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Equivalence assessment method for the resource efficiency of equipment, technologies and production systems

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Abstract

The paper analyses different assessment methods for the overall equipment effectiveness (OEE), energy efficiency and productivity of equipment and production systems. The proposed model and systematic assessment approach define the total and relative resource efficiency of equipment, technologies and production systems in the form of material, energy and information efficiency. This common resource efficiency assessment method is based on the physical and mathematical equivalence of efficiency indicators including probable events for resource usability. Three typical relations, determining any kind of efficiency, are obtained from those equivalents. Examples for resource efficiency assessment types are energy efficiency, productivity and accuracy. Integrated evaluation indicators for a comparative benchmarking of equipment, technologies and production systems are provided based on the equivalence assessment method and the proposed three typical relations. This method is also applicable to process chains.

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Keywords: equipment, resource efficiency, technology, production system

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1. Introduction

Progress in the development of technologies, systems, equipment and production is presently largely focused on efficient manufacturing systems during the design and exploitation phases. This becomes possible through improved performance indices and an increased degree of resource use, such as physical resources (energy, material, time), information and economical resources. **Therefore, procedures are required for resource efficiency analysis, assessment and set-up of parameters and characteristics** in order to make decisions in a prescribed and trustworthy manner. Referring to [1,2,3], **efficiency** is the extent of the use of any resource and the relative efficiency is described by the terms energy-efficiency, productivity, economical effectiveness or overall effectiveness in relation to this resource.

In all of the investigated systems (technologies, systems, equipment and production) **transformations** (processes) can be found, resulting in changed element **states**: input elements are being transformed into output elements. This model, as a system, contains the start conditions, nominal resource flow values for physical processes and limiting conditions for real flow values. Therefore, the relation between output values (power, information, time, etc.) E_{out} and input values E_{inv} is equal to the criteria efficiency E_e, where the numerator characterizes a possible maximal value and the denominator - the real work value performed by the equipment (or technological machine, technological or manufacturing system).

Different authors have investigated the assessment of different resource efficiency indicators and propose complex methods for the increased resource consumption efficiency in a functioning manufacturing system. Paper [1,2] propose the term efficiency as the relation of output process values E_{out} (energy, power, information, time etc.) to the input values E_{inv} and builds a general assessment method, applicable for the analysis of technologies, systems, equipment, technological machines and manufacturing in general.

Reference [4] proposes the following equipment and system efficiency indicators:

- indicator of machine operation time as the ratio of total equipment in use time excluding standstill to the overall equipment in use time,
- indicator of technical machine in use time as the ratio of total equipment in use time excluding standstill to the sum of total equipment in use time excluding standstill and own standstill time,
- indicator of equipment capacity usage as the ratio of the sum of total equipment in use time and own standstill time to the overall equipment in use time,
- general indicator of equipment in use as the product of the indicator of machine operation time and indicator of equipment capacity usage for the equipment exploitation time.

Paper [5] proposes a quantitative assessment method for all types of manufacturing equipment as the **overall equipment effectiveness (OEE)**. OEE permits the quantitative assessment of time losses influencing efficient equipment exploitation. OEE is the starting point for the derived analysis methods. Based on the overall equipment effectiveness proposed in [5], a standard for the effectiveness calculation and measurement [6] has been established. This standard proposes the application of the basic indicator – overall equipment effectiveness **OEE, measured in units of time**. The indicator OEE is easy to use, intuitively understandable and widely used in manufacturing corporations. Paper [7] proposes an efficiency assessment as the ratio of theoretical job execution time and actual manufacturing time. Here the equipment speed may differ between manufacturing tasks, e.g., caused by different operator qualifications. Therefore, preparation time or short equipment stops are not included in the standstill time, but are considered manufacturing time. Here, in case of different equipment operation speeds, the time consumption evaluation regarding standstill depends on the overall manufacturing management. Paper [8] proposes an alternative indicator to OEE. The authors explain that OEE is not supporting a precise efficiency measurement regarding the adjustment, reconfiguration and setup time. They propose the use of an indicator for the *overall equipment productivity*, which is connected to OEE through equipment capacity usage time.

Therefore, despite common theoretical background for overall resource efficiency and overall equipment effectiveness, different assessment methods have different systematically deviations and exclusive interpretations for terms and elements leading to different resource assessment results. A common equivalence assessment efficiency method is proposed for equipment, technologies and production systems.

2. **Equivalence assessment efficiency method**

Based on the definition of efficiency and the energy-information model of technological processes for product, part, article manufacturing [1,2], a model is proposed in figure 1, where transformations of all resource types and forms (energy, material, information) are present for equipment functionalities, manufacturing and systems. This approach enables the specification of the term ***efficiency*** as relative efficiency of all types of transforming system elements.

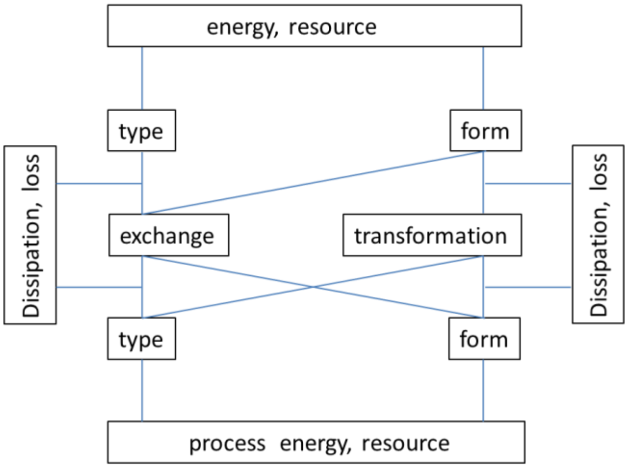

Fig.1. Resource transformation scheme

Unified laws describe transformation processes for different types and resources and make them independent from the designed, assembled, technical and technological equipment implementation. Papers [1,8,9] propose the term efficiency as the ratio of output values E_{out} (energy, power, information, time etc.) to input values E_{inp}. This relation in general is the **assessment criteria efficiency E_e**:

$$E_e = \frac{E_{out}}{E_{inp}}; \text{ or } E_e = \frac{E_{out}}{E_{out}^{f} + E_{out}^{ch}}; \qquad (1)$$

Alternatively for some resource forms and types:

$$E_e = \frac{\sum E_{out}}{\sum E_{out}^{f} + \sum E_{out}^{ch}}; \qquad (2)$$

The overall system efficiency E_0 is equal to the product of partial efficiencies E_e independent from the nature of each efficiency:

$$E_0 = \prod_{q=1}^{k} E_e^k; \qquad (3)$$

Therefore, the integrated efficiency indicator is equal to the product of E_e^m material, E_e^e energy and E_e^{in} information efficiencies:

$$E_e^i = E_e^m * E_e^e * E_e^{in}; \qquad (4)$$

This efficiency equation (1) is a general assessment method. Therefore it is applicable to the analysis of technologies, systems, equipment, technological machines and production and systems performing and transforming numerous resource types. **Types of energy** are kinetic, potential, dissipation, etc. **Forms of energy** are mechanical, electrical, thermal, chemical, magnetic, electromagnetic and gravitational.

The physical equivalence of resource type change and form transformations are applied to real processes.

Input resources are:

- one type and one form;
- one type and two forms;
- one type and three forms;
- two types and two forms; etc.

Output resources are:

- one type and one form;
- one type and two forms;
- one type and three forms;
- two types and two forms; etc.

Resource losses during the transformation from one form *k* to another form *n* consist of internal losses and transformation losses (dissipation). Resource losses apply during the transformation from one form *k* to another form *n* and during exchange from one form *k* to another form *n*. For instance, mechanical energy is the energy of plastic deformations or displacement or inter-crystal or interatomic interactions. Potential energy is the energy of elastic deformations.

Introducing process resource parameters (time, power, productivity, energy, etc.) into equation (1), a mathematical procedure is ready for implementation in order to deduce common laws for executing process transformations. Functional splitting between process resource transformations emphasizes the steady unity between resource exchange and transformation processes and supports a necessary universality of the efficiency assessment task and solution.

Therefore, the denominator in equation (1) represents the physical values and processes of the numerator, increased by a loss value. Therefore, the mathematical equivalence of transformations in equation (1) leads to standard types defined by the relation and quantity of the participating elements.

Table 1 Basic mathematical equivalent for efficiency assessment

Basic relation	Transformation into form	Characteristics	Value
$U_1 = \frac{a}{b}$	$U = \frac{a}{b}$	Some part of overall efficiency, event probability. Equal to or less than one.	Number
$U_2 = \frac{a}{a+b}$	$\frac{1}{1+b/a} = \frac{U_1}{1+U_1}$	Equal to or less than one.	Function
$U_3 = \frac{a}{a+c+d}$	$\frac{a}{c+d} * \frac{1}{1+(\frac{a}{c+d})} = \frac{1}{1+(\frac{c+d}{a})} = \frac{U_2}{1+U_2}$	Equal to or less than one.	Function
$U_4 = \frac{a+b}{c+d}$	$\frac{a}{c} * \frac{1+b/a}{1} * \frac{1}{1+d/c} = U_1 * \frac{U_2'}{U_2};$	Equal to or less than one. (c+d $\geq$ a+b)	Function
$U_5 = \frac{a+b}{c+d+e}$	$\frac{a+b}{d+e} * \frac{d+e}{c+d+e} = \frac{a+b}{d+e} * \frac{1}{1+c/(d+e)} = U_4 \frac{1}{1+U_2}$	Equal to or less than one. (c+d+e $\geq$ a+b)	Function
$U_6 = \frac{a+b}{(a+b)+(a_1+b_1)}$	$\frac{1}{1+a_1/a} * \frac{1+b/a}{1} * \frac{1}{1+(b+b_1)/(a+a_1)} = \frac{1}{1+U_1} * \frac{1}{U_2} * \frac{1}{1+U_4}$	Equal to or less than one.	Function

A difficulty in understanding lies in the selection and description of elements which have to constitute the system structure for resource transformations. Necessary information for equation (1) is available from physical and mathematical modelling. The physical model has to match the investigated object for the analysed processes and for influencing those parameters.

Therefore, an efficiency assessment in practise, regarding technological equipment, manufacturing and system is performed in equivalence to mathematical transformations presented in table 1. The first three relations U1, U2, U3 are the basic relations and they are relevant for the other relations. They characterize respectively: degree of resource consumption from the potential of technology, equipment, manufacturing or system; degree of resource consumption; degree of actual resource consumption.

3. Application example

Considering the development of information technologies and the creation of Industry 4.0, the proposed equivalence assessment method applies to information systems. The accuracy of the production process depends on the level of compliance or degree of approximation of the actual parameter (information parameter, geometric parameter, technological parameter) to their nominal, specified or ideal value (information image of the product). [9] In mechanical engineering, technical drawing are the basic sources of information about parameters, characteristics and part properties needed to manufacture with the planned technology. This drawing is the basic information source written in the input language. So long as methods and tools for the automatic interpretation of drawings and other technical documents (including their translation into the internal system language) are not available, a drawing is the only communication technique supporting information for automatic manufacturing systems.

An information transformation model is proposed as a "black box" with input information and resulting output information after transformation, including the necessary information for manufacturing needs. The overall information amount of the system (see fig. 1) is given as:

$$I_{\mathrm{o}} = \sum_{k=1}^{K}(I_{\mathrm{w}})_{\mathrm{k}} + \sum_{m=1}^{M}(I_{\mathrm{fp}})_{\mathrm{m}} + \sum_{n=1}^{N}(I_{\mathrm{cp}})_{\mathrm{n}} = I_{in} + I_{ot} + I_{us}; \qquad (5)$$

where $I_{in}; I_{ot}$ - the amount of input and output information respectively, I_{us} - the amount of transformed information used by the system; $(I_{\mathrm{w}})_{\mathrm{k}}$ - information about the product, $(I_{\mathrm{fp}})_{\mathrm{m}}$ - information about the physical process, $(I_{\mathrm{fp}})_{\mathrm{m}}$ - information about the management (control) process.

Therefore the amount of input information is equal to: $I_{in} = I_{in}^{tf} + I_{in}^{ot}$;

where I_{in}^{tf} - the amount of input information units, used for the transformation processes and system functions and necessary for the required amount and quality of the output information (product);

I_{in}^{ot} - the amount of input information units, not involved in transformation processes and system functions but containing the output information (e.g. management information like drawing number, department acronym, shop floor number, etc.).

Accordingly, the amount of output information is given by two parts: $I_{ot} = I_{in}^{ot} + I_{ot}^{tf}$; where I_{in}^{ot} - the amount of input information units, not involved in the transformation processes and system functions and not included in the output information; I_{ot}^{tf} - the amount of output information units, resulting from the transformation processes and system functions.

A value for the functional system time t_f (overall information I_0 processing time) and time t_h are introduced, necessary for the preparation of the input information volume. Therefore the information volume indicator for the information complexity and system usage (table 2) is given by the equation:

$$U_{cop} = \frac{I_{in}}{I_0} = \frac{I_{in}}{I_{in} + I_{ot} + I_{us}};. \qquad (6)$$

Taking into account the equivalence in table 1 and the variables in table 2, a general characteristic and index definition approach is proposed, which characterizes the system information efficiency. This fundamental indicator builds the basis for system type classifications in Industry 4.0. Next, substituting the previously assigned information types, the following system information efficiency indicators (see table 2 [2]) are invariant to investigated objects.

An overall automation efficiency indicator is proposed, resulting from innovative physical process implementation for technological processes aiming at part manufacturing. This indicator characterizes the time reduction (modification) for part manufacturing cycles compared to part manufacturing cycle time for the standard technological process.

Table 2. System information efficiency indicators

Indicator	Relation	Characteristics	Variance range
System information processing productivity	$U_{fh} = \frac{t_f}{t_h}$	Defines the functional system time consumption for input information unit preparation	0..1
Automation of system process functions	$U_{a.p} = \frac{t_h}{t_f + t_h} = \frac{1}{1+U_{fh}}$	Defines the percentage of the input information unit preparation from the overall system functional time	0..1
Input information complexity	$U_{eI} = \frac{I_{in}^{ot}}{I_{ot}^{tf}}$	Characterizes the ratio of input information not involved in system functions to the information of system process functions	0..1
Input information processing volume	$U_{val} = \frac{I_{ot}}{I_{in}^{tf}}$	Characterizes the amount of output information compared to input information for system process functions	0..1
Input information content degree	$U_{ic} = \frac{I_{us}}{I_{in}^{tf}}$	Characterizes the amount of used information compared to input information for system management process functions	0..1
Decrease in non-artificial work by system process functions	$U_{ht} = \frac{1+U_{eI}}{1+U_{val}}$	Characterizes the decrease of work load for data preparation and resulting from system process functions	0..1
Input information volume	$U_{cop} = \frac{1+U_{eI}}{2U_{eI} + U_{val} + U_{ic}}$	Characterizes the part of input information from the transformed information volume for one cycle of system process functions	0..1
Increased information processing productivity	$U_{gr} = \frac{1+U_{eI}}{U_{eI} + U_{val} + U_{ic}} = \frac{U_{cop}}{1-U_{cop}}$	Characterizes the information volume reduction of manual information processing derived from system application	0..∞

Integral automation indicator of technological process is given by:

$$U_i = \frac{t_f + t_h}{t_a + t_n}; \qquad U_i = \frac{t_f + t_v}{t_a + t_n}$$

where t_f, t_h, t_a, t_n - time (or costs), respectively, consumed for innovative technological process operations and time consumption for other operations and processes, supporting innovative technological process, respectively, for standard and innovative technological processes.

Table 3 is based on equivalences to table 1 and presents efficiency indicators – general productivity modification indicator (automation) of compared technological process variants, their variance range and short characteristics. Summarizing, the proposed common resource efficiency assessment method was approved for the information system efficiency and technological process variants.

Table 3. Efficiency indicators for technological process variants

Indicator	Equation	Characteristics	Variance range
Innovation modification	$U_n = \frac{N_a}{N}$	Ratio of the number of innovative physical processes to the total number of standard physical processes aiming at the creation of property *i*	0..1
Automation modification of the innovative technological process compared to standard process	$U_{an} = \frac{\sum_{i=1}^{N_a} t_i}{\sum_{i=1}^{N} t_i}$	Decreased work load for technological process aiming at part manufacturing with target properties compared to standard technological process	0..1
Automation of the technological process (system)	$U_C = \frac{t_f}{t_f + t_v}$	Time modification for operation and process execution in order to support the physical manufacturing process	0..1
Efficiency of innovative physical processes (technological operations)	$U_a = \frac{t_f}{t_a}$	Time modification for innovative physical process execution compared to the time for standard physical process execution aiming at the creation of property *i*	0..1
Efficiency of innovative physical process aiming at part manufacturing	$U_{ae} = \frac{t_f}{t_a + t_n} = U_{an} U_a$	Time modification for standard physical process execution compared to the time for the creation of property *i* needed by the innovative physical process	0..∞
General productivity modification indicator of innovative technological process	$U_i = \frac{U_{an} U_a}{U_C}$	Time modification for the overall creation of part property *i* by innovative and standard physical processes	0..∞
Efficiency of innovative technological process	$U_e = \frac{U_C}{U_{an} U_a}$	Total cycle time reduction for the creation of part property *i* by innovative and standard physical processes	0..∞

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