energy. Detailed analysis of each part is presented afterwards to provide some preliminary understandings on the pattern of energy consumption. Quantitative calculation methods and evaluation methods are useful, which collectively provide a solid foundation for comparative analysis. Lack of energy-related data currently hinders the progress. Moreover, a generalized methodology for multi-objective optimization, with inclusion of energy data, is given to support decision-making. Currently, experiment is being designed to investigate the relationship between different parameters and total energy, developing energy models, so as to facilitate the life cycle analysis and supply chain management of 3D printing. Comparison with traditional process in terms of energy utilization will also be done in future work.

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