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Metrisable assessment of the course of stream-systemic processes in vector form in industry 4.0

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Abstract

The goal of this paper is to present an innovative conception how to use metrisable vector structure of a manufacturing process, based on quantitative relations between the activity of input streams, features of the product, and effect of losses; all of which are excellent practical solution for Industry 4.0, and in turn intelligent factories. This solution can be a usefull way in the process of building sustainable organization. A vector representation of manufacturing processes was formulated, one which is based in system engineering. Three manufacturing system state vectors were proposed. These are: input stream vector $\underline{\phi}$, product features vector $\overrightarrow{P}$ which is also referred to as quality vector, and losses vector $\overrightarrow{S}$. Scalar, vector, and mixed products of these vectors may form constitutive equations of manufacturing processes. The relations between the vectors ϕ, $\overrightarrow{P}, \overrightarrow{S}$ provide a possibility for a metrisable, complex analysis and assessment of a contemporary manufacturing process. The paper shows practical methods for defining the size of the vector values within the process. The demonstrated vector description of stream-systemic processes can also be applied to non-material manufacturing.

Keywords Industry 4.0 · Metrisability of the manufacturing process · Manufacturing process state vectors · Sustainable organization

1 Introduction

Integration of intelligent networked and autonomous digital technology with physical technology (e.g. Internet of Things, robotics, autonomous vehicles, 3D printing, etc.) in the era called Industry 4.0 presents new possibilities in the areas of innovation and

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development of manufacturing lines and, above all, the establishment of intelligent factories (Davis et al. 2015, 2012; Kumar et al. 2015).

The activities connected with digitalization of production processes are needs to achieve the sustainable organization by implementic innovative holistic approach to production management. To achieve sufficient sustainability organization should develop the possibility to identify factors influencing holistic growth in long term. To achieve it we shouls implement new technical innovations connected with Industry 4.0.

The main goal for Industry 4.0 is to increase the automation so as to impact the operational efficiency and effectiveness of the enterprise (Gilchrist 2016; Ustundag and Cevikcan 2017; Schwab 2017). Industry 4.0 is based on the integration of new technical solutions (Schwab 2018; Sergi et al 2019; Kumar 2019; Gülseçen et al. 2019). In this case, the important aspect lies in the process of combining intelligent machines and systems as well as introducing a shift to the manufacturing system (Longo et al. 2017; Wang et al. 2016a, b; Zhan et al 2020).

Digital technology development and its influence on each aspect of life, including industrialisation, is an ongoing feature, of a global reach (Lom et al. 2016; Brettel et al 2014; Adolphs et al 2016). Interconnection networks between the newest technological achievements, such as the Internet of Things, artificial intelligence, or augmented reality are becoming more complex with increasing rapidity (Esmaelian et al. 2016; Gajdzik et al. 2019; Herceg et al. 2020; Hong et al. 2020). Manufacturing businesses have enormous datasets at their disposal. Customers require rapid responses, quality, fitting, and customisation to an unprecedented scale. The environment, on the other hand, calls for care, diligence in material management, well-considered manufacturing processes (Kabugo et al. 2020; Kagerman et al. 2013; Lasi et al. 2014; Lass and Gronau 2020). All this results in tensions, information overload, the feeling of being lost, but on the other hand brings awe towards the existing possibilities and gives hope for the efficient integration of the individual component parts of Industry 4.0 (Lee et al. 2015; Li et al. 2017).

For these reasons, contemporary manufacturers that work with Industry 4.0 require the introduction of an innovative method of a metrisable technical, market, economic, social, and ecological assessment, with the added component of varied customer specifications (Grozd and Piwnik 2019; Gajdzik and Wolniak 2021; Wolniak et al. 2019; Stecuła 2018; Pacana et al. 2020; Dobosz et al. 2016).

The need for complex assessment caused a search of global description of the flow of manufacturing processes based on advanced system engineering models (Drozd 2019).

The application of system engineering allows to give a “measurable” answer to the fundamental questions regarding the goal of the process, the utilisation of the process time, location of the process, staff qualification, means, and other improvement actions within Industry 4.0 (Drozd and Piwnik 2019a, b).

At the same time, mathematical models of system engineering allow for the construction of multi-criteria metrics and the application thereof to optimise the next technological, organisational, and other steps (Zdanowicz 2007; Kosieradzka 2004).

The goal of this paper is to present an innovative conception how to use metrisable vector structure of a manufacturing process, based on quantitative relations between the activity of input streams, features of the product, and effect of losses; all of which are excellent practical solution for Industry 4.0, and in turn intelligent factories. This solution can be a usefull way in the process of building sustainable organization.

2 Literature review

The fourth industrial revolution is a concept of making use of automation and data collection and exchange, as well as the implementation of a variety of new technologies that allow for the creation of the so-called cyber-physical systems, as well as introduction of a shift in manufacturing (Michalski et al. 2017; Motyl et al. 2019; Nagasawa et al. 2017; Niesen et al. 2016; Pilloni et al. 2018). It is also related to digitisation of manufacturing, where technological means and systems are intercommunicated, including internet-based communication, and where large volumes of manufacturing data are analysed (Posada et al. 2015; Romero et al. 2016; Saniuk et al. 2020; Santos et al. 2017). Industry 4.0 also is a repository of notions encompassing a range of modern technologies—including the Internet of Things, cloud computing, big data analysis, artificial intelligence, incremental printing, augmented reality, or cooperating robots (Sao et al. 2015; Schlechtendahl et al. 2015; Schmidt et al. 2015; Wolniak et al. 2020; Yu et al. 2020).

The second dimension of Industry 4.0 is the aspect of managing contemporary manufacturing, i.e. a change to the architecture of manufacturing management systems and shifting from linear processed and the traditional pyramid of manufacturing management systems towards interconnected networks and non-linear manufacturing (Pająk 2006). A combination of the abovementioned innovations with the new possibilities offered by artificial intelligence may lead to a revolutionary change in the manufacturing management systems, where systems will be highly autonomous, dynamically shifting their structure and functions within their organisation (Powierża 1997; Hawryluk 2019). This business area is also described in this paper, with its key features from the viewpoints of a manager, indicated.

Industry 4.0 is also a contemporary concept of the use of automation and robotisation, data processing and exchange, implementation of a variety of technologies that allow for the creation of the so-called cyber-physical systems, all in the context of the eventual changes of manufacturing (Hawryluk 2019).

Industry 4.0 is a definition of a digital shift in the global economy (Zhang et al. 2014; Zhong et al. 2017).

The fourth industrial revolution is an opportunity for development, especially for small and mid-scale manufacturing enterprises, as the accessibility barrier for newest manufacturing technologies is becoming increasingly lower and because such companies are more flexible in reacting to market requirements zimei et al. 2020; Sommer 2015; Weber 2015).

The gains from the implementation of Industry 4.0 rules for manufacturing businesses are (Scheer 2016; Kagermann 2014; Wolniak and Miśkiewicz 2020):

- Increased productivity—the potential of better utilisation of assets as well as minimising downtimes;
- Better planning and monitoring of manufacturing processes;
- Optimisation of manufacturing costs, due to the identification of losses and monitoring of the costs;
- Visibility of manufacturing information at different organisational levels of the company, possibility to trace the current state of manufacturing equipment;
- Manufacturing of “intelligent” products that allow for tracing (e.g. with the use of RFID tags) in their complete lifecycle, from manufacturing, through shipping and aftersales service, towards recycling;
- Implementation of new manufacturing models.

- Possibility to implement predictive maintenance;
- Better scalability of manufacturing, e.g. through the use of cloud services.

An important task that Industry 4.0 serves is the creation of intelligent factories, where manufacturing technologies are updated and processed by cyber-physical systems, IoT, and cloud processing (Arnold et al. 2016; Foidl and Felderer 2016; Grzybowska and Łupicka 2017).

In the era of Industry 4.0 contemporary manufacturing systems are capable of monitoring physical processes, may make informed decisions in the course of real-time communication, with the aid of human–machine interaction, machines, sensors, and so on (Jazdi 2014; Li 2020; Liu and Xu 2017).

Industry 4.0 combines the technology of embedded manufacturing systems with intelligent manufacturing processes in order to make way for a new technological era that will be a breaking point for the value streams in the industry, value streams of manufacturing, and business models (Sanders et al. 2016; Schröder et al. 2014; Xu 2017).

Industry 4.0 brings a promise of increased manufacturing flexibility, with mass adjustment capabilities, higher quality, and improved productivity. Thus, it allows companies to better face the manufacturing challenges associated with the production of increasingly customised products with a short market-readiness span and higher quality. Intelligent manufacturing is a valid component of Industry 4.0 (Zhou et al. 2015; Bauernhansl et al. 2015; Brettel 2015; Baure 2014).

3 Methods: results of our own research

In the era of Industry 4.0 contemporary manufacturing systems are capable of monitoring physical processes, may make informed decisions in the course of real-time communication, with the aid of human–machine interaction, machines, sensors, and so on.

The goal of this paper is to present an innovative vector structure of a manufacturing process, based on quantitative relations between the activity of input streams, features of a product, and effect of losses, all a perfect practical solution for Industry 4.0 and in consequence for intelligent factories.

The further part of the article demonstrates the relations between the distribution of systemic streams in time and the product and losses, all as simple vector functions.

The starting point for all considerations are new concepts of description, to be implemented by intelligent factories, and presented as vector fields of the activity of systemic streams, features of a product, and characteristics of losses.

The presented vector description of the functioning of the manufacturing system poses no limitations as to the character of the manufacturing system, which may also be of the non-material type.

The vector relations between distribution of streams, features of the product, and types of losses are scalar, vector, and mixed products of vectors that represent the activity of streams ϕ, product $\vec{P}$, and losses $\vec{S}$.

The relations of the vectors ϕ, $\vec{P}$, $\vec{S}$ reflect the synchronicity and unambiguity of the activity of the system, which is symbolically represented as the following relations:

$$\hat{O}_p(\phi_{E_i}, \phi_{M_j}, \phi_{I_k}\,\phi_{T_l}, \phi_{F_m}\,\phi_{K_n})\hat{P} + \hat{S} \tag{1}$$

The relations (1) are shown in Fig. 1.

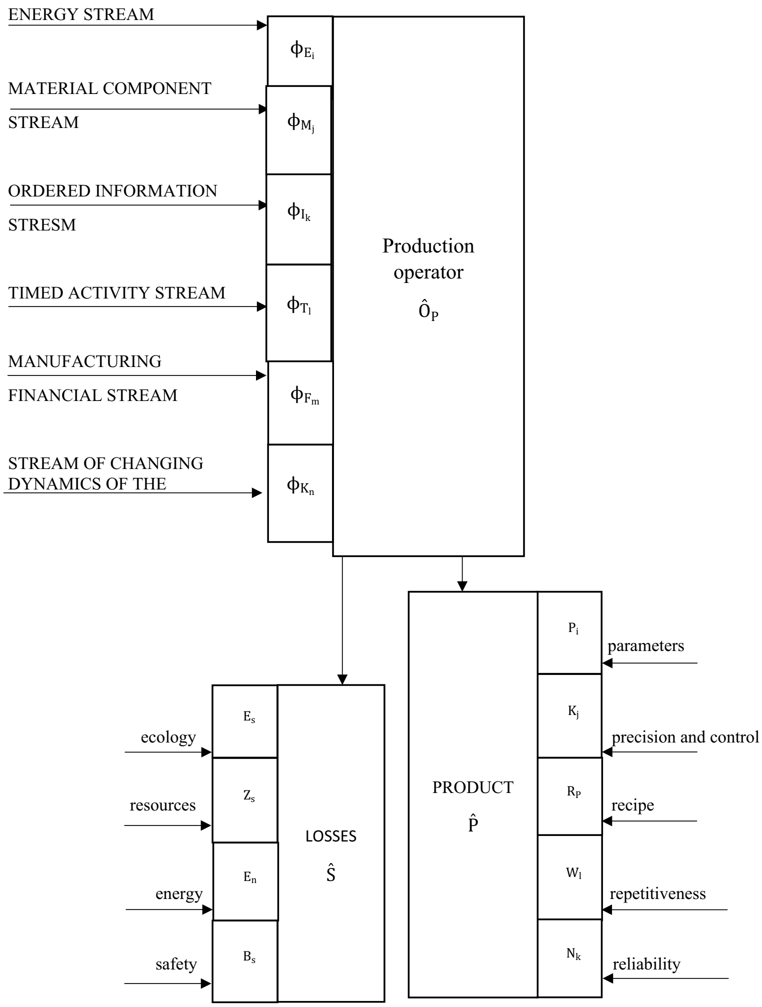


Fig. 1 Structure of a manufacturing process. Source: Own elaboration

In the literature on the subject and in practice, there are no proposals to present a metrisable vector structure of a manufacturing process, based on quantitative relations between the activity of input streams, features of the product, and effect of losses, which are an excellent practical solution for Industry 4.0 and, subsequently, for intelligent factories.

In the next part of the work, the possibilities of a vector description of the process using three system vectors: the vector if input streams ϕ, product vector $\vec{P}$, also understood as quality, and the vector of losses, $\vec{S}$.

3.1 Vector structure of an industry 4.0-based manufacturing system

The overview of the analysed manufacturing system was presented in Fig. 1.

The manufacturing operator acting space $\hat{O}_P$ is fed with six streams, the "power components" of the system. The number and type of streams as well as their significance compose to characterise the system—its goal may be material manufacturing, informational activity, didactics, or other.

Below are presented six streams that make up the powering components of the system, shown in Fig. 2.

1. The energy stream ϕ_{E_i} is a necessary set of i-elements which process various types of energy (mechanical, electrical, heat, chemical, and other). The energy stream ϕ_{E_i} will be further represented as a vector $\vec{r}_e$.
2. The material component stream ϕ_{M_j} is a set of j-elements that guarantee complete material safety of the manufacturing. These are raw materials, machines, installations, media, and other objects and materials. The stream ϕ_{M_j} is represented as a number of objects in time, and its vector representation is shown as $\vec{r}_m$.
3. The stream of ordered information ϕ_{I_k} is a set of k-elements of specialised theoretical and experimental knowledge. These are instructions, guidelines, algorithms, patents, and other segments of contemporary knowledge that guarantee the highest quality of the system. The stream ϕ_{I_k} is measured as amount of information in time and will be represented as the vector $\vec{r}_i$.
4. The timed activity stream ϕ_{T_l} is a set of l-elements of orders of sequences of actions of relations between streams in time. The elements also define timespans of individual operations and tasks and other activities that assure the completion of concept and

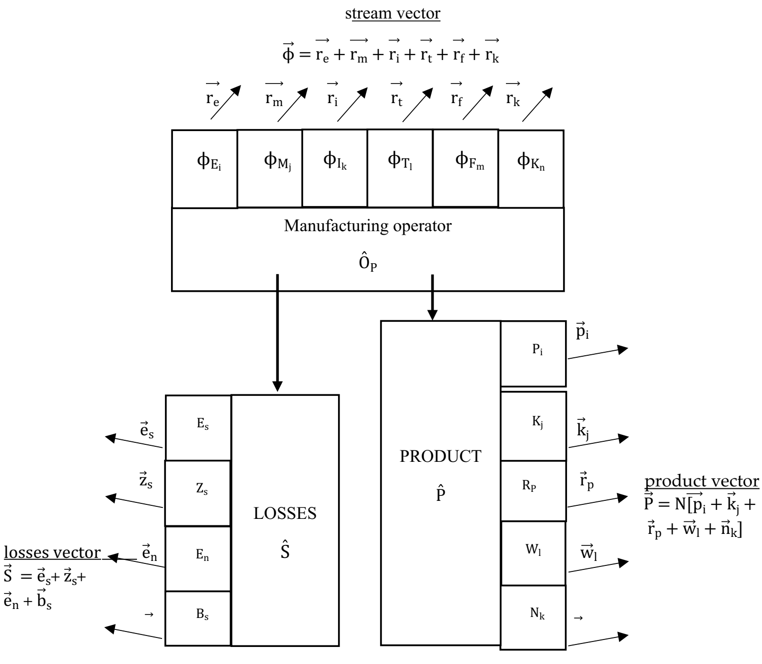


Fig. 2 Design of the vector structure of a manufacturing process. Source: Own elaboration

design assumptions of the streams. The stream ϕ_{T_l} is measured by number of ordered activities in time and its vector representation is $\vec{r}_t$.

5. The manufacturing financial stream ϕ_{F_m} is a set of m-elements that define the costs of individual stream relations, juncture trends, and other outlays guaranteeing reliable functioning of the system. The stream ϕ_{F_m} is counted in outlays in time and its vector representation is $\vec{r}_f$.
6. The corrections stream ϕ_{K_n} is a set of n-elements that describe the forced and unexpected changes to the predefined dynamics of the manufacturing process. This stream is characterised by high sensitivity to proper flows of the abovementioned system streams. The stream ϕ_{K_n} reflects the amount of corrections of relations and order in time and the vector representation thereof is $\vec{r}_k$.

The complete input stream set is represented by the vector ϕ which is the sum of vectors of individual streams, as shown in Fig. 2. The method for constructing the stream vectors is discussed in the further part of the paper.

The activity of the manufacturing operator $\hat{O}_P$ results in the product $\hat{P}$ and losses $\hat{S}$.

The product $\hat{P}$ us defined by the following vectors: parameter vector $\vec{p}_i$, precision and control vector $\vec{k}_j$, recipe vector $\vec{r}_p$, repetitiveness vector $\vec{w}_l$, reliability vector $\vec{n}_k$. All these are presented in Fig. 2.

The resultant product vector $\vec{P}$ is the product of reliability N and the vector sum of component vectors of the product, see Fig. 2.

The method of constructing the $\vec{P}$ product vector can be found in the next subsection.

The losses $\hat{S}$ are described by four vectors: ecological $\vec{e}_s$, resource $\vec{z}_s$, energy losses $\vec{e}_n$, and safety $\vec{b}_s$ vectors. The resultant $\vec{S}$ losses vector is a sum of the enumerated component vectors. The vector is presented in Fig. 2.

The method of constructing the losses vector is described in the following subsection.

According to the presented systemic approach, a manufacturing system is an intended activity of the operator $\hat{O}_P$ on the streams denoting an ordered set of relations between stream elements, all leading to the emergence of the product $\hat{P}$ and inevitable losses $\hat{S}$.

Within the system, all relations are active, i.e. each has a task of their own. Therefore, the description of the complete system needs to take into account simultaneous and unambiguous relation between the manufacturing operator, product, and losses. A strict description of the relation is immensely difficult but some assistance comes from the application of vector functions. For this reason, the further part suggests ways to order the functions of the vectors: stream ϕ, product $\vec{P}$, and losses $\vec{S}$.

Relations of these vectors result in the description of a system which meets the criteria of simultaneous and unambiguous relations between all the elements of a manufacturing system.

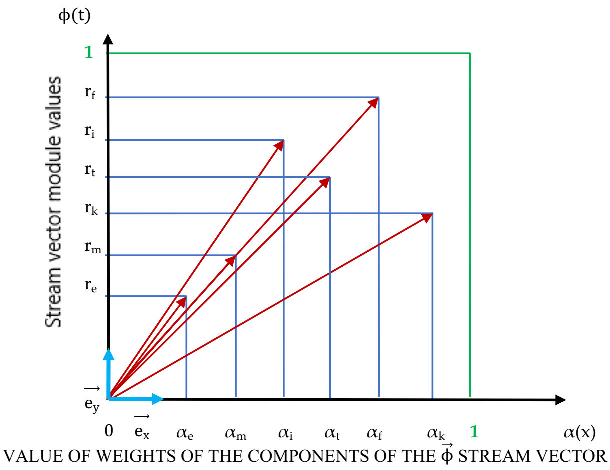
3.2 Manufacturing system vectors

3.2.1 Introduction

All the vectors of a manufacturing system are presented in a rectangular coordinate system, see Figs. 3, 4, and 5.

On the x axes of the coordinate systems, we mark the weight values of the individual vectors. In each case, the sum of all the weights for one part of the system is 100%.

Fig. 3 Components of the ϕ vector stream in a value system of their modules and weights. Source: Own elaboration



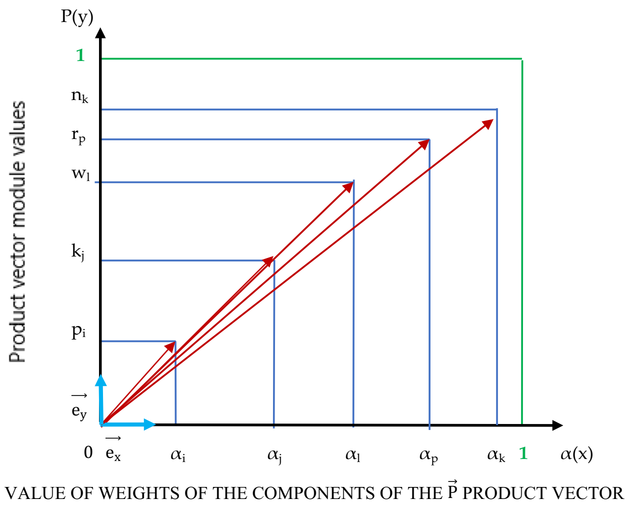


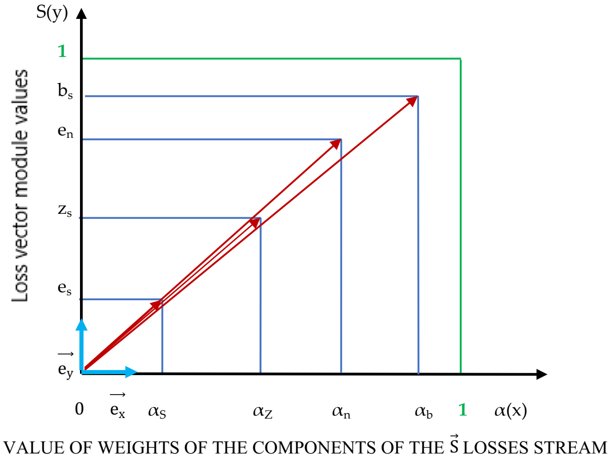
Fig. 4 Components of the $\vec{P}$ product vector in a value system of their modules and weights. Source: Own elaboration

The y axes contain the module values of the individual vectors of the system. The values of the modules of the vectors as well as weights are non-dimensional.

The x axis, i.e. the weight axis, is assigned a singular $\vec{e}_x$ versor, while the y axis is assigned a singular $\vec{e}_y$ versor. Thus, each of the vectors of the system will be a directed sector on the x–y plane and will have the following form:

$$\vec{a} = a_x\overrightarrow{e_x} + a_y\overrightarrow{e_y} \tag{2}$$

Fig. 5 Components of the $\vec{S}$ losses vector in a value system of their modules and weights. Source: Own elaboration



The a_x reflect values of individual weights, while the a_y values denote numerical values of the modules of the state vectors. The a_x and a_y values range from zero to one.

$$a_x \in [0, 1], a_y \in [0, 1] \tag{3}$$

Each of the manufacturing system vectors has their values of modules and weights reflected in a set [0,1]. The way of reflecting these values is shown in a further subsection.

3.2.2 Stream vector

The fundamental functions describing the controlled stream expenses in time will be introduced as non-dimensional relations that take into account the ratio of the actual expenses amount of elements of the stream sets to the same amounts as defined by the product concept norm.

These will be non-dimensional amounts that present the activity of streams in time $t_0 \le t < t_{fin}$ The values of these amounts are presented as a_y in the formula [3] as follows:

1. Non-dimensional momentary expense of the energy stream.

$$r_e(t) = \frac{\int_{t_0}^{t} \phi_{E_i}^{rz}(t) \cdot dt}{\int_{t_0}^{t} \phi_{E_i}^{n}(t) \cdot dt} \tag{4}$$

2. Non-dimensional momentary expense of the material stream.

$$r_m(t) = \frac{\int_{t_0}^{t} \phi_{M_j}^{rz}(t) \cdot dt}{\int_{t_0}^{t} \phi_{M_j}^{n}(t) \cdot dt} \tag{5}$$

3. Non-dimensional momentary expense of the ordered information stream.

$$r_i(t) = \frac{\int_{t_0}^{t} \phi_{I_k}^{rz}(t) \cdot dt}{\int_{t_0}^{t} \phi_{I_k}^{n}(t) \cdot dt} \tag{6}$$

4. Non-dimensional momentary expense of the activity in time stream.

$$r_t(t) = \frac{\int_{t_0}^{t} \phi_{T_l}^{rz}(t) \cdot dt}{\int_{t_0}^{t} \phi_{T_l}^{n}(t) \cdot dt} \tag{7}$$

5. Non-dimensional momentary expense of the financial stream.

$$r_f(t) = \frac{\int_{t_0}^{t} \phi_{F_m}^{rz}(t) \cdot dt}{\int_{t_0}^{t} \phi_{F_m}^{n}(t) \cdot dt} \tag{8}$$

6. Non-dimensional momentary expense of the correction stream.

$$r_k(t) = \frac{\int_{t_0}^{t} \phi_{K_n}^{rz}(t) \cdot dt}{\int_{t_0}^{t} \phi_{K_n}^{n}(t) \cdot dt} \tag{9}$$

The presented non-dimensional momentary stream expenses in time can be defined as experimental, while the process lasts.

After the formulas: (2), (4)–(9) have been take into account, we get the following formulas for the components of the stream vector:

$$\overrightarrow{r_e}(t) = \alpha_e \vec{e}_x + r_e(t)\overrightarrow{e_y} \tag{10}$$

$$\overrightarrow{r_m}(t) = \alpha_m \vec{e}_x + r_m(t)\overrightarrow{e_y} \tag{11}$$

$$\vec{r_i}(t) = \alpha_i \vec{e}_x + r_i(t)\overrightarrow{e_y} \tag{12}$$

$$\vec{r_t}(t) = \alpha_t \vec{e}_x + r_t(t)\overrightarrow{e_y} \tag{13}$$

$$\vec{r_f}(t) = \alpha_f \vec{e}_x + r_f(t)\overrightarrow{e_y} \tag{14}$$

$$\overrightarrow{r_k}(t) = \alpha_k \vec{e}_x + r_k(t)\overrightarrow{e_y} \tag{15}$$

The components of the stream vector are shown in Fig. 3.

The resultant of the $\vec{\phi}$ stream vector is the sum of component vectors and the following formula:

$$\begin{aligned}\phi(t) &= \overrightarrow{r_e}(t) + \overrightarrow{r_m}(t) + \overrightarrow{r_i}(t) + \overrightarrow{r_t}(t) + \overrightarrow{r_f}(t) + \overrightarrow{r_k}(t)\\ &= \vec{e}_x[\alpha_e + \alpha_m + \alpha_i + \alpha_t + \alpha_f + \alpha_k]\\ &\quad + \vec{e}_y\,[\overrightarrow{r_e}(t) + \overrightarrow{r_m}(t) + \overrightarrow{r_i}(t) + \overrightarrow{r_t}(t) + \overrightarrow{r_f}(t) + \overrightarrow{r_k}(t)]\end{aligned}$$

3.2.3 Product vectors

The product may be represented as four vectors and reliability vector N. The vectors are as follows:

1. $\overrightarrow{p_i}$ characteristic parameters vector

$$\overrightarrow{p_i} = \alpha_i \vec{e}_x + p_i \overrightarrow{e_y}, \tag{16}$$

2. $\overrightarrow{k_j}$ precision and control vector

$$\overrightarrow{k_j} = \alpha_j \vec{e}_x + k_j \overrightarrow{e_y}, \tag{17}$$

3. $\overrightarrow{r_p}$ recipe vector

$$\overrightarrow{r_p} = \alpha_p \vec{e}_x + r_p \overrightarrow{e_y}. \tag{18}$$

4. $\overrightarrow{w_l}$ repetitiveness vector

$$\overrightarrow{w_l} = \alpha_l \vec{e}_x + w_l \overrightarrow{e_y}, \tag{19}$$

5. $\overrightarrow{n_k}$ reliability vector

$$\overrightarrow{n_k} = \alpha_k \vec{e}_x + n_k \overrightarrow{e_y}, \tag{20}$$

The values for α_i, α_j α_p, α_l, α_k are weights, while the values p_i, k_j, $r_{p,}$ w_l, n_k are experimentally defined according to procedures fitting a given type pf product.

The resultant of the $a\vec{p}$ product vectors is the vector sum of the mentioned components, multiplied by the reliability of the process N, and is presented as:

$$\vec{p} = \mathrm{N} \times \left(\overrightarrow{p_i} + \overrightarrow{k_j} + \overrightarrow{r_p} + \overrightarrow{w_l} + \overrightarrow{n_k}\right). \tag{21}$$

The value of the module of the vector $\vec{p}$ lies within the range [0,1] and is interpreted as the quality of the product.

3.2.4 Losses vectors

Losses within the system are described as the sum of the following four component vectors:

Ecological vector

$$\overrightarrow{e_s} = \alpha_s \vec{e}_x + e_s \overrightarrow{e_y}, \tag{22}$$

Resource vector

$$\overrightarrow{z_s} = \alpha_z \vec{e}_x + z_s \overrightarrow{e_y}, \tag{23}$$

Energy loss vector

$$\overrightarrow{e_n} = \alpha_n \vec{e}_x + e_n \overrightarrow{e_y}, \tag{24}$$

Safety vector

$$\vec{b}_s = \alpha_b \vec{e}_x + b_s \vec{e}_y. \tag{25}$$

The values of $\alpha_s, \alpha_z, \alpha_n, \alpha_b$ are the weights of the abovementioned vectors. The values.

e_s, z_s, e_n, b_s are empirically defined according to the procedures designated for the type of manufacturing process.

The resultant of the $\vec{s}$ losses vector is a sum of the component vectors and is presented as:

$$\vec{s} = \vec{e}_s + \vec{z}_s + \vec{e}_n + \vec{b}_s, \tag{26}$$

The module value of the $\vec{s}$ vector lies within the range [0,1]. The components of the vector $\vec{s}$ are shown in Fig. 5.

4 Vector constitutive relations of a contemporary manufacturing process

A complex metrisable evaluation of a manufacturing process ought to contain the relation between the distribution of input streams and the quality of the product and measurable effects of losses.

A set of three vectors, $\phi, \vec{P}, \vec{S}$, representing the state of the process, allows to formulate a constitutive equation of the manufacturing process.

There are a few possible relations between the three abovementioned vectors. Those which are important lead to better understanding of the phenomena and optimisation towards the attractiveness of the product, its energy consumption, and costs.

The relations between the vectors $\phi, \vec{P}, \vec{S}$ may be functions or vectors, the results of whose calculation are scalar and vector values.

Vectors are e.g. the products of $(\phi x\ \vec{P}) * (\vec{S})$, presented as follows:

$$\vec{V} = (\phi \times P) * (S) = \begin{vmatrix} \vec{e}_X & \vec{e}_Y & \vec{e}_Z \\ P_X & P_Y & P_Z \\ S_X & S_Y & S_Z \end{vmatrix} * \sqrt{s_x^2 + s_y^2} \tag{27}$$

Vector representations of the manufacturing process can also be achieved through the sum of the vectors $\vec{\phi}, \vec{P}, \vec{S}$ and their double vector product. The formula is:

$$\vec{\Sigma} = \phi + \vec{P} + \vec{S}, \tag{28}$$

$$\vec{D} = \left(\phi \times \vec{P} \times \vec{S}\right), \tag{29}$$

Modules of the vectors: $\vec{\Sigma}$and $\vec{D}$ may be scalar functions of the manufacturing process.

There are a number of combinations of calculations with the use of the vectors:ϕ, $\vec{P}$, $\vec{S}$. Applying these combinations and the interpretation thereof depend on the goals of the manufacturing system and staff qualification.

5 Summary

The paper presents a new idea of a metrisable vector structure of a manufacturing process, based on quantitative relations between the activity of input streams, features of the product, and effect of losses, which are an excellent practical solution for Industry 4.0 and, subsequently, for intelligent factories. The use of the method can improve the measurement of all processes and plays important rol to improve the sustainability of the organization. In this way the organization can improve all production activirties that leads to organization success without compromising the needs of the future. The effect is possible because we can use special, innovatie vector analysis linking in one system many aspects of sustainability: ecological, resources, energy loss, safety, ect. A complex approach to metrisable evaluation and beter data analysis is very usfull in the business decision process and affects all aspects of the organization activities.

A possibility of a vector process description was presented, based on three system vectors; These are: the vector if input streams ϕ**,** product vector $\vec{P}$, also understood as quality, and the vector of losses,$\vec{S}$.

The constitutive equations of the manufacturing system may be e.g. scalar, mixed, and vector products of various combinations of the state vectors ϕ,$\vec{P}$,$\vec{S}$.

The article presents a new description of a manufacturing process that allows for metrisable (measurable) quantitative and complex assessment of the contemporary manufacturing system within Industry 4.0. This opens up the possibility to take into account market, economic, social, or ecological criteria needed to achieve the sustainability of the organization, as well as assuring proper conditions within ergonomics and manufacturing time—a very important aspect in the functioning of intelligent factories.

The new idea of a metrisable vector structure of a manufacturing process has been developed with Industry 4.0 in mind, however the system is constructed in a way where apart from material manufacturing it may be applied to analysis of other processes, i.e. information processing, education, strategy, games, etc. The increased measurement of organizational activities can leads to sustainable organization. This is very important in the process of enhancing the value of organization.

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Compliance with ethical standards

Conflict of interest The author declare there is no competing interest.

References

Adolphs, P., Auer, S., Bedenbender, H., Billmann, M., Hankel, M., Heidel, R.: Struktur der verwaltungsschale: Fortentwicklung des referenzmodells für die Industrie 4.0- komponente. Bundesministerium für Wirtschaft und Energie (BMW), Berlin, pp. 345–361 (2016)

Arnold, C., Kiel, D., Voigt, K.I.: How Industry 4.0 changes business models in different anufacturing industries. In Proceedings of the XXVII ISPIM Innovation Conference–Blending Tomorrow's Innovation Vintage, At Porto, Portugal, pp. 1–11 (2016)

Bauer, W.: Industrie 4.0. Volkswirtschaftliches Potenzial für Deutschland. Berlin: BITKOM, (2014)

Bauernhansl, T., Hompel, M., Vogel-Heuser, B.: Industry 4.0 in production. Automatisierung und Logistik. Wiesbaden, Springer, pp. 12–19 (2015)

Brettel, M.: How virtualization, decentralization and network building change the manufacturing landscape. An Industry 4.0 Perspective. Int. J. Mech. Aerosp. Ind. Mechatron. Eng. **8**(1), 37 (2015)

Brettel, M., Friederichsen, N., Keller, M., Rosenberg, M.: How virtualization. Decentralization and network building change the manufacturing landscape. An industry 4.0 perspective. Int. J. Mech. Aerosp. Ind. Mechatron. **8**, 37–44 (2014)

Davis, J., Edgar, T., Porter, J., Bernaden, J., Sarli, M.: Smart manufacturing, manufacturing intelligence and demand-dynamic performance. Comput Chem **47**, 145–156 (2012)

Davis, J., Edgar, T., Graybill, R.: Smart manufacturing. Annu. Rev. Chem. Biomol. pp. 141–160 (2015)

Dobosz, M., Saja, O., Pacana, A.: Improvement of health and safety conditions at selected workplaces, Conference: International Conference on Engineering Science and Production Management (ESPM), Slovacia, 2015, production management and engineering science, pp. 55–59 (2016)

Drozd, R.: Reliability of production machines in the bakery industry - theoretical and practical issues. Sci. Didact. Equip. ABID **3**, 229–239 (2019)

Drozd, R., Piwnik, J.: Mathematical models of process quality on the example of the bakery industry. Sci. Didact. Equip. ABID **4**, 232–241 (2019b)

Drozd, R., Piwnik, J.: The influence of robotization on the reliability of the production process in the bakery industry. Sci. Didact. Equip. ABID **3**, 221–228 (2019a)

Esmaeilian, B., Behdad, S., Wang, B.: The evolution and future of manufacturing: a review. J Manuf. Syst. **39**, 79–100 (2016)

Foidl, H., Felderer, M.: Research Challenges of Industry 4.0 for Quality Management. Innovations in Enterprise Information Systems Management and Engineering, pp 121–137, Springer, Berlin (2016)

Gajdzik, B., Wolniak, R.: Influence of the COVID-19 crisis on steel production in Poland compared to the financial crisis of 2009 and to boom periods in the market. Resources **10**(1), 1–17 (2021)

Gajdzik, B., Grabowska, S., Wyciślik, A.: Explanatory preview of directions of changes in development of industry 4.0. Tech. Rev. **1**, 5–9 (2019)

Gilchrist, A.: Industry 4.0 The industrial internet of things. Publishing Apress USA, pp. 54–60, (2016)

Grzybowska, K., Łupicka, A.: Key competencies for industry 4.0. Econ. Manag. Innov. **1**, 250–259 (2017)

Gülseçen, S., Reis, Z.A., Gezer, M., Erol, C.: Industry 4.0 from the MIS Perspective. Publishing Peter Lang GmbH, Internationaler Verlag der Wissenschaften, New edition, pp. 55–59 (2019).

Hawryluk, P.: Automation and robotization of production processes - difficulty or necessity. Industrial Transport and Agricultural Machines, HMR – TRANS Sp. z o.o., Wrocław Tom No 1, pp. 12–15 (2019)

Herceg, I.V., Kuc, V., Mijuškovic, V.M., Herceg, T.: Challenges and driving forces for industry 4.0 Implementation. Sustainability **12**, 4208 (2020)

Hong, J., Shuyu, S., Hongtao, X., Shukuan, Z., Yong, Ch.: Enterprises network structure and their technology standardization capability in Industry 40. Syst. Res. Behav. Sci. **37**(4), 749–765 (2020). https://doi.org/10.1002/sres.2716

Jazdi, N.: Cyber physical systems in the context of industry 4.0 in IEEE. In International conference on automation. Quality and testing, robotics, pp. 1–4 (2014)

Kabugo, J.C., Jämsä-Jounela, S.-L., Schiemann, R., Binder, C.: Industry 4.0 based process data analytics platform: A waste-to-energy plant case study. Int. J. Electr. Power Energy System **115**, 211–234 (2020)

Kagermann, H.: Chancen von Industrie 4.0 nutzen. InVogel-Heuser: Industrie 4.0 in Produktion, Automatisierung und Logistik; Bauernhansl T, Hompel M, Springer Fachmedien: Wiesbaden, Germany, pp.14–2 (2014)

Kagermann, H., Wahlster, W., Helbig, J.: National Academy of Science and Engineering. Recommendations for implementing the strategic initiative Industrie 4.0: Final report of the Industrie 4.0 Working Group, (2013)

Kosieradzka, A.: The method of multi-criteria assessment of productivity. Business management. Polish Society of Production Management No 2, Opole pp. 37–45 (2004)

Kumar, A., Baldea, M., Edgar, T.F.: Smart manufacturing approach for efficient operation of industrial steam-methane reformers. Indus Eng Chem Res **542015**, 4360–4370 (2015)

Kumar, K., Zindani, D., Davim, P.: Digital manufacturing and assembly systems in industry 4.0 (Science, Technology, and Management) 1st Edition. pp. 34–39, CRC Press, Boca Raton (2019)

Lasi, H., Fettke, P., Kemper, H., Feld, T., Hoffmann, M.: Industry 4.0. Bus. Inf. Syst **6**, 239–242 (2014)

Lass, S., Gronau, N.: A factory operating system for extending existing factories to Industry 4.0. Comput. Ind. **115**, 103–128 (2020)

Lee, J., Bagheri, B., Kao, H.A.: A cyber-physical systems architecture for industry 4.0-based manufacturing systems. Manuf. Lett. **3**, 18–23 (2015)

Li, B., Hou, B., Yu, W., Lu, X., Yang, C.: Applications of artificial intelligence in intelligent manufacturing. Rev. Front Inform. Tech. El **18**(1), 86–96 (2017)

Liu, Y.K., Xu, X.: Industry 4.0 and cloud manufacturing. A comparative analysis. J. Manufacturing **139**(3), 034701–034701 (2017)

Lom, M. Pribyl, O. Svitek, M.: Industry 4.0 as a part of smart cities in 2016. Smart Cities Symposium Prague (SCSP), pp. 1–6 (2016)

Longo, F., Nicoletti, L., Padovano, A.: Smart operators in industry 4.0: A human-centered approach to enhance operators capabilities and competencies within the new smart factory context. Comput. Ind. **113**, 144–159 (2017)

Michalski, G., Rutkowska, M., Sulich, A., Rothe, R.: The green jobs and the Industry 4.0. In Enterprises and Economiesin the Face of Contemporary challenges. Management-Restructuring-Innovation; Global CCS Institute, Krynica, Poland, pp. 1–12 (2017)

Motyl, B., Baronio, G., Uberti, S., Speranza, D., Filippi, S.: How will change the future engineers skills in the industry 4.0 framework. A questionnaire survey. Proc. Manuf. **11**, 1501–1509 (2019)

Nagasawa, T., Pillay, C., Beier, G., Fritzsche, K., Pougel, F., Takama, T., Bobashev, I.: Accelerating clean energy through industry 4.0 manufacturing the next revolution. United Nation Industrial Development Organization, Vienna, Austria (2017)

Niesen, T., Houy, C., Fettke, P., Loos, P.: Towards an integrative big data analysis framework for data-driven risk management in industry 4.0 in 2016. In 49th Hawaii international conference on system sciences (HICSS), pp. 5065–5074 (2016).

Pacana, A., Ulewicz, R.: Analysis of causes and effects of implementation of the quality management system compliant with ISO 9001. Polish J Manag Stud **21**(1), 283–296 (2020)

Pająk, E.: Production management. Product, technology, organizations. PWN Publishing, Warszawa pp. 97–104 (2006)

Pilloni, V.: How data will transform industrial processes. Crowdsensing, crowdsourcing and big data as pillars of industry 4.0. Future Internet **10**(24), 123–129 (2018)

Posada, J., Toro, C., Barandiaran, I., Oyarzun, D., Stricker, D.: Visual computing as a key enabling technology for Industrie 4.0 and Industrial Internet. IEEE Comput Graph Appl **35**(2), 26–40 (2015)

Powierża, L.: Elements of systems engineering, Warsaw University of Technology Publishing House, Warszawa pp. 23–34 (1997)

Romero, D., Bernus, P., Noran, O., Stahre, J., Fast-Berglund, A.: The operator 4.0: human cyber-physical systems and adaptive automation towards human-automation symbiosis work systems. In APMS (advances in production management systems), pp. 201–222 (2016)

Sanders, A., Elangeswaran, C., Wulfsberg, J.: Industry 4.0 implies lean manufacturing. Research activities in industry 4.0 function as enablers for lean manufacturing. J. Ind. Management **9**(3), 23–33 (2016)

Saniuk, S., Grabowska, S., Gajdzik, B.: Social expectations and market changes in the context of developing the Industry 4.0 concept. Sustainability **12**(1362), 12–28 (2020)

Santos, K., Loures, E., Piechnicki, F., Canciglieri, O.: Opportunities assessment of product development process in industry 4.0. Procedia Manuf. **11**, 358–1365 (2017)

Sao, F., Cheng, Y., Zhang, L.: Advanced manufacturing systems: socialization characteristics and trends. J. Intell Manuf. **28**, 1–6 (2015)

Scheer, A.W.: Industrierevolution 4.0 ist mit weitreichenden organisatorischen Konsequenzen verbunden (Industrial Revolution 4.0 is associated with far-reaching organizational consequences). Inf. Manag. Consult. **3**, 10–11 (2016)

Schlechtendahl, J., Keinert, M., Kretschmer, F., Lechler, A., Verl, A.: Making existing production systems Industry 4.0-ready. Prod. Eng. **9**, 143–148 (2015)

Schmidt, R., Möhring, M., Härtinga., Reichstein, C., Neumaier, P., Jozinović, P.: Industry 4.0-potentials for creating smart products: Empirical research results. In Abramowitz, W. (Ed), Business information systems, pp. 16–27. Springer, Cham (2015)
Schröder, M., Indorf, M., Kersten W.: Industry 4.0 and its impact on supply chain risk management, pp. 15–18 (2014)
Schwab, K.: The Fourth Industrial Revolution,World Economic Forum. Publishing Studio Emka, pp. 78–90 (2017)
Schwab, K.: Shaping the Future of the Fourth Industrial Revolution Publishing. Penguin Books, pp. 23–30 (2018)
Sergi, B.S., Popkova, E.G., Bogoviz, A.V., Litvinowa, T.N.: Understanding Industry 4.0: AI, the Internet of Things, and the Future of Work. Emerald Publishing Limited, pp. 77–88 (2019)
Sommer, L.: Industrial revolution-Industry 4.0. Are German manufacturing SMEs the first victims of this revolution. J. Ind. Eng. Manag. **8**, 1512–1532 (2015)
Stecuła, K.: Decision-making dilemmas in mining enterprise and environmental issues, i.e. green thinking in mining. In Proceedings of the 18th International Multidisciplinary Scientific Geoconference, SGEM 2018, Albena, Bulgaria, 30 June–9 July 2018; 18, 357–364 (2018)
Ustundag, A., Cevikcan, E.: Industry 4.0 Managing The Digital Transformation. pp. 12–20, Springer, Berlin (2017)
Wang, S., Wan, J., Zhang, D., Li, D., Zhang, C.: Towards smart factory for Industry 4.0: A self-organized multi-agent system with big data based feedback and coordination. Computer Network, 101, pp. 158–168 (2016)
Wang, S.Y. Wan, J. Li, D. Zhang, C.: Implementing smart factory of Industrie 4.0: An outlook. Int J Distrib Sens N, pp. 315–325 (2016)
Weber, E.: Industrie 4.0. Wirkungen auf Wirtschaft und Arbeitsmarkt (Industry 4.0. Impact on the economy and labor market). Wirtschaftsdienst **95**, 722–723 (2015)
Wolniak, R., Miśkiewicz, R.: Practical application of the industry 4.0 concept in a steel company. Sustainability **12**(14), 123–129 (2020). https://doi.org/10.3390/su12145776
Wolniak, R., Grebski, M.E., Skotnicka-Zasadzień, B.: Comparative analysis of the level of satisfaction with the services received at the business incubators (Hazleton, PA, USA and Gliwice, Poland). Sustainability **11**(10), 1–22 (2019)
Wolniak, R., Saniuk, S., Grabowska, S., Gajdzik, B.: Identification of energy efficiency trends in the context of the development of industry 4.0 using the Polish steel sector as an example. Energies **13**, 8–67 (2020)
Xu, X.: Machine Tool 4.0 for the new era of manufacturing. Int. J. Adv. Manuf. Tech. **92**(8), 1893–1900 (2017)
Xu, L.D.: The contribution of systems science to Industry 40. Systems Research and Behavioral Science **37**(4), 618–631 (2020). https://doi.org/10.1002/sres.2705
Yu, S., Ling, L., Hui, S., Dazhi, Ch.: The transformation and upgrade of China's manufacturing industry in Industry 4.0 era. Syst. Res. Behav. Sci. **37**(4), 734–740 (2020). https://doi.org/10.1002/sres.2714
Zdanowicz, R.: Modeling and simulation of manufacturing processes. Publishing house of the silesian university of technology. Edition II, Gliwice pp. 12–15 (2007)
Zhan, S., Yongping, X., Wei, X., Yong, Ch., Liuliu, F., Xiaobo, X.: Smart factory in Industry 4.0. Syst. Res. Behav. Sci. **37**(4), 607–617 (2020). https://doi.org/10.1002/sres.2704
Zhang, L., Luo, Y., Tao, F., Li, B.H., Ren, L., Zhang, X.: Cloud manufacturing. A new manufacturing paradigm Enterp. Inf. Syst. U.K. **8**(2), 167–187 (2014)
Zhong, R.Y., Xu, X., Klotz, E., Newman, S.T.: Intelligent Manufacturing in the Context of Industry 4.0. A review. Engineering **3**, 613–630 (2017)
Zhou, K., Liu, T., Zhou, L.: Industry 4.0.:towards future industrial opportunities and challenges. In Proceedings of the IEEE 2015 12th International Conferenceon Fuzzy Systemsand Knowledge Discovery (FSKD), Zhangjiajie, China (2015)
Zimei, L., Kefan, X., Ling, L., Yong, C.A.: paradigm of safety management in Industry 4.0a. Syst. Res. Behav. Sci. **37**(4), 632–645 (2020). https://doi.org/10.1002/sres.2706

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