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Joint decisions of machining process parameters setting and lot-size determination with environmental and quality cost consideration

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ABSTRACT

In today's highly competitive market, it is not enough to produce high quality products at lower costs but also sustainability has to be factored in the decision making process. The objective of this research is to propose an optimization model that considers both losses due to negative environmental impact and rework cost for a product-mix production planning problem manufactured through turning operation. The mathematical model solves simultaneously for the optimal production quantities and machining parameters that maximize the total expected profit. Surface roughness is used as a metric to assess the desired quality level of the finished machined part. Roughness was modeled as a random variable using normal distribution while rework cost was calculated in terms of probabilities of exceeding roughness target and upper tolerance limit. Energy consumption and CO_2 emissions are estimated using lifecycle analysis (LCA) approach and used to quantify the environmental cost. A numerical example is used to illustrate the adequacy of model proposed through a turning study. Results revealed the importance of taking a system approach when solving for optimum machining parameters and lot-sizing if quality and environmental costs are considered. It was shown that a stringent quality cost target will drive process parameters such as feed and nose radius to lower values in order to minimize rework cost. Moreover, and in order for environmental cost to significantly impact decision makers, carbon selling price or cap limit needs to be stringent enough to drive emission reductions.

1. Introduction

Due to globalization and fierce competition, firms have focused their attention and efforts on market responsiveness and/or the cost efficiency of their production. A persistent trend throughout history of machining is higher and higher cutting speeds in order to increase production efficiency and shorten machining times. The objective is to maximize the production rate while maintaining a high quality product at a low cost. However, machining at high speeds may result in higher energy consumption, tool breakage, excessive tool wear, tool chatter, rough surface finish and dimensional variability in the work-piece, if the cutting operation variables are not properly selected. These variables include tool characteristics, cutting parameters, lubrication and work holding fixtures. So, one of the most critical tasks in process planning is the selection of those parameters. Controlling those variables influences the performance, cost and quality of the machined part.

In the last two decades, governments and firms are becoming more conscious about the side effects of manufacturing processes on quality and environment. Herrmann and Thiede [1] reported that industry sector is responsible for consuming nearly half of Germany electrical energy and 40% of total CO_2 emissions. A machining operation requires power which depends on the cutting force, cutting speed and the mechanical efficiency of the machine tool. During machining, approximately 98% of the energy is converted into heat that causes a very high rise in temperature at the tool chip interface. A cutting fluid is used to address the heat generated at shear and friction zones; however usage of the cutting fluid leads to other problems like its contamination, disposal and filtration which results in other environmental side effects. Dry machining is an alternative to reduce the problems of cutting fluid but it leads to different problems like overheating of the tool affecting quality of machined products. In addition, dry machining is usually done at lower speeds to prolong tool life which in return negatively affect the production rate.

Recent studies on sustainable manufacturing focused on energy savings to reduce unit production cost and environmental impacts which included energy consumption, use of cutting fluids, waste management, disposal of worn tools, and material consumption

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Nomenclature

Symbol	
a	Pre-determined carbon cap (I)
c_i	Variable order cost per kg of material *i* (I)
c_e	Carbon allowance price (I)
c_{qi}	Quality loss coefficient of material *i* (I)
C_{CO2}	CO_2 emission costs
$CH_{CO_2 i}$	Emission associated with recycling of metal chip *i*
C_{Kw}	Power consumption cost in $/kWh (I)
CO_{CO_2}	Emission generated from disposal of coolant (I)
C_{Rei}	Rework cost of material *i*
C_{di}	Direct energy costs of material *i*
C_g	Grinder's rate (I)
C_{id}	Indirect energy cost
C_{nti}	Non-traditional costs of material *i*
C_o	Labor cost rate ($/min.) (I)
C_{pi}	Total machining cost per unit product *i*
C_{ri}	Cost per kg of raw material *i* (I)
C_t	Cutting tool cost per edge (I)
d_i	Depth of cut of product *i*
d_{ri}	Depth to be removed of material *i* (I)
D_i	Demand for each product *i* (I)
e_i	Carbon emission per unit of product *i*
E	Cutting tool parameters (I)
E_f	Mechanical efficiency of the machine tool (I)
$E_{CO_2 i}$	Emission generated due to electricity consumption when cutting material *i*
E_c	Environmental cost
f_i	Feed of product *i*
ICorresponding	Inventory holding cost per unit
I_c	Inventory cost
I_c^f	Average inventory cost for finished product
I_{ri}	Raw material *i* inventory holding cost (I)
k_i	Fixed order cost of material *i* (I)
λ_i	Raw material demand
LO_{CO_2}	Emission generated from the lubricant
L_i	Length of the shaft of material *i* (I)
m	Material types (I)
M	Total mass of raw material required
$M_{CO_2 i}$	Emission due to production of product raw material *i*
n	Cutting tool exponent (I)
n_e	Number of cutting edges per insert (I)
n_p	Number of pieces per tool
NR_i	Nose radius of product *i*
ϕ_i	Shaft diameter of product *i* (I)
p_i	Selling price of product *i*
$P_{CO_2 i}$	Total CO_2 emission generated due to machining of material *i*
P_{gi}	Machining gross power consumption of material *i*
P_m	Machine's motor power (I)
P_t	Insert price (I)
P_{ui}	Specific power of the material *i* (I)
q	Traded carbon allowances
ρ_i	Density of the material (I)
r_i	Number of multiple passes of material *i*
RM_i	Raw material cost of material *i*
R_{MRi}	Material removal rate of material *i*
R_0^i	Surface roughness target of product *i* (I)
s_i	Salvage value of product *i* (I)
SR	Selling revenue
τ_i	Takt time
T	Total available production time (I)
TM_i	Machining cost of material *i*
TL_{CO_2}	Emission generated from the cutting tool
T_g	Time to grind (I)
T_{mi}	Machining time for product *i*
T_{hi}	Tool handling time for product *i*
T_t	Tool changing time (I)
U	Profit
V_i	Cutting speed of product *i*
X_i	Production quantity of product *i*
μ_{R_i}	Average roughness of material *i*
σ_{R_i}	Roughness standard deviation of material

[2–4]. Since all these activities lead to increasing the carbon footprint directly or indirectly, manufacturing plants are facing increasing pressure to reduce their carbon footprint, driven by concerns related to energy costs and climate change. The potential to reduce energy costs lies in increasing energy efficiency of the production processes and management approaches [2]. In general, energy efficiency refers to achieving the identical output with less energy consumption [3].

In an effort to reduce energy consumption, the Congressional Budget Office (CBO) of the Congress of the United States provided four different emission reduction policies [4]: mandatory carbon emissions capacity, carbon emissions tax, cap-and-trade, and investment in the carbon offsets. The policies state that a company has a certain emissions' cap set either by the government or the company itself that should not be exceeded. In case the company exceeded the carbon emissions cap, it must pay taxes to the government. Companies can also trade unused allowances with other companies. The trading price depends on the supply and demand of the market. This allows companies to compensate other companies' emissions and increase their emissions cap. Such governmental policies and regulations forced the industries to account for sustainability and environmental impact when taking any decision.

Sustainable Manufacturing (SM) requires strategic attention in today's competitive environment owing to dependence of many organizations on natural resources along with generation of wastes and environmental pollution. In order to ensure competitiveness in the field of manufacturing, a balance between economic, environmental and social dimensions needs to take place. The increasing emphasis on sustainable production requires maintaining the resource efficiency and effectiveness along the product, process and production system lifecycle.

The objective of this research is to provide a feasible solution to decision makers when solving lot sizing problems on how to reduce their energy consumption and carbon footprint while satisfying production demand and quality constraints. The objective is to find the optimum machining setting and production quantities that would maximize profit, maintain a high quality performance while reducing the negative environmental side effect during production. The rest of the article is presented as the following: section two outlines the background of the problem and literature surveyed, section three presents the proposed model, a numerical example is presented in section four, followed by results and conclusions in sections five and six respectively.

2. Background

Turing is a major material removal process, where a single point tool removes material from a rotating work piece to form a cylindrically shaped object. It depends on three main cutting parameters