Survey of Common Practices in Sustainable Aerospace Manufacturing for the Purpose of Driving Future Research

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Abstract

This paper reports on a survey taken of common practices in the aerospace manufacturing industry with respect to environmental stewardship and sustainable manufacturing. This review identifies several major elements with respect to sustainable manufacturing and organizes them into two groups: manufacturing related and facility related. Manufacturing related activities are subdivided into four categories: product modification, product improvement, process modification, and process improvement. Facility activities are subdivided into two groups: regulatory and general. The purpose of this review is to establish what common practices are with respect to sustainable manufacturing so that it can aid in the identification of less or uncommon practices. Identifying such practices is expected to help drive and guide future research efforts by preventing repetition of work and redundant efforts. This review identifies several gaps in current practices and provides a plan for future research addressing these gaps.

Keywords:

CIRP International Conference; Life Cycle Engineering; Aerospace, Sustainability, Sustainable Manufacturing

1 INTRODUCTION

With the increasing focus on environmental stewardship, aerospace manufacturing companies are striving to engage in more environmentally benign practices. This is evident in the increase in number and detail contained within environmental reports released, often annually, by many major aerospace manufacturing companies. The drivers for becoming more environmentally benign can range from the need to meet ever more stringent government regulations, positive publicity through publicity of environmentally benign activities, and possible economic cost savings through securing a supply of resources. The details as to what drives the desire for environmentally benign activities within these companies is outside of the scope of this review. Within the scope is an analysis of the results of these drivers.

Since the products produced by the aerospace manufacturing industry can be very similar to each other across different companies, certain trends can emerge with respect to environmental stewardship. These trends may not only reflect what is being done, but what is not being done by various aerospace companies. Establishing these trends can prove to be valuable data for motivating future work or committing future resources.

2 MOTIVATION FOR WORK

There are two motivating questions for research. The first motivating question: *What are common practices in the aerospace industry with respect to environmental stewardship?* This can be rephrased so that it provides more meaningful research answers: *What are uncommon practices?* It is important to identify the gaps in current work. This is important because it helps drive future research and future commitments while preventing redundant efforts. The second motivating question is: *Why aren't these practices more common?* This review focuses on answering the first question as a lead in to broader research. This paper wishes to identify what are uncommon or missing practices with regard to environmental stewardship in the aerospace manufacturing industry. Once this is done, work can be performed to answer the second question of *why*. Answering the second question is reserved for future work.

3 METHODOLOGY AND DATA SOURCES

This review looked at the environmental practices performed by several major aerospace manufacturing companies. These companies include but are not limited to the following (in alphabetical order):

- Airbus
- Boeing Company
- Bombardier Aerospace
- General Dynamics Corp. (Gulfstream)
- Lockheed Martin Corp.
- Northrop Grumman Corp.
- Textron (Bell and Cessna)
- United Technologies Group

Information about specific environmental practices was derived primarily from each company's environmental report. These reports are publically released and generally available. Deeper investigation into industry practices beyond publically available were not heavily pursued for a number of reasons. Foremost is that many companies were unable to share information beyond what was stated in public reports on account of it being experimental and/or involving proprietary processes and practices. This review strives to establish common practices so that companies in the industry can learn from each other. This requires that information used to establish these practices be public and commonly available. Lastly, there is an assumption that any initiatives, activities, or practices that are made available publically are assumed to be beyond the developmental or conceptual stages and have reached a level of maturity where they can be discussed, assessed, and scrutinized properly.

Beyond reports produced by companies involved in the aerospace manufacturing industry, third party sources were also used. These include scholarly or academic publications that involve research into aspects of environmentally benign aerospace manufacturing. These articles provide more detailed and objective information. Academic articles also provide insight into potential new initiatives that may be in the developmental stage, but can be assessed and scrutinized without damaging fallback onto company's who may not have fully developed the concepts. These articles essentially provide a more risk-free exchange of knowledge amongst companies.

4 DEFINITIONS AND SYSTEM SCOPE

The aerospace manufacturing industry (the industry) is responsible for producing a number of aerospace products that can range from military and civilian airplanes, helicopters, and unmanned aerial vehicles, to rockets, missiles, satellites, and space vehicles. The majority of the industry, however, is consumed with the production of military and civilian airplanes and helicopters. These products represent over 70% of the total establishments of aerospace companies and over 90% of money from sales. [13] Furthermore, the aerospace industry is responsible for approximately 2% of global man-made greenhouse gas emissions and a similarly small fraction of other man-made environmental burdens. [1][5][13] Since the production of exotic products, such as rockets, missiles, satellites, and space vehicles, represents a small fraction of the overall industry, and the industry represents an even smaller fraction of global environmental burdens, these exotic products are acknowledged, but focus is placed on military and civilian aircraft.

One method of determining a product's environmental burden is to perform a life cycle analysis where environmental inputs and outputs to the system are inventoried and their impact is assessed. The United States Environmental Protection Agency (EPA) defines four phases of life for a product: raw material harvesting, manufacturing, use, and disposal. Each phase of life consumes natural resources and energy while producing solid and water-born waste, atmospheric emissions, toxic releases, and other co-products, as depicted in Figure 1. [15]

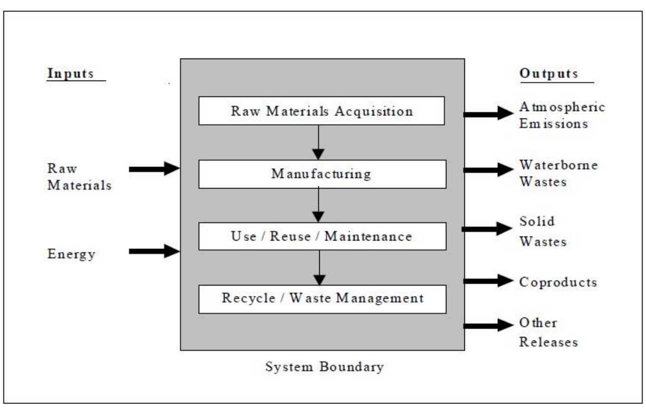

Figure 1: Environmental Protection Agency's definition of a product life cycle, its inputs and outputs

Each of these inputs and outputs places a burden on the environment and influences the overall sustainability of the product. Sustainability can be briefly defined by what are known as the Daly Rules, named for professor and economist Herman E. Daly. The Daly Rules define something as sustainable when it has three characteristics: [41]

- The element consumes renewable resources slower than the environment is capable of replenishing these resources
- The element consumes non-renewable resources at a rate slower than renewable alternatives can be found and implemented
- Pollutants and waste cannot be released faster than the rate at which the environment can process and render them benign

It is impossible to eliminate environmental burdens from a system, but it is possible to manage them such that they are more environmentally benign. It is important to note that sustainability is not assumed to be an absolute, but rather a relative measure. There is no perfectly sustainable system, only a more or less sustainable system. Likewise, there is no system that is perfectly environmentally benign, only more or less environmentally benign. It is assumed that sustainability can be used as a marker of environmental stewardship.

For the purposes of this review, special attention is given to the manufacturing phase of life for a product. Manufacturing can be defined as a gate-to-gate process where value is added to raw materials harvested from the environment to produce a product that enters the use phase once it is ready and capable of performing its intended functions in their entirety. [27][28] Since the industry under review is the aerospace manufacturing industry, burdens from the manufacturing phase are of most interest because the manufacturers are directly responsible for the burdens produced during this phase. Before moving forward, t would be useful to define sustainable manufacturing. According to the United States Department of Commerce's International Trade Administration (ITA), sustainable manufacturing can be defined as follows: [45]

Sustainable Manufacturing is defined as the creation if manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound.

Reflecting attributes of the Daly Rules, the ITA definition mentions consuming resources and producing waste. Furthermore, the ITA definition expands on the Daly Rules by adding a practical component to the definition that is necessary for any real-world industry. This is the addition of the criteria that sustainable manufacturing must include safety and sound economics.

This review is assessing an aerospace manufacturing process, which can be distinguished from other manufacturing processes by the products they produce. An example of a metalworking process in aerospace manufacturing is seen in Figure 2. [13]

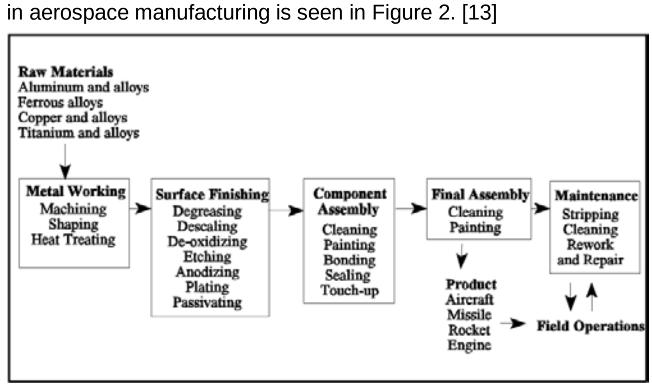

Figure 2: Five parts of an aerospace metalworking process

Each of these parts is assumed to consume the inputs and produce outputs as defined in Figure 1. These five components represent the lean definition of aerospace manufacturing. The term *lean manufacturing* is often used to describe a manufacturing process that consumes resources only for the necessary, value adding processes required to produce a product. In this review, when the term *manufacturing* is used, it is in a lean sense, focusing explicitly on the value adding processes.

Realistically, processes are not truly lean. Infrastructure must exist to support the process. This infrastructure includes manufacturing facilities to house the process, facilities for employees involved in the process, and any non-lean, but necessary auxiliary processes. In this review, when the term *facility* is used to describe an operation or process, it is assumed to imply the non-lean, auxiliary processes that are required by a manufacturing process.

5 COMMON PRACTICES

5.1 Manufacturing Practices

Manufacturing practices can be broken into four types: product modification, product improvement, process modification, and process improvement. The *product* is what is being made and the *process* is how it is made. *Modification* implies a change or alteration in the product or process, while an *improvement* keeps them the same, but more efficient or smoother running. There is some gray area between modification and improvement, but it is used here as a general means of distinguishing initiatives.

Product Modification

The industry trend seen in the aerospace industry as a whole in terms of product modification is a gradual but clear shift to more fuel efficient vehicles with larger range and larger passenger capacity. With respect to the ITA definition, future generations of planes address many issues of sustainable manufacturing. New materials, such as composites, have lower processing costs and are easier to form into complex shapes and structures. Composite processes generally produce less waste than metal processes, reducing the total mass of waste that requires post processing. Furthermore, composites do not require environmentally harsh metal surface finishing processes, such as de-oxidizing, anodizing, or plating that can produce harmful waste containing elements such as cadmium. [11][27][28][43]

The aerospace industry has gone through iterations where they modify the product to meet new or stricter demands by consumers. For instance, the Boeing 737, the workhorse of the Boeing short-range passenger-carrying fleet, was derived from earlier 707 and 727 model planes. The 737 was cheaper, more fuel efficient, and had a smaller environmental footprint than previous models built for the same purpose. Similarly, the Boeing 787 is intended to be an improvement over the similarly sized 767. The 787 is more fuel efficient, has a smaller use phase footprint, and replaces much of the traditional metal in the airframe with composites. [5] Composites have an advantage over metals like aluminum due to their increased strength to weight ratio leading to lower fuel consumption and can have smaller manufacturing costs when it comes for forming and shaping. [8]

Airbus has similarly introduced next generation aircraft differing from previous designs. Both Boeing and Airbus are considering *next-next generation* aircraft that replace the traditional fuselage-wing design with a design derived from the flying wing style of airplane. This shape would increase passenger load, would be more fuel efficient, and would have a number of other benefits. [1][5]

Product Improvement

When the cost a new aerospace product is too high, there is often effort to try to improve existing products. An example of such an improvement can be seen in the winglet retrofit package The Boeing Company offers for earlier versions of the 767. The winglets improve lift and overall efficiency of the airplane, reducing environmental burdens during the use phase. However, going upstream to the manufacturing phase, other benefits can be realizes. Foremost, with retrofit packages such as winglets for the 767, Boeing is able to improve on existing products without having to build entirely new planes. Since the retrofit package goes on existing planes, the only added manufacturing cost is that of the package itself and not a whole new plane. Similar retrofit packages and aerodynamic improvement kits exist for the 737 and the 777 series of Boeing planes. [5]

An industry-wide improvement includes elimination of chromium-based paints. Chromium in paint has been shown to be carcinogenic and a general hazard to health. Removing the requirement for this type of paint would significantly improve safety for employees. Other similar improvements include replacing toxic Halon fire suppressants with safer ones. With regard to other harmful chemicals, there has been a gradual reduction across the industry with the quantity of these chemicals used and released. Updating computer hardware and software, improvements in the textiles used for carpets and seats, new and improved on-board fuel cell technology, improved hydrophobic surfaces, amongst other improvements help increase the sustainability of the product and reduce the environmental footprint of the manufacturing process. [1][5][6][18][33][35][42][47]

Process Modification

A number of modifications can be made in the manufacturing process that can still yield a product of the same quality without having to significantly change the product itself. For instance, fabricating components through powder metallurgy processes as opposed to traditional forging processes yields parts with tighter dimensional tolerances while reducing the cost and amount of waste produced during the process. [27] Other modifications include changing the temper of metals to states that are more easily worked. Machining aluminum that was annealed from the T3 temper condition to O temper condition and then aged back to T3 has less tool bit wear and consumes less energy than machining the same aluminum in the T3 temper condition, but yielding a product with similar quality characteristics. [39] Other forming trends include dry or nearly dry machining processes, significantly reducing or eliminating the amount of hazardous waste produced from coolants and lubricants.

Some further advantages exist when working with composites. The process can be modified to include the formation of features in the composite lay-up stage, reducing the need for additional machining or shaping after the composite is formed. Large cutouts and other features can be included in the original lay-up either reducing the amount of machining needed. However, any machining of metal matrix composites can lead to excessive tool bit wear on account of the abrasive nature of the composite dust produced. Furthermore, there can be quality control issues with drilling composites, such as delamination and excessive surface roughness. [3]

Process Improvement

An example of how the industry has improved their process is found in the evolution of the Boeing 737 manufacturing line. When the 737 first went into production, manufacturers used techniques on the production floor that were similar to the lower volume planes of previous generations. To prevent production hold-ups, surplus parts were stored on-site to ensure a constant supply. This proved to be too costly and too inefficient. Boeing changed the process to include improvements such as *just-in-time* supply chain and more efficient handling of parts and assemblies. These improvements were not only more cost effective, helping with the economic soundness of the process, but they were more efficient, leading to reduced environmental burdens. [10]

Other aerospace manufacturers, such as Airbus and Lockheed Martin, have also adopted, and are constantly trying to improve upon, a leaner supply chain to improve cost effectiveness and reduce environmental impacts. Just-in-time manufacturing reduces costs associated with storing surplus components, while more involved cooperation with suppliers and vendors leads to better, more efficient shipping practices. Companies have also worked with vendors to begin using reusable shipping containers, reducing waste produced by packing materials and cardboard boxes, making the process much leaner. [1][5][33]

An easy way to make the process more sustainable is to simply improve the efficiency of the process. There are clear advantages to keeping equipment current and up to date. Outdated machines, even when performing the same tasks, may waste more energy due to inefficiencies. Other improvements can include switching from pneumatic hand tools to electric hand tools. Electric tools have a higher power conversion ratio than pneumatic hand tools. [17]

5.2 Facility Practices

There are a number of facility level practices that are being undertaken. They are divided into two categories: *regulatory* and *general*. Regulatory initiatives are undertaken to meet with environmental legislation, attain certification status, or meet an external or internal code of conduct. General practices cover open ended initiatives that are more or less voluntary and are not required to meet certification status nor are mandated in any way.

Regulatory Compliance

First and foremost, all manufacturing facilities must adhere to the statutes and regulations set forth by the applicable governing body, be it the state, national government, or international organization. The specific details of each statute and regulation may change from region to region, but the underlying intentions are the same. These regulations are intended to maintain a certain quality of air, land, and water so as to minimize risk to people and the environment. A list of some major statutes and regulations within the United States is given below. Some of these are general regulations that apply to all industries, while some are specific to the aerospace industry [7][13]

- Resource Conservation and Recovery Act
- Comprehensive Environmental Response, Compensation, and Liability Act
- Emergency Planning and Community Right-To-Know Act
- Clean Water Act (both general and industry specific clauses)
- Clean Air Act (both general and industry specific clauses)
- Safe Drinking Water Act
- Toxic Substance Control Act
- Resource Conservation and Recovery Act (industry specific)
- Comprehensive Environmental Response, Compensation, and Liability Act (industry specific)

Outside of the United States, regulations such as *REACH* (Registration, Evaluation, Authorization, and Restriction of Chemical Substances) hazardous material regulations and the Clean Sky initiative parallel statutes and regulations in the United States. [9][16] Companies, like Airbus, involve themselves in regulatory councils, such as the Advisory Council for Aeronautic Research in Europe, the Air Transportation Action Group, amongst others. [1]

Apart from legal regulations, companies in the industry can try to attain various certifications that can reflect their progress towards environmental stewardship. One of the most common certifications sought by many facilities is the ISO 14001 Certification of manufacturing sites and subsidiaries. [22] With each annual report, aerospace companies advertise which new locations had attained ISO 14001 certification in the previous year. Another common certification sought by industry facilities is the Leadership in Energy and Environmental Design (LEED) certification, which provides different certification levels reflecting the particular site's environmental stewardship commitment levels. [46] With regard to safety, companies like General Dynamics and Lockheed Martin seek compliance and certification under the Occupational Health and Safety & OHSAS 18001. [18][33]

There also exist internal company initiatives within the aerospace industry that are unique to that particular company. These vary from company to company, but a specific example can be seen within The Boeing Company, who introduced *Lean+* workshops to help streamline the company and seek to reduce inefficiencies and waste as far down as the manufacturing floor. [5]

General Initiatives

There are a vast variety of initiatives and practices that are not held to a strict standard, but are generally common practice amongst many industry leaders. Due to the fast variety of such programs, it is beyond the scope of this paper to discuss them in detail. These initiatives can include recycling drives, awareness campaigns, outreach programs, public transportation promotion initiatives, employee recognition activities, and so on. Some specific examples include improved plumbing in employee facilities [5][33], switching to improved and more efficient lighting [5][33][47], and more efficient heating and cooling for climate control in buildings [47], and so on. Many of these initiatives go hand-in-hand with trying to achieve certain certification statuses, such as the LEED certification for efficient buildings.

6 POTENTIAL GAPS IN CURRENT PRACTICES

As mentioned in the motivation for this review, there is value in identifying the gaps in research so that future efforts can be appropriately committed.

One major gap comes in what parts of the manufacturing process are the target of environmental efforts. Significant effort is expended in addressing material working and surface finishing, since these are considered to be the *heavy hitters*. Large amounts of energy is consumed and large amounts of waste is produced during material working and forming, while surface finishing processes produce a significant amount of chemical waste. The gap is in the little attention paid to component and final assembly. Furthermore, reuse and remanufacturing of components off of retired systems can be considered value adding processes that can be included in the manufacturing process, yet there is a seeming lack of attention paid to reuse and remanufacture. There are some instances of initiatives, such as the Airbus PAMELA end of life initiative [1], but it is unclear how widespread such initiatives are, and it is evident that other parts of the process receive much more attention.

Another major gap is the lack of information about automation and its positive or negative effects on the environment. Potentially learning from the automotive industry where automation is commonplace, the aerospace industry seems to have been slow to adopt automation in its facilities. [27][28] Automation is known to exist in the aerospace manufacturing industry [48][49], particularly with composite forming [4][34], machining [49], and fastening [20], but the industry still heavily relies on non-automated processes [19][20].

Continuing to draw from the automotive industry, facilities can perform *turndown* activities where equipment is shut down or put into a low energy idle state when it is not in use or planned to be used for some time. [17] Turndown activities can help make the process leaner by reducing unnecessary power consumption while the process is not active.

While preparing this review, it also became clear that there was no standard or universal metric for assessing the sustainability or environmental impact of aerospace manufacturing processes. Some companies used revenue adjusted metrics, while others used metrics adjusted for number of products produced. In other cases, it was not clear how certain values and improvements were calculated or what elements of the manufacturing process they included. There exists the need for a general list of metrics that can be applied to the broad aerospace manufacturing industry that can provide insight to the sustainability of companies within the industry. These metrics can be used to consistently compare a company's year to year performance, compare environmental performance across multiple companies within the industry, or assess the environmental performance of the industry as a whole for comparison to other industries.

It was suggested by the report from Boeing [10] that the manufacturing process was reworked and streamlined to be more efficient. However, there is no clear indication from the industry on what the actual environmental benefit is from redesigning the manufacturing process to reduce stocking parts and reducing unnecessary activities during manufacturing. Boeing indicates that this sort of streamlining has made the process better, but it is unclear what the environmental benefits are and whether such practices are or should be adopted by the whole industry.

Finally, there is a significant lack in regulatory framework that exists specifically for the aerospace manufacturing industry. Many legal acts and regulations target the manufacturing industry as a whole, and little are tailored specifically to the unique needs of the aerospace industry. These acts or regulations do not always need to be prohibitive, striving to limit or control what the aerospace industry is doing. These acts can be promotional, offering incentive for aerospace companies to adopt certain practices.

7 FUTURE WORK

Several areas in sustainable aerospace manufacturing were identified that warrant further research. Gaps in the research were identified, and now research can be undertaken to address these gaps. The research will determine what initiatives can be undertaken to fill these gaps. Due to the ever changing nature of the industry and global policy involving environmental stewardship, continued research into what practices are common and what practices are uncommon or missing from the industry must be performed. Continuing to review practices of the aerospace manufacturing industry will help keep future research on track and prevent unnecessary and duplication of work.

8 SUMMARY

This paper reviewed some major practices in the aerospace manufacturing industry with regard to sustainability and environmental stewardship. It was found that common practices could be divided into two groups: manufacturing practices and facility practices.

Manufacturing practices include processes directly involved in the production of aerospace products. Manufacturing practices were subdivided into four categories. Product modification included changing the actual product to be more sustainable. Product improvements included altering existing products so that they were more efficient and easier to manufacture without having to significantly change the product. Process modification involved changing the manufacturing process so that the product, remaining unchanged, could be produced more efficiently and more economically. Finally, process improvements involved making alterations to the process so it was leaner and more efficient.

Facility practices fell into two subcategories: regulatory and general. Regulatory practices represented mandatory legal codes that needed to be met, as well as non-mandatory certifications and recognitions for lean, environmentally benign, or sustainable processes. General practices in facilities included public transportation initiatives for employees, recycling initiatives, and environmental awareness workshops.

Finally, potential gaps were identified. These gaps are areas where there is little research or practices that are not common place. Determining where there are gaps in existing practices can help drive future research efforts.

9 ACKNOWLEDGMENTS

We would like to thank The Boeing Company for providing funding for this research as well as providing help and insight during the preparation of this review. We would also like to acknowledge The Ford Motor Company and Ford Land for providing cross-industry insight and information.

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