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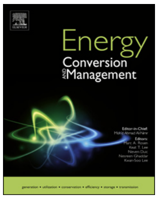

Energy modeling method of machine-operator system for sustainable machining

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ABSTRACT

Characterizing and modeling the energy consumption of machining processes has been recognized as an effective measure to improve the energy efficiency of the manufacturing process and to reduce carbon emissions. Activities related to machine tools and operators in machining processes result in energy consumption and carbon emissions. However, energy evaluation for the activities related to operators has often been ignored in the energy modeling of machining processes, due to its complexity and variability. Consequently, energy-saving strategies developed without considering the energy consumption of operators are not optimal. To bridge this gap, this paper develops an energy consumption evaluation method for the activities related to machine tools and operators, and establishes a novel energy model of machine-operator systems to assess the energy efficiency of machining processes. The research results provide a promising method to identify new energy-saving potentials of machine-operator systems. The recommended energy-saving strategy regarding this method is different to traditional strategies, but with it a better energy-saving effect can be achieved. Finally, a case study of energy modeling and analysis for a CK6153*i* CNC machine-operator system is examined, showing an energy-saving potential of 15.85% and illustrating the effectiveness of the proposed method.

1. Introduction

Nowadays, energy issue has become a major focus for the manufacturing industry [1]. Promoting energy efficiency in buildings is also an important issue in the building industry [2]. Moreover, many processes have high energy consumption but low energy efficiencies in the chemical industry [3]. The importance of energy issues in industry escalates rapidly due to the increase of energy cost and the challenges from reducing emissions [4]. Improving energy efficiency by analyzing energy use is an important step toward reducing greenhouse gas and energy consumption [5]. Worldwide, the industrial sector is responsible for 37% of total energy consumption and 17% of total CO_2 emissions [6]. Moreover, industrial energy consumption shows a rapid upward trend in the foreseeable future, with an annual growth rate of 1.3% from 2013 to 2025 [7]. Production processes and manufacturing activities play a major role in industrial energy consumption, and are responsible for approximately 90% of energy consumption in the industrial sector [8]. Therefore, both manufacturing industries and machine tool builders have a strong incentive to reduce energy consumption and CO_2 emissions [9]. The manufacturing industry in particular has a remarkable potential for energy-saving and emission-reduction [10]. According to the report of the International Energy Agency (IEA), manufacturing industries have an energy-saving potential of 25–37 EJ, about 18–26% of the total industrial consumption [11]. Similarly, the worldwide manufacturing industries' energy-saving potential is estimated to be 20% until 2050 [12]. Machining is one of the most important and widespread processes employed in manufacturing industries [13]. Consequently, reducing the energy consumption and carbon emissions of machining process could alleviate the energy burden [14] and improve the environmental performance of manufacturing processes [15]. Energy and carbon efficiency estimation and improvement of the machining process prove to be ongoing challenges to manufacturing industries [16]. Activities related to machine tools and operators in machining processes both result in massive

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Nomenclature

ANOVA	Analysis of Variance
AR	A-axis Rotating
BR	B-axis Rotating
CC	Chip Conveying
CFS	Cutting Fluid Spraying
CNC	computer numerical control
CR	C-axis Rotating
DF	Driving Forklift
E_l	energy consumption of activity$l$of machine tool [J]
E_p	energy consumption of Therblig$p$of machine tool [J]
i	index for the stage of machining
IEA	International Energy Agency
j	index for the sub-stage of machining for the machine
k	index for the sub-stage of machining for the operator
l	index for the activities of machine tool during machining
L	number of activities of machine tool during machining
LT	lighting
LW	Loading Workpiece
m_i	number of substages in machining stage i
m_{op}	weight of operator [kg]
MC	Material Cutting
MEC	machine energy consumption of machine-operator system [J]
MEC_i	machine energy consumption of stage i of machining process [J]
MEC_{ij}	machine energy consumption of sub-stage j during machining stage i [J]
MET	Metabolic Equivalent
MOS	machine-operator systems
n	number of stages for machining the part
N_m	total number of measurements for walking duration
OEC	operator energy consumption of machine-operator system [J]
OEC_i	operator energy consumption of stage i of machining process [J]
OEC_{ik}	operator energy consumption of sub-stage k during machining stage i [J]
p	index for the Therblig type
P_{lp}	power of Therblig $p$in activity$l$ [W]
P	number of Therblig types
$P_{ij}^{mt}(t)$	power function of machine tool during sub-stage j in machining stage i
$P_{ik}^{op}(t)$	power function of operator during sub-stage k in machining stage i
P_{kg}^{op}	power consumption of operator per kg weight $[\mathrm{W{\cdot}kg^{-1}}]$
P_L	power of Therblig-lighting [W]
P_{op}	power consumption of operator [W]
P_r	running power of operator [W]
P_{SO}	power of Therblig-standby operating [W]
P_{TEER}	resting energy expenditure rate of operator $[\mathrm{kcal{\cdot}kg^{-1}{\cdot}h^{-1}}]$
P_w	walking power of operator [W]
RM	Resting Metabolism
RN	running
s_{lp}	execution state of Therblig$p$ in activity$l$
SiS	Sitting Still
SO	Standby Operating
SR	Spindle Rotating
StO	Standing Operation
StS	Standing Still
t	duration of machining a part [s]
t_i	duration of machining stage i [s]
t_{ij}	duration of sub-stage j in machining stage i [s]
t_{ik}	duration of sub-stage k in machining stage i [s]
t_l	duration of activity$l$ [s]
$t_{w,\kappa}$	κ^{th} measured walking duration of walking stage [s]
TC	Tool Changing
TEC	total energy consumption of machine-operator system [J]
TS	Tool Selecting
$\mathbf{TP}_{(l,:)}$	matrix constructed by l^{th} row of Therblig power matrix
$\mathbf{TP}_{(:,p)}^{T}$	transpose of the matrix constructed by p^{th} column of Therblig power matrix
$\mathbf{TT}_{(l,\,:)}^{T}$	transpose of the matrix constructed by l^{th} row of Therblig time matrix
$\mathbf{TT}_{(:,p)}$	matrix constructed by p^{th} column of Therblig time matrix
u_i	number of sub-stages in machining stage i for the operator
UW	Unloading Workpiece
v_r	running speed [km/h]
v_w	walking speed [km/h]
WK	walking
XF	X-axis Feeding
YF	Y-axis Feeding
ZF	Z-axis Feeding

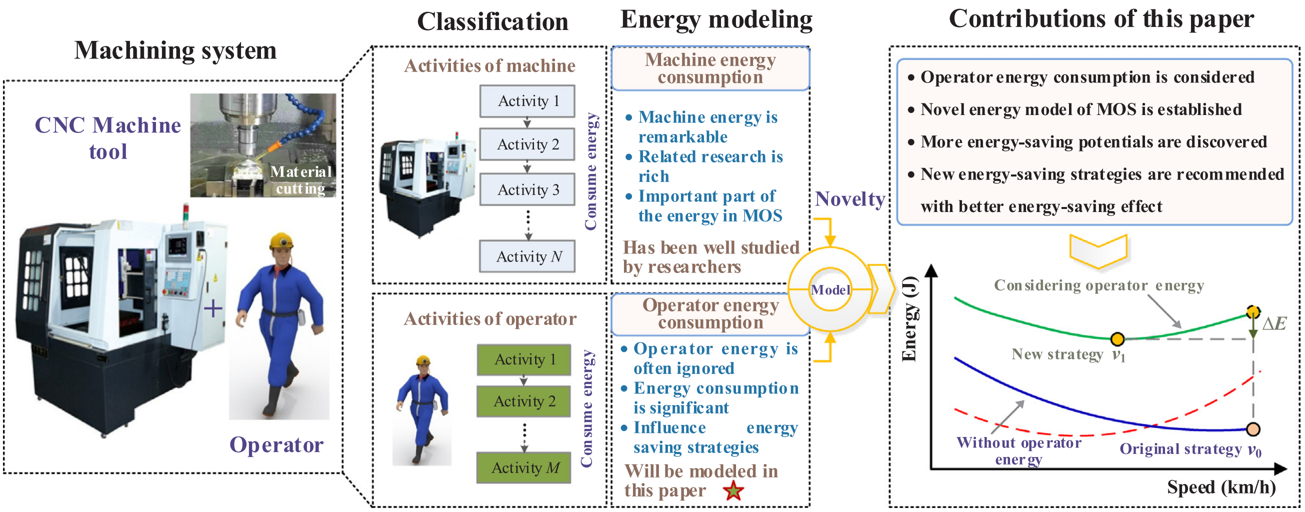

Fig. 1. Innovation and contributions of the paper.