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ENERGY CONSUMPTION MODELING OF PROCESSES IN THE AUTOMATED MANUFACTURING SYSTEMS

Jerzy Honczarenko[1], Artur Berliński[2]

[1] *Warsaw University of Technology, Poland*
[2] *West Pomeranian University of Technology Szczecin, Poland*

Corresponding author:
Artur Berliński
West Pomeranian University of Technology Szczecin
Faculty of Mechanical Engineering and Mechatronics
Department of Mechanical Technology
Piastów 17, 70-310 Szczecin, Poland
phone: +48 91 4494893
e-mail: artur.berlinski@ps.pl

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Abstract
High-tech manufacturing such as machining at high speeds, laser, electrical discharge machining are highly energy intensive. Automation of assistant processes such as transport, storage, quality control also causes increasing of energy consumption. In this context, important is estimating and minimize the volume used energy. The main contribution of paper is the evaluation method of energy production processes in automated production systems, based on the equation energy formulation. Simple calculation energy consumption example was also presented for elementary transport operations in a high storage depot. Implantation this method enables rating power consumption of manufacturing process on design stage where used are technical subsystems such as: machines, conveyors, manipulators etc. Designing processes with power rating consumption enable saving energy in manufacturing processes that is important for their economic efficiency.

Keywords
energy consumption, manufacturing process, saving energy.

Introduction

Manufacturing processes require various forms of energy, but primary it is electricity used to power technological machinery, transportation and assembly equipment. Electricity is obtained from processed fossil fuels in a solid, gas or liquid form. Processing of these fuels poses ecological threats to the environment and their utilization is restrained by their limited natural reserves. Therefore, it is important to be able to predict and minimize energy used in manufacturing processes.

Ecology and saving energy are the current trends in the latest solutions in machine tools [1]. Many producers of technological equipment, esp. machine tools, try to decrease electricity consumption in the face of constantly growing industry requirements for more power input in the industry sector. New solutions being developed by machines' manufacturers are chiefly attempts at enhancing the efficiency of mechanical and electrical systems and monitoring and minimizing power consumption by machine control systems.

While automation seems to be the dominating tendency, energy consumption of auxiliary processes is no less important as they ensure smooth running operation of assembly, transportation, storage, handling, control, information flow, etc. There are very few models in the literature which describe manufacturing processes in the energy aspect of the issue [2–4]. While these models mainly describe main, basic processes, which aim at obtaining direct changes in processed materials, auxiliary processes can also be the source of energy savings in production processes. Therefore, it is important to minimize energy consumption also in the sphere of auxiliary activities and operations.

A modeling of energy consumption of auxiliary processes makes it possible to asses the amount of used energy, e.g. at the stage of construction or technological design of a given product, i.e. it is possible to optimize the level of energy consumption, which influences production costs of a final product.

Energy consumption of a manufacturing process

Production energy consumption can be defined as the amount of energy used in a production process referred to the amount of production. Depending on the criteria of measuring energy input into a production process of a certain amount of products, a direct and cumulative energy consumption can be differentiated [5].

Direct energy consumption means the use of energy carriers directly at a technological process of manufacturing a given product. However, this definition of energy consumption does not include all the energy necessary to manufacture a product (or perform a service). The total energy consumption necessary to manufacture a product (or perform a service) is referred to as cumulative energy consumption. In other words, it is the total amount of the original energy used in all processes necessary to manufacture a product or a service.

Direct energy consumption can be referred to the process of manufacturing a product and it is possible to differentiate energy consumption of basic processes and energy consumption of auxiliary processes. Energy consumption of a basic process is the amount of energy used during the process of changing a semi-finished product into a completely finished product with required properties, shape, dimensions and desired position of respective parts and systems in case of processes and assembly operations. Energy consumption of auxiliary processes is the amount of energy provided to subsystems responsible for controlling a manufacturing process (e.g. subsystems of transportation, storage, handling, control, information flow, etc.).

Earlier studies [2, 4] analyzed a life cycle of a product pointed out important fields of energy consumption. An analysis of successive stages of a generalized manufacturing process using machining methods helped the authors to develop the model of energy consumption presented in Fig. 1.

The model presented in the earlier papers reveals that direct energy consumption is also affected by a number of auxiliary actions. Energy consumption of machining is connected with a product being manufactured through the volume of machined allowance.

$$E_c = k_c \cdot 10^{-3} \cdot \prod_{i=1}^{n} K_i \cdot V_i, \quad [\mathrm{J}], \tag{1}$$

where E_c – energy consumption of cutting [J], k_c – specific resistance of cutting [N/mm^2], K_i – correction coefficients, V_i – volume of material [mm^3].

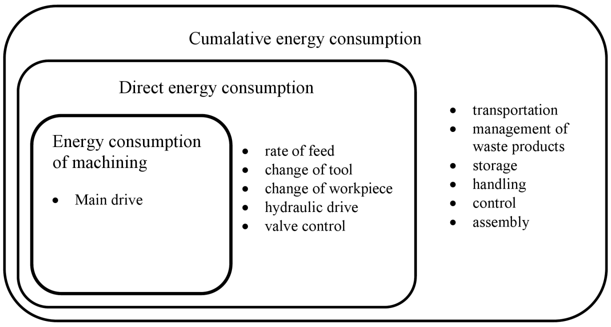

Fig. 1. Significant fields of absorption and energy in a production system [4].

The energy input of a machine tool and auxiliary processes can be determined from a relation that only takes into consideration an average power of an electric drive used in a system [4], e.g.:

$$E_t = \sum_{i=1}^{n} P_i \cdot (t_g + t_j), \quad [\mathrm{J}], \tag{2}$$

where t_j – time of idle run, t_g – main time of production station,P_i – average power of a system used during work operation.

The part of energy used to power the environment of a production system amounts to 60–90%, according to the authors of [4].

Analytical model of energy consumption of transport subsystems

Production processes require constant material feeding conducted by the so-called transport subsystem. The function of a transport subsystem is performed by various technical machines and systems, such as transport carrier trolleys, roller conveyors, conveyor belts, overhead conveyors, robots, overhead travelling cranes, etc. Transport equipment which operates in automated manufacturing systems and which needs no maintenance is usually electrically powered. Energy consumption of modern subsystems electrically powered is not constant, but it depends on a number of factors, such as: organization of a production process, mass to be transported, mass of a transport medium, inertia of a mechanical system, kinematic characteristics of transport (velocity, accelerations), number of empty runs, etc.

While considering an idealized model of a transport subsystem (as e.g. in Fig. 2), it is possible to assess its energy requirements, through an analysis of energy transformations in a time of mass transfer, more precisely than by using a relation from earlier papers [3] and [4]. Individual elements of energy consumption of a transported mass movement are the results of all the forces, found in a complex model, which create the balance of the driving force. An energy model of a transported mass can be given by an equation which expresses the principal of equivalence of work and energy. Motion energy consumption is the work of driving force performed on a length of a transport route. Driving force can be expressed using various equations describing various phases of motion. For variable conditions the energy equation of transferred mass can take the following form:

$$E = \int_0^S F_n ds \overline{F_n}, \tag{3}$$

where F_n – instantaneous value of driving force, s – elementary distance $\overline{F_n}$ – average value of driving force, S – total distance or a dependence in the function of time:

$$E = \int_{s_0}^{T_1} F_n v dt, \tag{4}$$

where t – time of drive phase.

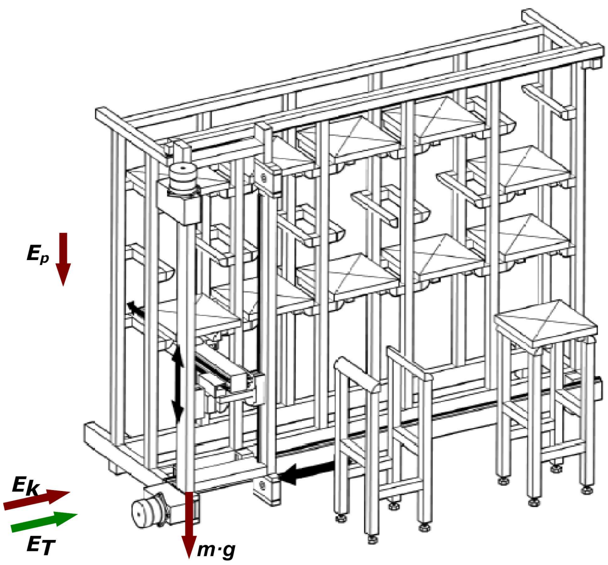

Fig. 2. An example of transport subsystem in an automated manufacturing system and elements of energy balance: E_p – potential energy, E_k – kinetic energy, $m \cdot g$ – deadweight, E_T – energy of rolling resistance component.

All the components of motion energy consumption are the result of the forces accounted for in a complex model which create driving force balance for any phase. In transport systems energy is usually spent to overcome both motion friction and the resistance of lifting the weight of a transport mass, which is equivalent to the increase of potential energy. For an accelerated motion it is also necessary to take into consideration energy needed to overcome inertia force, which is equivalent to the increase of kinetic energy. In a general case, the balance of longitudinal forces for any phase of motion can be expressed by the following relation:

$$F_n = T + F_w + F_k, \tag{5}$$

where F_n – driving force, T – component of rolling friction resistance force F_w – component of lifting resistance force, F_k – component of inertia resistance force

Energy consumption is, therefore, the sum of energy spent on overcoming all the components on the right side of the following equation:

$$E = E_t + E_w + E_k, \tag{6}$$

where E_t – energy spent on overcoming friction resistance, E_w – energy spent on overcoming lifting resistance, E_k – energy spent on overcoming inertia resistance.

The form of the balance of longitudinal forces which act on any given transportation means depends mainly on the method of setting them in motion and its kinematic parameters. It can, therefore, contain components with a different algebraic sign. During a run of a transport device, its velocity profile consists of several states which include acceleration, steady motion and braking.

During the acceleration phase energy is spent on overcoming all the components of resistance forces and inertia force. In a steady motion – only on overcoming resistance forces. The braking process is basically limited to dissipation of earlier accumulated kinetic energy. This function is usually performed by modern electric drives. At the same time the remaining part of this energy is spent to overcome static resistance of motion. Because the energy balance is so diverse, depending on the method in which a transport device is set in motion a determination of energy consumption of a transport device moving in three states; acceleration, steady motion, braking, requires to take into consideration energy spent during these three states:

$$E = E_t^+ E_w + \Delta E_k^a - \Delta E_k^u, \tag{7}$$

where ΔE_k^a – increase of kinetic energy during acceleration state, ΔE_k^u – change of kinetic energy during stopping state.

The successive components of spent energy can be expressed using the following relations:

$$E_t = mg \int_0^L f_t ds = mgf_t L, \tag{8}$$

$$E_w = mg \int_0^H dh = mgH, \tag{9}$$

$$\Delta E_k^a = -\Delta E_k^u = m \int_o^{s_a} ads = \frac{m}{2}(v_1^2 - v_0^2) = \frac{m}{2}v^2 \tag{10}$$

where m – mass, f_t – coefficient of rolling resistance, ds – elementary way, L – transport distance s – acceleration (braking) distance, g – gravitational acceleration, H – height of lifting, a – acceleration, ν – velocity.

Energy spent on overcoming inertia force, which is equivalent to kinetic energy, will also depend on the type of powertrain used in a device and on the change of rotary motion into linear motion of a transport device. The inertia force of an object moving in a translational motion is defined by the second law of motion:

$$F_b = m \cdot a, \tag{11}$$

where m – mass of an object, a – acceleration.

If a linear motion also involves motion of rotational elements, it is necessary to take into consideration the kinetic energy of such a system. The inertia force in such an object can be expressed by:

$$F_b = \delta \cdot m \cdot a, \tag{12}$$

where δ – coefficient of rotating masses that takes into consideration inertia of powertrain::

$$\delta = 1 + \frac{4 \cdot I_k}{m \cdot r^2}. \tag{13}$$

The amount of kinetic energy taking into consideration the inertia of powertrain can be given by the following relation:

$$E_k = m \cdot \delta \int_o^{s_a} ads. \tag{14}$$

An omission of the coefficient of rotating masses (δ=1) can be a justified simplification in case of modern electric drives in which the kinematic chain is very short (e.g. a single timing belt). Taking into consideration all the above needs, energy requirements of a single transport action between two points of a distance can be expressed by the following relation:

$$E = mgf_t L + m_w gH + m\delta v^2, \tag{15}$$

where m_w – mass subject to potential resistance (transport mass plus mass of parts of a transport device responsible for lifting).

In studies on the efficiency of internal transport, individual energy consumption seems to be an important criterium. Individual energy consumption can be defined either as the ratio between energy and distance:

$$\Psi = \frac{E}{L} \tag{16}$$

or the product of mass and distance (run energy consumption):

$$\Phi = \frac{E}{m \cdot L}. \tag{17}$$

An example of calculations

Tables 2 and 3 present an example of calculations of transport operations energy consumption for a high storage rack stacker shown in Fig. 2. For the investigated high storage rack stacker there are 15 transport operations connected with moving cargo from a loading station to successive storage points distributed in 3 × 15 system and the same number of storage points in the opposite direction – from the high storage rack to the loading station. In the storage rack material is stored on transportation pallets with the mass of 3.2 tons each. Each transportation operation consists of a single elementary motion in the horizontal axis (the length of the storage rack) and in its vertical axis (the height of the storage).

Table 1
Parameters of an example of energy consumption model for a rack stacker.

Mass [kg]	Vertical stacker	Horizontal stacker	Cargo
	14.4	6.04	3.20
Rolling resistance coeficient	0.025		
Transport velocity [m/s]	0.5		

The parameters of the model include the following pieces of equipment: the mass of the vertical and horizontal stackers, the transportation mass, gravitational acceleration, the coefficient of rolling friction, the velocity in horizontal motion (Table 1), the transportation distance in horizontal and vertical directions (Tables 2 and 3). In this particular case only the mass of empty transportation pallets (i.e. the same value for all the places in the storage) was taken into consideration.

Table 2
Energy consumption values of transportation operations from the loading station to the storage.

Motion energy consumption [Wh]		Horizontal displacement [mm]				
		200	400	600	800	1000
Vertical displacement t upward [mm]	400	0.011	0.011	0.011	0.012	0.012
	250	0.007	0.007	0.007	0.008	0.008
	100	0.003	0.003	0.004	0.004	0.004

Table 3
Energy consumption values of transportation operations from the storage to the loading station.

Motion energy consumption [Wh]		Horizontal displacement [mm]				
		200	400	600	800	1000
Vertical displacement t upward [mm]	400	0.00	30.0007	0.0010	0.0013	0.0016
	250	0.0003	0.0007	0.0010	0.0013	0.0016
	100	0.0003	0.0007	0.0010	0.0013	0.0016

The calculated values of transportation energy consumption demonstrate that in the investigated case both the height and direction of storing are significant. The energy consumption of transport operation to higher storage shelves is higher than that for more distant shelves in the horizontal direction. This observation can be important in planing a distribution of materials of various masses.

Conclusions

The method of energy consumption assessment can be used as a tool for analyzing various variants of control strategy of technological, transport and storage machines, etc. in the function of motion parameters, such as acceleration velocity useful in conducting transportation operations with a minimized use of energy and assumed efficiency.

The presented approach will also make it possible to assess energy consumption of other manufacturing processes, e.g. in machining given that mass and kinematic parameters of a machine tool are known. The presented method is the first step on the way to model and design energy requirements of manufacturing processes to enables rating power consumption of manufacturing process on design stage where used are technical subsystems such as: machines, conveyors, manipulators etc.

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