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SUSTAINABLE PROCESS PLANNING FOR SUBTRACTIVE AND ADDITIVE MANUFACTURING UNIT PROCESSES

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ABSTRACT

Sustainability in manufacturing implies regarding economic, environmental and social aspects and is of increasing concern to companies and consumers. Traditionally, process planning decisions were mainly based on costs and quality. This paper shows a method to compare different process chains in terms of sustainability indicators. It proposes to include non-value adding steps such as quality control or transport. The method is explained with a case study, where students design, plan, manufacture, and test models for water table experiments. Common additive and subtractive manufacturing processes are applied.

INTRODUCTION

Sustainability includes an economic, environmental and social dimension, which is of increasing importance to manufacturers [1, 2]. Common factors considered are energy and material efficiency, emissions, waste, costs, productivity, investment, impacts on society, safety, health, etc. [3].

Product design including material and necessary manufacturing tolerances are a big lever for impacting a factory's sustainability [4]. These choices are covered by product design and planning, covering **which** product types and versions are produced. Still, it needs to be detailed **how** the products are manufactured in terms of processes and parameters. In process planning the following questions are answered:

- How many products are made in total and in which frequency and batch size?
- Which manufacturing processes are used?
- What are the parameters, machines, tools, auxiliary materials for each process?

Process planning is an optimization problem to find the optimal process sequence with the associated optimal process parameters with minimum cost [5]. This offers great potential for sustainability improvements.

The first decision is about which unit processes are chosen to manufacture the part. The same part can be made with many different unit processes and process sequences. For example, a

tube can be cast or sintered near-net-shape, extruded from semi-finished parts, or bent and welded from sheet metal [6]. The evaluation criteria in process planning are plentiful: processing time, quality, availability, costs, energy, etc. [7]. It is often difficult to decompose the planning process into smaller steps, because most steps are influencing all other steps [8]. Also most manufacturing processes lack physical models that can be used to compute fast and accurate solutions, so human expertise is needed in process planning [8]. Additional challenges come from the new cloud based manufacturing environment in which decisions on process planning might become web-based, distributed and collaborative [9].

At UC Davis, a new course on integrated STEM education in aerospace design and manufacturing is under development, funded by the NSF IUSE (Improving Undergraduate STEM Education) program. This course will teach undergraduate students with simple mathematics what makes airplanes fly, while also showing how computer simulations, manufacturing, and experimental validation are integrated in the modern engineering world. To visualize the airflow, a water table experiment will be used to show shock waves around airfoils and other models (Fig. 1). The model surfaces need to be smooth to avoid turbulences. The dimensional accuracy is critical for the comparison between the computational simulation and the water table experiments. The students will need to produce the models during the course duration while considering sustainability in manufacturing. This is a relevant and timely topic.

FIG. 1 SHAPES FOR THE WATER TABLE EXPERIMENTS

First, a method is developed to explain and visualize process planning. Non-value adding processes are included in the discussion to make the students aware of their implications on sustainability. Second, an explanation of the most important considerations on planning scope, detail, and decision criteria is given. The sustainability indicators are chosen. Third, data is recorded for different subtractive and additive manufacturing processes. Fourth, the different unit processes and steps are combined to alternative process chains. Finally, a simple and transparent decision tool helps to compare the different indicators. These steps are explained in the following.

METHOD

Explaining and visualizing process planning

The value-adding manufacturing processes can be differentiated into: primary shaping, forming, separating, coating, property changing, and joining [10]. These unit processes build a process chain where each process subjects the part to discrete changes (Fig. 2). Unit processes can be characterized through theoretic calculations as described by the Unit Process Life Cycle Inventory (UPLCI) method and/or measurements of energy consumption, material consumption, and process emissions, as described by the Cooperative Effort on Process Emissions in Manufacturing (CO2PE) method [11].

FIG. 2 VALUE-ADDING UNIT PROCESSES

To evaluate the overall sustainability of a process chain, however, we need to also consider non-value adding steps such as transport, part loading/unloading, and quality control, because they can add considerable time, energy, and costs (Fig. 3).

FIG. 3 PROCESS CHAIN INCLUDING UNIT PROCESSES AND NON-VALUE ADDING STEPS

The choice of unit processes and non-value adding, auxiliary steps depends on the available blank material, machines and machine times as well as company expertise.

Certain processes might need to be outsourced, which can add costs, time, handling, and transport. The process planner needs to satisfy multiple interfering criteria, traditionally production time, costs, and quality. From a sustainability standpoint, additional criteria might become important, such as energy use, material efficiency, waste, emissions, worker training, and more. These broader criteria are chosen as sustainability indicators in the following.

Choice of sustainability indicators

There is an extensive number of potential sustainability indicators available as collected and publicly available through the NIST Sustainable Manufacturing Indicators Repository (SMIR) [12]. This repository uses five categories: environmental stewardship, economic growth, social well-being, technological advancement, and performance management [13]. Due to their high industrial relevance, we propose to use the following minimum indicators for this study:

- Production time
- Costs per part (consisting of material acquisition costs, energy costs, tooling costs, and machine costs) [14]
- Quality (surface roughness and dimensional tolerances)
- Energy consumption (An alternative indicator is energy intensity, e.g. energy divided by volume of final part)
- Residual intensity

In addition, we propose to consider intensity indicators on part quality, for example the resources spent are divided by the quality improvement gained, (i.e. energy per difference in average surface roughness R_a [15]). Social sustainability indicators could be the duration of manual labor or the minimum expertise level needed to perform the tasks.

Recording of unit process data

While manufacturing the shapes in Fig. 1, the students will record as much data as possible. Additional data will be pre-recorded before the course to increase the number of possible process chains. The attached data sheet gives a guideline (Annex A). Most data can be measured, but few estimations have to be made where measurement is not feasible in a safe class room setting, such as 3-phase power metering. In this case, pre-recorded data, such as power profiles for machine tools, is given and used to derive values. All data is displayed in Microsoft Excel sheets. For simplicity, all processes are coded by the manufacturing principle (S = sawing, T = turning, M = milling, BG = belt grinding, etc.) and a running number for each set of parameters, auxiliary equipment, machine, and tools. Three additive manufacturing processes, four subtractive manufacturing processes and quality control as non-value adding step are chosen.

Additive Manufacturing Processes. Three different additive principles are used for this project: Wire extrusion (W), vat photopolymerization (VP), and polyjet modeling (PJM). Wire extrusion, also known under the tradename Fused Deposition Modeling (FDM), is used widely by home users because of the low equipment cost and simple process design. It works with a

thermoplastic polymer wire that is fed through a heated nozzle. The heated wire is deposited by an xy-feed system on a platform that is moved up and down to produce the part layers [16, 17]. Vat photopolymerization, also known as Stereolithography, is the oldest additive manufacturing technology and is based on photopolymerization of a curable polymer [16, 17]. The platform is then submerged in a bath of liquid polymer. A UV light beam is focused on the top of the platform, where it hardens the polymer. The beam and platform are moved in x-y direction relative to each other to build each layer.

The multijet modeling or polyjet process uses a head similar to ink-jet printing to deposit photopolymers [16, 17]. Ultraviolet bulbs beside the jets cure the layers immediately. Again, the downward movement of the platform defines the layers.

Additive manufacturing has many advantages over conventional manufacturing operations, such as reduced material waste and energy consumption, shortened time-to-market, just-in-time production, and production of structures not possible otherwise [18]. However, high-volume production of parts with low complexity and high accuracy will still be dominated by conventional manufacturing in the near future [18].

Subtractive manufacturing processes. For this project, only removal processes involving chip formation are used due to their high importance in industry. All students who will take the new course will have a manufacturing processes class as prerequisite and are therefore already familiar with the processes: turning (T), milling (M), sawing (S) and belt-grinding (BG).

In turning, the cutting tool is moved along the axis of a rotating workpiece. In milling, a rotating, multi-edge milling tool removes material from a stationary workpiece with different areas of the milling tool - circumferential area (slab milling) or the face (end milling). In sawing, a multi-toothed saw cuts straight paths through the stationary workpiece with a relative motion of the saw. Belt-grinding is an abrasive machining process where the tool consists of abrasive grits in a bond on a backing. The belt is moved at high speeds (700 – 1,800 m/min) against the workpiece to take off small chips. All processes are used for high volume removal processes, but can also produce fine surfaces if the feedrates are low. [17]

Quality control steps. Quality control includes measuring the external dimensions with calipers (QCA) or micrometers (QMM) or a coordinate measurement machine (QCMM). For 2D roughness measurements (QR), a tactile roughness tester Mitutoyo SJ210 with a force of 4 mN is available.

Generation of alternative process chains

To produce a certain part, generic unit processes can be added to a chain (e.g. sawing cuts a part from a blank, turning produces outer surface, milling produces a slot, etc.). The recorded unit process variants however cannot be added arbitrarily because the output quality of one unit process variant might not qualify as input for another unit process variant. This

needs to be pointed out, but will not be the focus of this study. The students build alternative process chains first from generic unit processes (Fig. 2), then detailing the unit process variants (Fig. 4).

FIG. 4 PROCESS CHAIN WITH SPECIFIC UNIT PROCESS VARIANTS AND NON-VALUE ADDING STEPS

The students need to critically consider the finishing processes with regard to surface quality, edge roundness, time, effort, and user skills required. The process chain data is combined in Excel sheets.

Calculation of sustainability indicators

The Excel data sheets will give the values of the chosen sustainability indicators. These values are entered into the scoring tool (Table 1). The scoring model is described in reference [19]. The user has to find the optimum value for each indicator. For example, for energy consumption, there is a theoretical minimum resulting from processing energy and machine idle energy. All residuals, water and air releases intensities would equal 0 in the best case [19]. For the model described in this paper, the optimum value of each sustainability indicator is simplified in that way that it is just the minimum value (e.g. for roughness, costs, energy usage) or maximum value (e.g. for energy efficiency, renewable materials content) of the compared alternatives.

The degrees of fulfilment (DF) range from 1 (poor, low sustainability) to 10 (optimum value). The degree of fulfilment for each sustainability indicator and process chain (DF_{xi}) are then calculated (equation (1)). The degrees of fulfilment can be displayed as radar charts or columns and give a first finger print of the process chain.

TABLE 1 SCORING TOOL PART I, AFTER [19]

Sustainability indicators	Optimum value (DF = 10)	Chain 1		Chain 2		Chain n	
		Value	DF	Value	DF	Value	DF
Production time	Min. of ($t_1 ; t_n$)	t_1	DF_{T1}	t_2	DF_{T2}	t_n	DF_{Tn}
Costs	Min. of ($C_1 ; C_n$)	C_1	DF_{C1}	C_2	DF_{C2}	C_n	DF_{Cn}
Quality (Ra)	Min. of ($Ra_1 ; Ra_n$)	Ra_1	DF_{Ra1}	..	..	..	..
Energy consumption	Min. of ($E_1 ; E_n$)	E_1	DF_{E1}	..	..	..	..

$$DF_{xi} = 10 - \left(integer \left(\frac{x_i - \min(x_1; x_n)}{\max(x_1; x_n) - \min(x_1; x_n)} \cdot 9 \right) \right) \quad (1)$$

In a following step (Table 2), the chosen sustainability indicators are given weights factors (WF), adding up to 100%. The weight factors, WF, are multiplied with the degrees of fulfilment, DG, to utility values (U). Summing up the utility values, U, condenses the different indicators to one overall score while having transparency on the largest contributing factors.

TABLE 2 SCORING TOOL PART II, AFTER [19]

Sustainability indicators	Weight factors	Chain 1		Chain 2		Chain n	
		DF	U	DF	U	DF	U
Production time	WFA	DF _{A1}	WFA *DF _{A1}	DF _{A2}	WFA *DF _{A2}	DF _{An}	WFA *DF _{An}
Costs	WFC	DF _{C1}	WFC *DF _{C1}	DF _{C2}	WFC *DF _{C2}	DF _{Cn}	WFC *DF _{Cn}
Quality (Ra)	WFRa	DF _{Ra1}	WFRa *DF _{Ra1}	..	..	..	..
Energy consumption	WFE	DF _{E1}	WFE *DF _{E1}	..	..	..	..
	$\sum WF = 100\%$		$\sum U_1$		$\sum U_2$		$\sum U_n$

FIRST RESULTS

Cylinders with a diameter of 37.59 mm (1.48 in) and height of 25.4 mm (1 in) were produced with different methods. Process chain 1 started with an aluminum Al6065 rod, diameter 38.1 mm (1.5 in) as raw material, then included turning on a lathe (T1) and band-sawing (S1). The turning process required 42 seconds for set-up and 52 seconds for processing. The machine maximum power was 2024 W. The band-saw process required 10 seconds for set-up and 25 seconds for processing. The band-saw has a maximum power of 1560 W.

Process chain 2 consisted of wire extrusion (W1) of PLA polymer. Set-up was done in about 10 minutes (including programming) and printing required 54 minutes. The printing machine had a maximum power of 122 W.

Process chain 3 included vat photopolymerization (VP1) and post-processing steps which are not included here. The vat photopolymerization machine proposed rotating the cylinder as shown in Fig. 5, which includes additional support structures and changes the slicing of the cylinder into layers (Fig. 6). The set-up took 10 minutes due to the liquid resin requiring time for mixing. Printing itself took 5 hours and 27 min. The machine has a maximum power of 22.5 W.

The part surface roughness was taken with a tactile roughness tester on the circumferential cylinder area, parallel to the cylinder axis as shown in Fig. 6.

FIG. 5 VAT PHOTOPOLYMERIZATION

FIG. 6 CYLINDER DIMENSIONS, SLICING AND DIRECTION OF ROUGHNESS MEASUREMENT

Due to current data availability, only processing time, quality (roughness parameter Rz), and energy are compared (Table 3).

TABLE 3 RESULTS IN SCORING TOOL, PART 1

Sustainability indicators	Optimum value (DF = 10)	Chain 1 (T1, S1)		Chain 2 (W1)		Chain 3 (VP1)	
		Value	DF	Value	DF	Value	DF
Production time [s]	129	129	10	3840	2	20220	1
Quality (Ra) [μm]	1.29	1.29	10	13.8	1	8.8	5
Max. energy consumption [Wh]	40	40	10	110	2	122.6	1

In the next step the results can be weighted. Scenario 1 values only economic dimensions. Here, production time is weighted 60% and quality 40% and energy consumption not at all (0%). The results show that Chain 1 is about 238% more favorable than chain 2 and 385% more than chain 3 (Table 4). Chain 2 is preferred over chain 3.

TABLE 4 RESULTS IN SCORING TOOL, PART 2, SCENARIO 1 (ECONOMY FRIENDLY)

Sustainability indicators	Weight factors	Chain 1 (T1, S1)		Chain 2 (W1)		Chain 3 (VP1)	
		DF	U	DF	U	DF	U
Production time [s]	60%	10	6	2	3.6	1	0.6
Quality (Ra) [μm]	40%	10	4	1	0.6	5	2
Max. energy consumption [Wh]	0%	10	0	2	0	1	0
	$\sum WF = 100\%$		10		4.2		2.6

TABLE 5 RESULTS IN SCORING TOOL, PART 2, SCENARIO 2 (ECO-FRIENDLINESS)

Sustainability indicators	Weight factors	Chain 1 (T1, S1)		Chain 2 (W1)		Chain 3 (VP1)	
		DF	U	DF		DF	U
Production time [s]	25%	10	2.5	2	0.5	1	0.25
Quality (Ra) [μm]	25%	10	2.5	1	0.25	5	1.25
Max. energy consumption [Wh]	50%	10	5	2	1	1	0.5
	$\Sigma \text{WF} = 100\%$		10		1.75		2

A second scenario emphasizes eco-friendliness. Energy consumption (50%) is valued as highly as time (25%) and quality (25%) combined. Now, chain 1 is even more favorable than chain 2 (571%) and chain 3 (500%), but chain 3 is preferred over chain 2 (Table 5).

These results are strident because very diametric values are used. The cylinder as given shape is a classic example where turning is superior to other manufacturing processes. Once material costs are added or more complex shapes are made, the sustainability indicators and overall results will change.

CONCLUSION AND OUTLOOK

A transparent and simple method to compare different process chains has been developed. Displaying the complete process chain including value-adding and non-value-adding steps is important to understand the sustainability impacts. Work in progress collects data on quality control, handling, and set-up steps. The method allows to discuss the benefits and problems of subtractive and additive manufacturing. Compared to traditional manufacturing processes, 3D printers enable a flexible production of innovative products in low quantities. Traditional subtractive processes however are fast and able to machine a wide variety of materials.

This method will be applied in a new undergraduate course, which is tentatively scheduled for Spring Quarter 2017 and is under development in an NSF-funded project. The course will cover design of airfoils, computational analysis of air flow, manufacturing of airfoil models, experiments with a water table, and comparison between experimental and analytical results. Sustainable process planning will be tackled as one learning outcome for the students. The shown case study on three process chains with different manufacturing principles will act as first example. On-going work expands the data collection to more processes and more models. An Excel-macro is being programmed. The airfoil design code is under development and the water table is being enhanced.

The students will learn from first-hand experience about manufacturing quality criteria, such as processing time (resulting from the path and auxiliary times), processing energy, surface roughness, dimensional accuracy, etc. Furthermore, the students will learn about the broader picture of process planning and quality control comparable to industrial procedures as well as

sustainability in manufacturing. They will appreciate how process planning can improve the part quality through changing processing parameters or tools in subtractive machining and reducing layer thickness and part orientation in additive manufacturing.

NOMENCLATURE

BG	belt-grinding
C	costs
DF	degree of fulfilment
E	energy consumption
QCA	quality control of dimensions with caliper
QCMM	quality control of dimensions with coordinate measurement machine
QMM	quality control of dimensions with micrometer
QR	quality control of 2D roughness
Ra	average surface roughness
Rz	average peak-to-valley height
S	Sawing
STEM	Science, TEchnology, Mathematics
t	time
T	Turning
U	utility value
VP	vat photopolymerization
W	Wire extrusion
WF	weight factor

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The project website can be found at URL: <http://research.engineering.ucdavis.edu/stemaerospace/>

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ANNEX A

DATA SHEET FOR UNIT PROCESSES

Data Form for manufactured parts (more data should be included if possible)

Header	
Form number (running number)	
Name of student	
Date	
Part information	
Part name (cylinder, diamond, airfoil, nozzle)	
Additional information on design (version no.)	
Part height [inch]	
Part height [mm]	
Part diameter or width [inch]	
Part diameter or width [mm]	
Material type	
State of incoming part (extruded, as pellets, etc.)	
Material costs	
Main manufacturing operation	
Manufacturing operation (FDM, SLA, Powder-bed, turning, milling, etc.)	
Machine tool name and specification	
Machine hourly rate [\$ / h]	
Max. power [W]	
Description of operation (feed direction, steps, etc.)	
Workpiece clamping	
Processing parameters as applicable:	
Tool type (material, coating, edge radius, specifications, etc.)	
Coolant use (type, amount)	
Feed rate [mm/min]	
Cutting speed [mm/min]	
Depth of cut [mm]	
Down-milling / up-milling	
Printing head	
Layer thickness	
Additional information	
Length of set-up [s or min]	
Length of operation [s]	
Energy consumption [J, kWh]	
Maximum forces (normal, tangential, axial) [N]	
Emissions	
Waste produced (coolant, scrap, chips, plastic)	

Post-processing	
Post-processing type (manual grinding, polishing, etching with acetone, etc., including parameters)	
Length of set-up [min]	
Length of processing [min]	
Processing parameters as applicable:	
Tool type	
Power tool type	
Abrasive chip type (tumbling)	
Acetone percentage	
Material costs	
Additional information	
Workpiece quality	
Average surface roughness Ra (in x direction)	
Average surface roughness Ra (in y direction)	
Average surface roughness Ra (in z direction)	
3D measurements	