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ScienceDirect
Procedia CIRP 69 (2018) 447 – 450
www.elsevier.com/locate/procedia

25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark

Advancements in Unit Process Life Cycle Inventories (UPLCI) Tools

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Abstract

Interest in environmental benefits and impacts of products continues to evolve. Direct macro-creation of pieces, parts, and components assembled into products is an essential final step, requiring energy and chemical profiles. The UPLCI effort is a multi-university effort to create reusable, quantitative descriptions of the energy/mass efficiencies of each unit process step (e.g. drilling, joining, surface coating, etc.) that work together to take materials as inputs and achieve the final manufacturing step to products (industry, consumer, and military).
The majority of all macro-shape construction have been catalogued in taxonomies as 100 - 120 separate unit processes. The UPLCI effort has completed 31 unit processes and recently undertook a trial application. An aviation component (jet fuel nozzle) was analyzed using the UPLCI approach. It had 14 subassemblies, required 67 separate unit processes, and involved 4 different materials. This paper describes the results and important lessons learned from the UPLCI industrial process approach to life cycle analysis.

Peer-review under responsibility of the scientific committee of the 25th CIRP Life Cycle Engineering (LCE) Conference

Keywords: Unit Process; Reusable Life Cycle Inventory; UPLCI; Product Environmental Footprint

1. Introduction

The production of metals, polymers, and chemicals represent the inputs to the macro shape-building processes that finally produce products for industry and consumer markets. Life cycle tools are often applied to these chemicals and material inputs (referred to as molecular shape-building steps) and the resulting supply chains. Overcash has begun to address these large-scale supply chains as a part of the Environmental Genome [1]. Quantifying the final macro shape-building manufacturing stage is less frequently done since less process information to construct transparent step-by-step analyses appears to be available.

The macro shape-building processes are individual unit processes in which material is transformed from the chemicals and raw material shapes (sheets, billets, rolls, etc.) into a clearly defined product or intermediate-stage product. Note: The term unit process in manufacturing chemicals was first used in 1850 by Davis [2] as the similarities of specific equipment or machines (like distillation) were recognized as a core methodology for manufacturing. Since 1905, books incorporating the term unit process have been the core of chemical engineering education and serve as the basis for design and improvement [2]. The life cycle concept starting in about 1960 evolved much later and used the term unit process to represent the entire facility making a specific chemical (that is, a collection of unit processes). Thus, the life cycle community has adapted a noun that has two meanings and thus confusion with the major original definition. This paper uses the original definitional concept, extended to the structure-building equipment (like drilling or joining) found in the final manufacturing of a product.

A typical product manufacturing plant has a number of unit processes that typically operate in series (the process line) to affect these transformations. Several taxonomies [3,4,5,6,7] are available listing the majority of the unit processes found in

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doi:10.1016/j.procir.2017.11.138

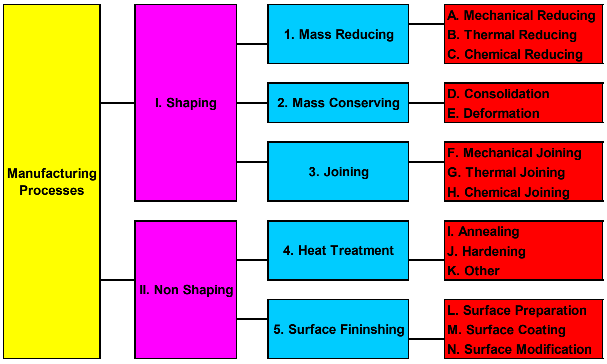

Fig. 1. Major categories common to various manufacturing unit process taxonomies.

manufacturing plants (about 100-120 unit processes). The taxonomies are usually subdivided into five major unit process groups (mass conserving, mass reducing, joining, heat treatment, and surface finishing), Figure 1. New processes that are developed and can thus be added to these taxonomies.

2. Objectives

Our objectives are to explain more completely the UPLCI concept, to update the growth of these tools (Table 1), and to describe an example of applying this analysis tool to a complex part (the jet fuel nozzle). The objective of the example of a jet fuel nozzle is to show how detailed and extensive calculations can be conducted to provide an assessment of the life cycle inventory of the manufacturing steps of a complex part.

3. Methodology

The fuel nozzle has a complex shape and can be subdivided into fourteen individual parts, Figure 2.

The materials are oxidation- and corrosion-resistant metals capable of high strength and stability at high temperatures. The fuel nozzle, Figure 2, was geometrically subdivided into fourteen separate parts.

Each of the fourteen parts of the conventional fuel nozzle was laid out to be manufactured by typical unit processes. The range of unit process per part was from 3 to 11, Table 2. As a limitation to this analysis, the energy and steps to fully assemble the fourteen parts into the fuel nozzle were not included, although two parts included energy of joining. Overall, there were fourteen parts involving 64 UPLCI (with overlap of UPLCI) that are each calculated to give the manufacturing energy (kJ/step to make each part) through respective unit processes to the final part needed in the jet fuel nozzle product. It is important to note the energy values are not per unit weight since the parts are transformed from starting material to final part and progress through different weights and shapes.

In order to estimate the energy use for each unit process in each part the initial weight and shape, the final weight and shape, and the metal materials had to be specified for each unit process.

Table 1. Summary of UPLCI Completed (Environmental Clarity, 2017) [12].

Category	UPLCI
Material conserving	Brake forming
Material conserving	Epoxy composite curing
Material conserving	Thermoforming
Material conserving	Vacuum assisted resin transfer molding
Material reducing	Boring
Material reducing	Drilling
Material reducing	Electric discharge machining (EDM)
Material reducing	Grinding
Material reducing	Milling
Material reducing	Punch pressing
Material reducing	Reaming
Material reducing	Sawing
Material reducing	Shearing
Material reducing	Turning
Material reducing	Vibratory mass finishing (VMF)
Material reducing	Water jet cutting
Joining	Diffusion bonding
Joining	Friction stirred welding
Joining	Gas metal arc welding
Joining	Submerged arc welding
Joining	Tungsten inert gas welding
Heat treatment	Annealing
Heat treatment	Carburizing
Heat treatment	Flame hardening
Heat treatment	Induction hardening
Surface finishing	Electroplating
Surface finishing	Residue removal by oven cleaning
Surface finishing	Residue removal by turbo washing
Surface finishing	Residue removal by ultrasonic cleaning
Auxiliary	Compressed air
Auxiliary	Metal working fluids

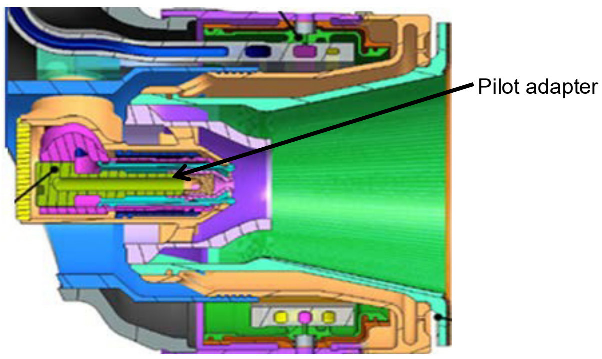

Fig. 2. Jet fuel nozzle showing part three (pilot adapter)

Table 2. Summary of conventional unit processes for each part of a jet fuel nozzle.

Part No.	Part Name	UPLCI Needed
1	Pilot swirler	Turning, EDM, VMF, turbo washing
2	Outer swirler	Milling, boring, VMF, turbo washing, welding
3	Pilot adapter	Turning, milling, VMF, turbo washing
4	Pilot lever arm and elbow	Water jet cutting, milling, milling finishing, VMF, turbo washing
5	Seal plug	Turning, VMF, turbo washing
6	Inner swirler and elbow	Milling, fine milling, VMF, turbo washing
7	Outer shell	Milling, sawing, VMF, turbo washing
8	AFT shell	Milling, annealing, milling, sawing, EDM, VMF, turbo washing
9	ML metering set	Milling, face milling, baking, nickel plating, diffusion bonding, drilling, brake forming, furnace brazing, fine milling, VMF, turbo washing
10	Shroud	Milling, VMF, turbo washing
11	Outermost heat shield	Milling, sawing, VMF, turbo washing
12	Slip seal	Turning, VMF, turbo washing
13	Outer heat shield	Milling, sawing, VMF, turbo washing
14	Steam house adapter	Milling, VMF, turbo washing

4. Results

The energy and mass efficiency analysis of manufacturing is achievable using life cycle inventory technology. One challenge is often that conventional manufacturing involves 10-50 machines (unit processes) for which energy measurements would have to be taken in the plant environment.

To make life cycle analyses of conventional unit processes more tenable, the concept of unit process life cycle inventory (UPLCI) was developed in which calculations are made of the active, idle, and basic phases of unit process energy in order to estimate a specific part. That is, each incremental step (often a stand-alone machine) is estimated for the specific part as this is transformed from raw materials to final product, Figure 3.

The UPLCI principles were developed [8,9,10] about eight years ago and an effort mounted to create a unit process energy and mass efficiency tool for each separate unit process in the taxonomies. This has been a multi-university effort and a summary has been published [11]. To date about 31 have been completed across all five of the unit process categories, Table 1 (Environmental Clarity, Inc., 2017) [12]. This is about 30% of the whole taxonomy of unit processes.

A major innovation of this UPLCI approach is the inclusion of the significant idle and basic energy components. This is a substantial improvement over current unit process data in such databases as GABI or Ecoinvent which usually reported only active or tip energy (MJ/kg metal or MJ/cm^3 metal). These UPLCI are continuing to be refined and tested for various manufacturing process lines. In general, for collaborative projects these UPLCI are provided as

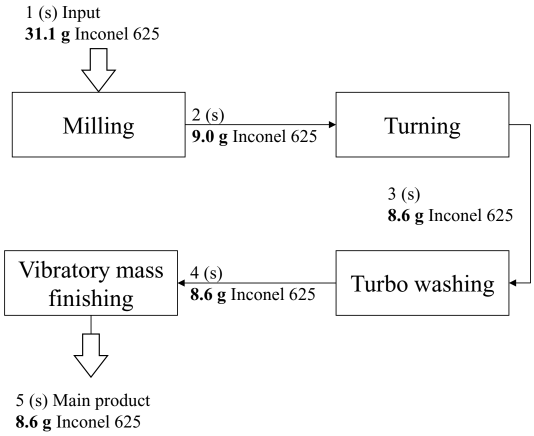

Fig. 3. Process flow diagram of unit processes to make jet fuel nozzle part three (pilot adapter) of 14 total parts

open-source tools (contact Michael Overcash: mrovercash@earthlink.net); however, resources for establishing web access are not now available. The UPLCI as a reusable calculational concept was started and continues to be developed as a reusable tool for others to use for different materials, shapes, and final product functionality.

The cumulative energy to manufacture this complex jet fuel nozzle product by conventional unit processes is shown in Figure 4. The detailed calculations and assumptions are beyond the scope of this paper. Part nine is by far the most energy intensive and this is attributed to a diffusion bonding (a joining process) step (which is 93% of the total part nine manufacturing energy). Looking deeper into this UPLCI, it is the high temperature (0.75*$T_{melting}$ of the metal workpiece) heat loss from the hot zone isolation area and the long time to achieve bonding. Such heat losses are common in high temperature metal processing. In Figure 5, the percent of each of the three components of the energy is given. Active energy ranged from a few percent to 40-90% of the total energy of any given part, across these fourteen parts. Most previous studies have only included the active or tip energies, which does not cover the majority of conventional part manufacturing energy (10-95%). These UPLCI tools include estimates of the idle and basic energies. Overall, the UPLCI tools allow users to employ different materials, initial shapes, and intermediate shapes to calculate the manufacturing energy and material loss of the part or component. The UPLCI documents employ an example to help users follow the methodology. In addition, Tables of needed physical properties are given to accommodate a range of materials. The UPLCI is the first reusable tool to aid in establishing the full energy and mass footprints of manufacturing a given product.

5. Conclusions

Having applied the reusable UPLCI concept to a complex, multi-part, and multi-process case, there are a number of lessons learned,

- In making each part, the first step for the material being processed requires estimating the pre-processing size, shape, and weight. This pre-processing object is the

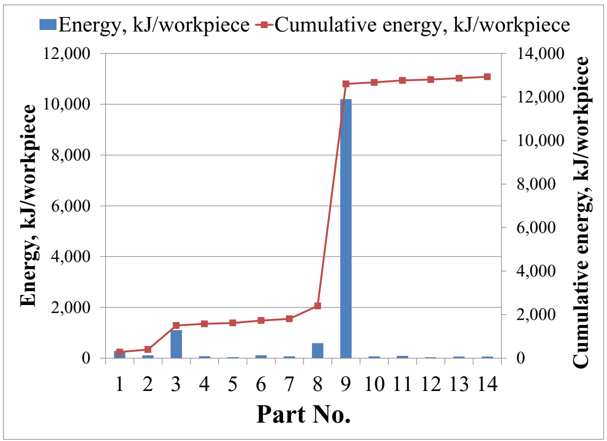

Fig. 4. Energy by part of conventional jet fuel nozzle (total energy = 12,916 kJ/workpiece)

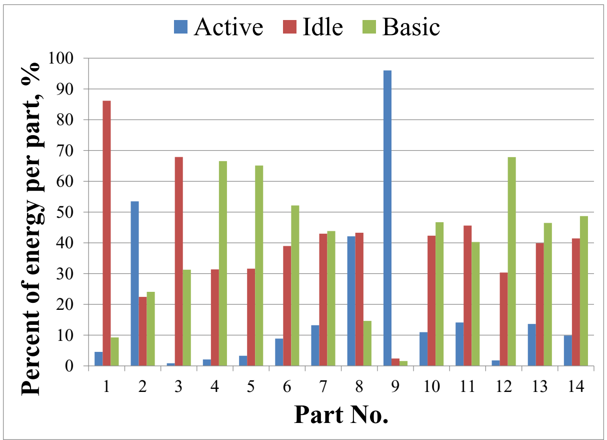

Fig. 5. Distribution of active, idle, and basic energies of conventional manufacturing unit processes producing jet fuel nozzle

purchased material for macro-shape forming (a sheet, a billet, etc.), known as an initial condition.

- For each unit process, the initial size, shape, and weight from the preceding unit process as well as the final size, shape, and weight after completing the unit process must be estimated. This is a logical extension of how a part is designed or can often be estimated by physically examining the initial and final part.
- Transparent assumptions and calculations are necessary to allow technical review of results.
- Often the physical part is needed to provide step-wise data on the how each unit process is performed.
- From basic physical measurements and material specification, the UPLCI approach provides a rapid estimation of energy and material use without in-plant instrumentation and extensive study. However, sound engineering analysis of the product being manufactured has to be included with the UPLCI tool. The approach has proven to be feasible and thus an important addition to the overall life cycle of any product which also needs the life cycle of each material in the product.

Acknowledgements

Special thanks go to Todd Rockstroh at GE who patiently documented the jet nozzle parts.

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