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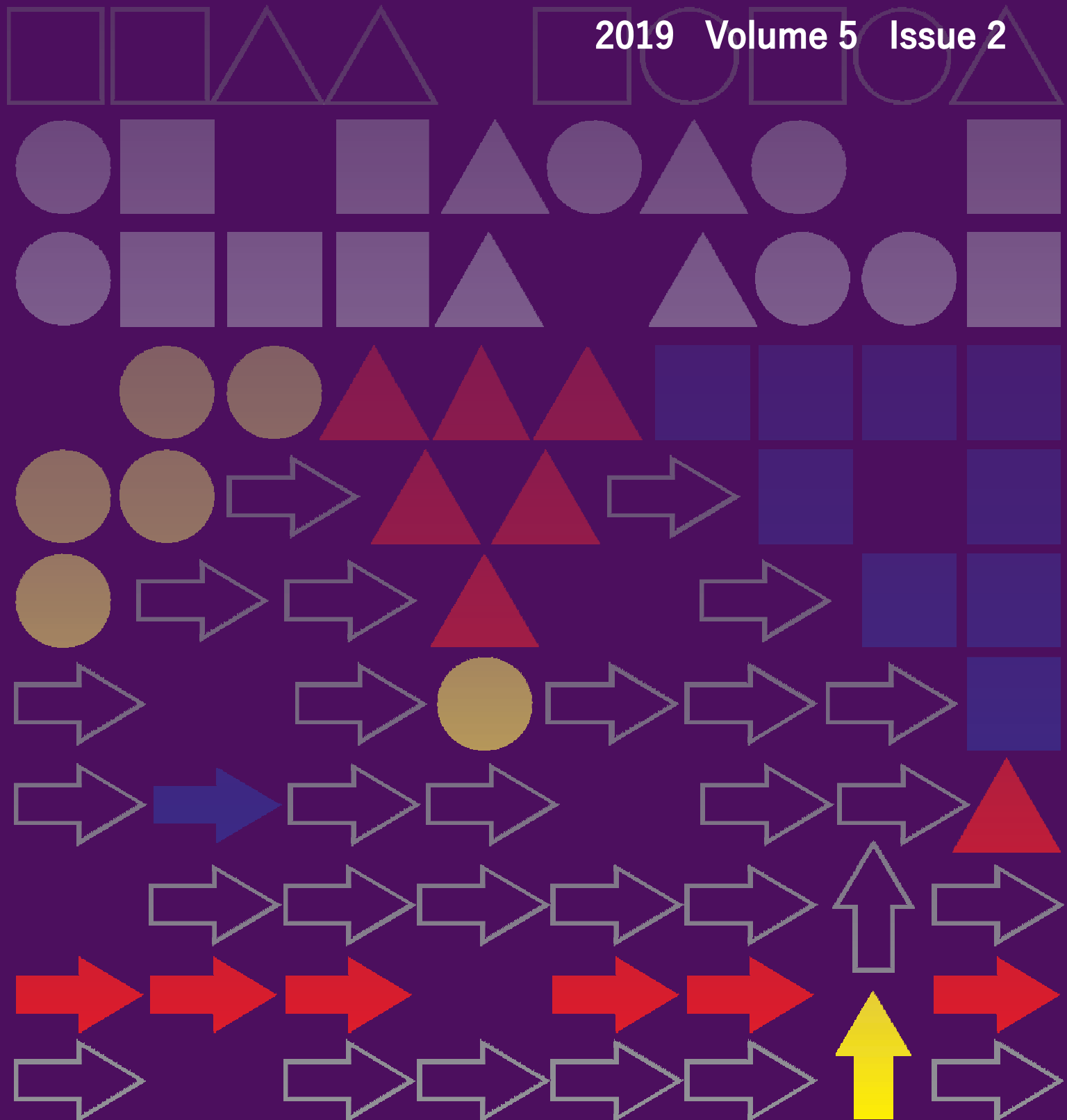
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DYNAMIC MODEL MILLING MACHINE

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Keywords: processing system, milling machine, tool wear, sound trend, predictive model

Abstract: The article describes the mathematical modelling results of the dynamics in order to determine the regularity of change in the model milling machine during the cutting tool wear. A close correlation between the sound trend accompanying the metalworking process and the roughness trend of the machined surface is shown. The calculation results serve as the basis for solving the problem of operational resource tool prediction. The tool wear operational forecast allows for the first time in the material processing history to put into practice an effective adaptive control technology of the cutting process, which determines the novelty of the material described in the article.

1 Introduction

The research purpose of the processing system dynamics is to study the regularity of its dynamic behaviour. Knowing these regularities allows you to purposefully manage the metalworking process and avoid the appearance of defects in the work piece.

These regularities appear [1] in:

- the trend and the spectral composition of the sound
- generated during the materials cutting processing;
- the trend of the roughness height parameter and its
- profile, which changes during the cutting process due to tool wear.

These parameters have a decisive influence on the metalworking quality.

The mathematical description of the lathe elastic system must be connected with the processes occurring in the working area of the processing system [2-12].

Each adopted dynamic model uniquely corresponds to a certain differential equations system describing its behaviour. These equations can be considered as a dynamic system mathematical model. Depending on the type of differential equations, mathematical models can be linear and nonlinear [5].

In a linear dynamic model, the elastic forces are proportional to the deformations, the viscous resistance forces to the velocities, and the inertial forces to the

accelerations. The article discusses a similar linear dynamic model milling machine.

2 Methodology of modelling

The research purpose was to establish dynamic behaviour regularity of the processing system during the technical condition (wear and destruction) of the cutting tool changes and the nature of this regularity in the amplitude sound wave trend accompanying the metalworking machines work.

The research subject was a typical technological metalworking system dynamic model – technological system of the milling machine.

The research technique consisted in:

- computer simulation of the processing system oscillations when changing due to cutting tool wear and destruction, its stiffness and damping characteristics;
- comparing the modelling results and verification experiments to confirm the calculations reliability and to identify regularity of changes manifestation in the dynamics of the processing system in the behaviour of the sound wave trend amplitude accompanying its work.

Dynamic model milling machine - the mass, stiffness and viscous coefficients of the simulated lathe nodes are indicated on the model diagram, respectively, using m , k

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and c . These parameters characterize each simulated machine nodes partial oscillations in the direction perpendicular to the main axis for the simulated node axes of stiffness and damping. The generalized coordinate ξ_i describes the spatially oriented oscillations of the mass centre of each of the i -th modelled elements of the technological system.

Differential equations using the complex amplitude method by substitution $\xi(\tau) = \xi_A \cdot \exp(i\omega\tau)$, where ξ_A

– is the oscillation amplitude of the mass centre of the simulated machine element, m , were transformed into a algebraic equations system with complex coefficients. These algebraic equations system was solved by the Gauss method.

The model diagram is shown in Fig. 1, and its parameters – in Table 1. The oscillations of the model were described by means of six differential equations (1). In this case, the oscillations of the following elements of the technological

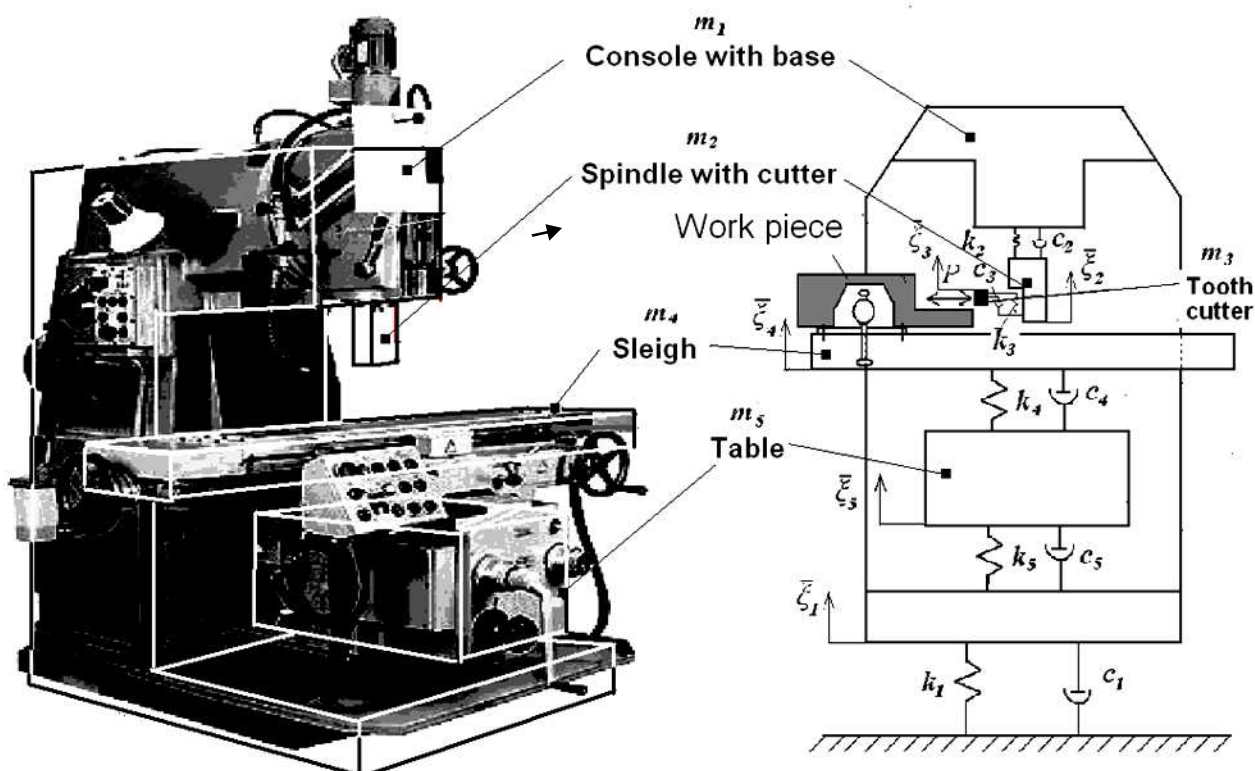


Figure 1 Dynamic Model of a milling machine technology system

Table 1 Dynamic model parameters of a milling machine

Dynamic parameter	Simulated technological system node (mass number)				
	base console (1)	spindle with chuck and cutter (2)	tooth cutters (3)	slides (4)	table (5)
Mass m_i, kg	3 494	17	$0,3 \cdot 10^{-6}$	305	500
Stiffness coefficient $k_i, N/m$ (f_i, Hz)	$8,6 \cdot 10^9$ (250)	$8,1 \cdot 10^6$ (110)	$1,9 \cdot 10^8$ ($4,14 \cdot 10^6$)	$6,3 \cdot 10^{12}$ (228)	$1,2 \cdot 10^9$ (250)
Viscous resistance coefficient $c, N/m/sec$ (quality factor Q)	$1,8 \cdot 10^6$ (3)	2 348 (17)	0.5 (10)	$1,4 \cdot 10^5$ (3)	$2,6 \cdot 10^8$ (3)

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Note. Contact force $P_{CF} = 107 \text{ N}$; stiffness k was determined by the following formula: $k_i = m_i (2\pi f_i)^2$, where f_i – is the frequency of natural partial oscillations of the simulated node was calculated by the identification method; damping c_i was determined by the following formula: $c_i = \frac{\sqrt{k_i \cdot m_i}}{Q_i}$, where Q_i – is the quality factor

(value) of the peak of the own partial oscillations of the modelled node was calculated by the identification method.

System were considered: base console (m_1, k_1, c_1); spindle with cutter (m_2, k_2, c_2); tool blades (m_3, k_3, c_3); sleigh (m_4, k_4, c_4); table and work piece (m_5, k_5, c_5).

Differential equations:

$$\begin{aligned} m_1 \ddot{\zeta}_1 + c_1 \dot{\zeta}_1 + k_1 \zeta_1 - c_2 (\dot{\zeta}_2 - \dot{\zeta}_1) - k_2 (\zeta_2 - \zeta_1) + c_3 (\dot{\zeta}_3 - \dot{\zeta}_1) + k_3 (\zeta_3 - \zeta_1) &= 0; \\ m_2 \ddot{\zeta}_2 + c_2 (\dot{\zeta}_2 - \dot{\zeta}_1) + k_2 (\zeta_2 - \zeta_1) &= 0; \\ m_3 \ddot{\zeta}_3 + c_3 (\dot{\zeta}_3 - \dot{\zeta}_1) + k_3 (\zeta_3 - \zeta_1) &= -P(t); \\ m_4 \ddot{\zeta}_4 + c_4 (\dot{\zeta}_4 - \dot{\zeta}_5) + k_4 (\zeta_4 - \zeta_5) &= P(t); \\ m_5 \ddot{\zeta}_5 - c_4 (\dot{\zeta}_4 - \dot{\zeta}_5) - k_4 (\zeta_4 - \zeta_5) - c_5 (\dot{\zeta}_1 - \dot{\zeta}_5) - k_5 (\zeta_1 - \zeta_5) &= 0; \end{aligned} \quad (1)$$

Algebraic equations:

$$\begin{aligned} [(k_1 + k_2 + k_3 - \omega^2 m_1) + i\omega(c_1 + c_2 + c_3)]\zeta_1 - (k_2 + i\omega c_2)\zeta_2 - (k_3 + i\omega c_3)\zeta_3 &= 0; \\ -(k_2 + i\omega c_2)\zeta_1 + [(k_2 - \omega^2 m_2) + i\omega c_2]\zeta_2 &= 0; \\ [k_3 + i\omega c_3]\zeta_1 - [(k_3 - \omega^2 m_3) + i\omega c_3]\zeta_3 &= -P(t, \omega); \\ [(k_4 - \omega^2 m_4) + i\omega c_4]\zeta_4 - (k_4 + i\omega c_{42})\zeta_5 &= P(t, \omega); \\ -(k_5 + i\omega c_5)\zeta_1 - (k_4 + i\omega c_4)\zeta_4 + [(k_5 + k_4 - \omega^2 m_5) + i\omega(c_5 + c_4)]\zeta_5 &= 0; \end{aligned} \quad (2)$$

3 Results from experiments

The sound was measured using a microphone placed near the cutting zone (Figure 2).

The results of experimental computational research are presented in Fig. 3 and Fig. 4. They are usually a comparison of calculated and experimental data. The calculation results are obtained when solving the equations system (2). The system solution was carried out repeatedly when changing the cutting time from 0 to T , equal to the period of durability (resource) tool with a time step

$\Delta \tau = 1 \text{ sec}$. At the same time, at each time step, the frequency characteristics of the model oscillations were determined with successive changes in frequency from 0 to 2,500–3,000 Hz with a step in frequency $\Delta f = 10 \text{ Hz}$.

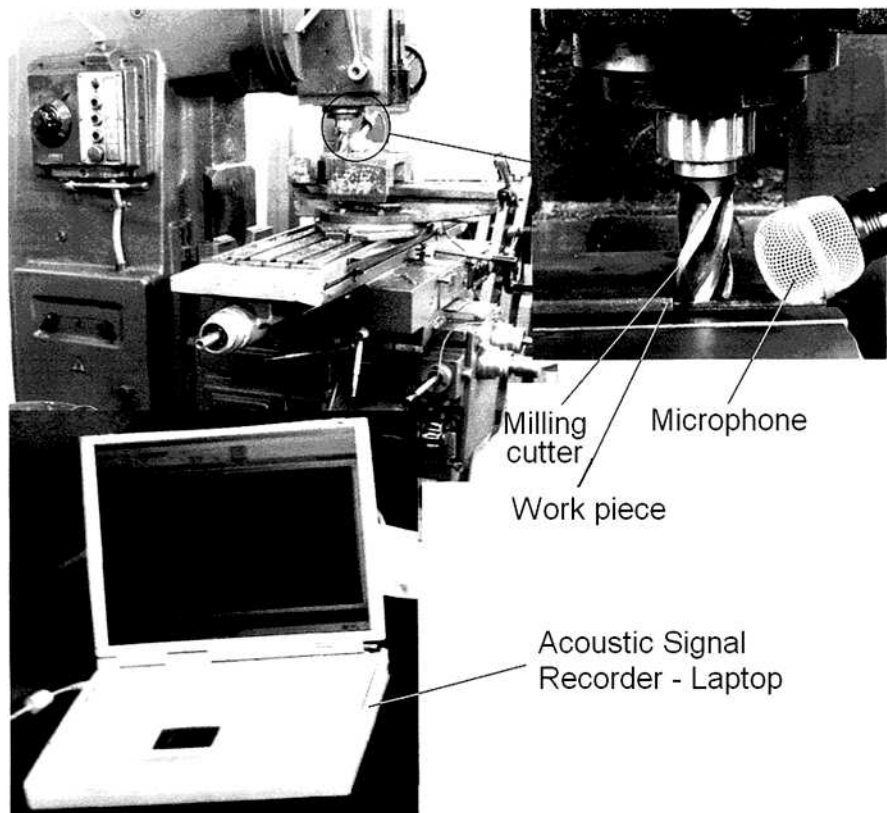


Figure 2 Placement the microphone near the cutting area

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To assess the developed model reliability in the calculation in addition to the trend of the sound wave amplitude were investigated:

- the change nature over time of the sound implementation;
- sound trend generated during the cutting process;
- roughness profile;
- roughness profile trend.

The sound was measured using a microphone placed near the cutting zone (Figure 2).

Fig. 4a shows the actual and calculated sound spectra accompanying the cutting process, which visually coincide quite well with each other. This is also indicated by the quantitative degree assessment of their coincidence, described by their correlation coefficient, equal to 0.684 (Figure 3b). The most important are the

calculations describing the nature of the trend in sound \bar{E}_S (Figure 3c) as the cutting blade wears. Correlation coefficient between calculated and experimental sound trend values \bar{E}_S equals $R = 0,993$ (Figure 3d). This information shows that the model reproduces well enough not only the frequency sound filling, but also describes the trend change nature of the sound over time as the instrument wears.

Fig. 4 shows the calculated trend of the altitude parameter Ra roughness and the roughness profile calculation.

At the same time, a fundamentally important result of calculations is the determination of the fact that sound trends \bar{E}_S (Figure 3c) and roughness (Figure 3a) are identical.

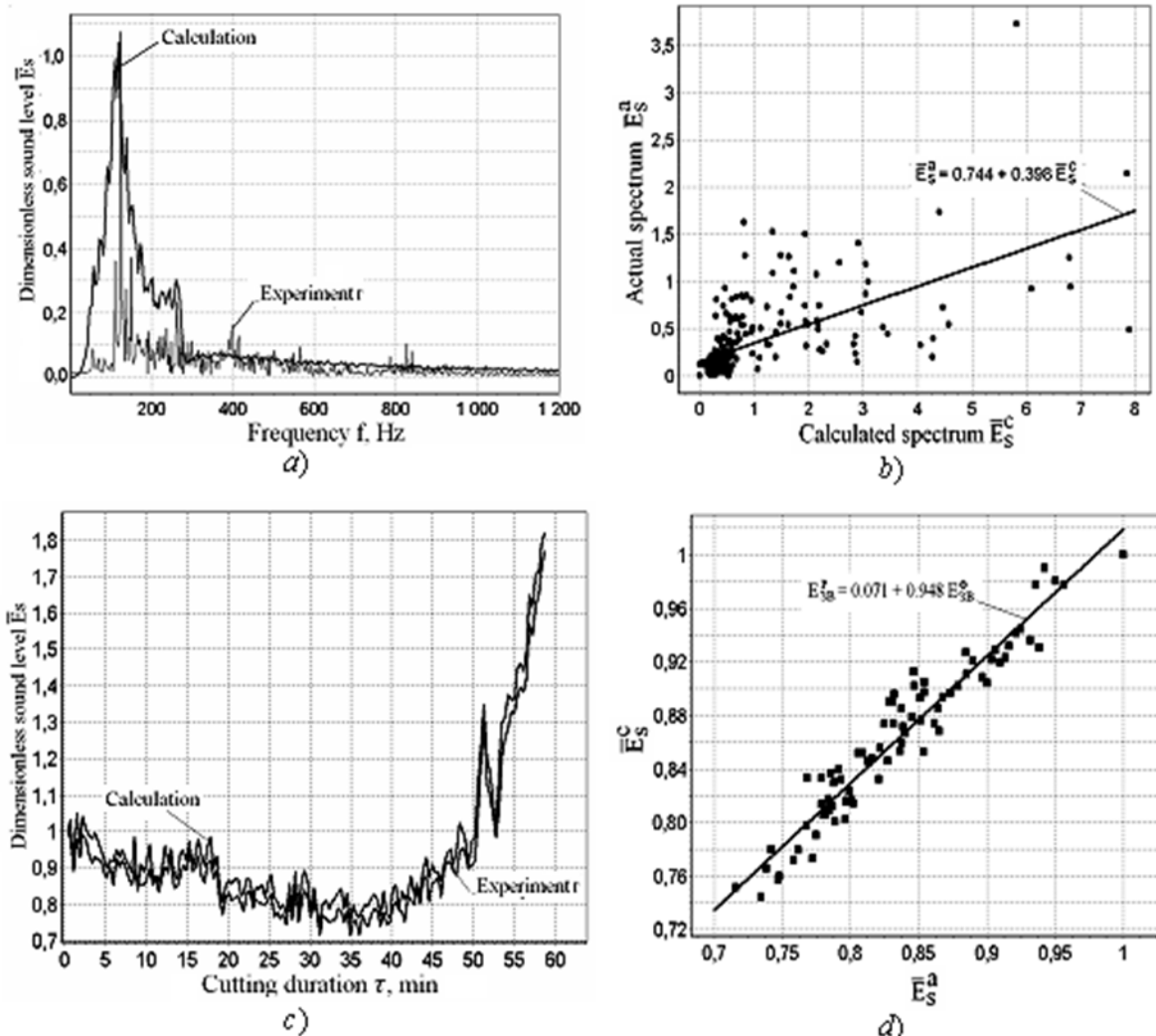


Figure 3 Results of calculating the spectrum and trend of sound accompanying cutting processing: a - comparison the calculated and actual sound spectra; b - regression line between the actual and calculated spectra; c) comparing actual and calculated sound trends; d) regression line between actual and estimated sound trends

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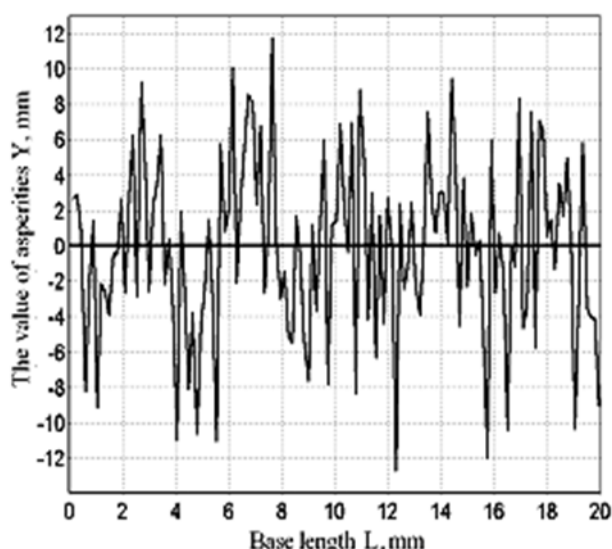
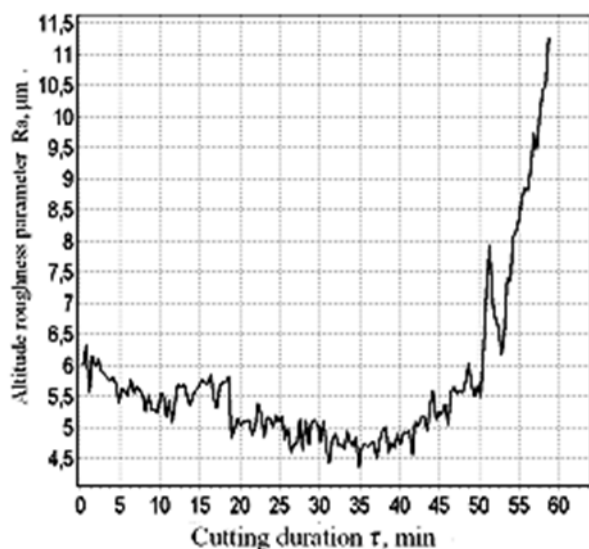


Figure 4 Roughness parameters obtained by the calculated method:
a – is trend of altitude parameter roughness Ra; b – is roughness profile Y

4 Conclusion

The mathematical modelling results of the dynamics of a milling machine serve as the basis for solving the problem of operational tool life prediction. This problem solution allows for the first time in the processing materials history to put into practice an effective technology of adaptive cutting process control.

To implement this technology, tool life prediction should be performed in real time directly during the processing of materials by cutting. In this case, the prediction technique should be based on the predictive model, which should be a time function and have a minimum of parameters, which must include the desired durability of the cutting tool T as a numerical value.

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SIMULATION OF ECOLOGICAL INNOVATIONS PERCEPTIONS IN SLOVAKIA

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SIMULATION OF ECOLOGICAL INNOVATIONS PERCEPTIONS IN SLOVAKIA

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Keywords: innovation, ecological innovation, Kano model**Abstract:** Ecological innovations are the object of interest in many areas what has subsequently reflected in the fact that the interest of companies in their implementation has increased. Research, development and implementation of eco-innovation is a global phenomenon supported by the policies of most countries as well as the EU. However, not only research and development of innovation is significant, but especially their implementation and adoption should be in the interest of companies. The paper brings the results of the survey in which we have monitored the perception of ecological innovations in different age categories of Slovak respondents. The Kano model is the primary used survey method. The results denote a low level of acceptance of environmental innovations by domestic customers

1 Introduction

The findings from previous period show that it is not sufficient only to innovate, but companies should focus on the creation of innovations applied on the principle of sustainable development represented by ecological innovation. Also the European Union (EU) emphasizes the necessity of ecological innovations realization which increases the environmental protection and the EU industry competitiveness that rests in more effective technologies introduction and more effective resources using in business processes and models. The aim of the idea is to transform Europe into a low-carbon economy which is able to use resources more effectively. The notion fulfilment requires the environmental technologies application which are the essential part of the EU economy [1].

Lešková [2] states that ecological innovations reduce the material requirement. Other benefits of ecological innovation lie in closed material flows utilization and new materials creating or using. They are also focused on energy requirements reducing by alternative energy sources creating or using. In the area of healthy lifestyle and sustainable consumption, ecological innovations minimize a total amount of emissions or existing environmental load and health risks.

Ecological innovations are in charge of Innovation Management. It implements them through innovation of sustainable resources and material from the environment using. It takes into account the growing importance of socio-economic development [3-6].

The Slovak Republic also supports ecological innovation creation through the Slovak National Strategy of sustainable development in cooperation with effective principles.

Ecological innovations can be understood as a tool which enables companies to transform environmental restrictions into opportunities to decrease the costs. Their benefits also include obtaining the better reputation and advantage on new markets. The companies are primary interested in promoting the performance of environmental innovations of the product to customers, as well as to make the realisation of these innovations better [7-9].

The ecological innovations are important because of their impact on decision-making process of the consumer. It results in the marketability of the product itself [10]. It is necessary to consider the product at different levels during the product innovations creating, while each level increases the value of the product to the customer [11-13]. Companies realizing innovations should follow modifications in preferences of their consumers and also to notice the new manufacturing technology of its eco-friendly products when they choose and launch the products on the market.

Regarding the mention information, the aim of the paper is to monitor the perception of the ecological innovations among various age categories of Slovak respondents and to present the perception in the 3D simulation method.

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2 Methodology

The research is focused on the perception of ecological innovations. We have applied the Kano model in order to recognize customers' attitudes towards the demands or requirements of the surveyed object [14]. This model realizes a research where the Kano questionnaire is applied. The questionnaire obtains couples of questions about customer's requests. Every question involves two parts: customer's feeling about presence of a certain feature in a product (functional section of the issue), and customer's feeling about absence of a certain feature in the product (dysfunctional of the issue).

These couples of positively and negatively formed issues include the performance of monitored parameters (specifically for ecological innovations) – price of products, quality of products and ecological innovations of products. We have monitored in detail ecological innovations in the area of:

Environmental product safety, The importance of eco-innovation, The origin of ecological innovation, Slovak products with enviro brand, Ecological innovation, The concept of eco-innovation, Availability of ecological-innovation, Information on eco-innovation, Attractiveness of eco-innovation, Advertising of ecological innovation, The price of ecological innovation. Taking into account the methodology respondents were able to answer each question (statement) on a scale from 1 to 5 representing strong agreement or strong disagreement with the question (statement).

The respondents sample consisted of 740 consumers in Slovakia, keeping the same size of respondents for each determined age category. The answers were elaborated according to the cross rule [14], that allows to categorize monitored parameters in the following categories how respondents perceived ecological innovations [14-23]:

- M (must be requirements) – are obligatory requirements that customers consider as normal and are automatically expected. Their fulfilling is reflected in customers' satisfaction.
- O (one-dimensional requirements) – are those attributes of the product that lead to fulfilment and

satisfaction. Compared to the obligatory requirements customers do not expect them automatically.

- A (attractive requirements) – have an obvious impact on customer's satisfaction because it is a requirement that customers did not expect, but it is attractive for them.

- R (reverse requirements) – are contradictory, they bother customers, as they require some additional action from them.

- I (indifferent, irrelevant requirements) – are requirements not influencing customer's satisfaction or dissatisfaction.

- S – are sceptical, questionable requirements.

The results of Kano model enable to divide the monitored ecological innovations into categories of mandatory, attractive, indifferent and reverse functions. Subsequently the weight was assigned to these requirements in identified categories as follows: $M = 3$, $A = 2$, $O = 1$, $I = 0$, $R = -1$ [5,17,18]. Based on the sum of values, we can compare customers' perceptions of ecological innovations and we identify the target age group for ecological innovations [18].

Subsequently, a 3D simulation was applied to forecast the respondents' perception of ecological innovations in Slovakia.

3 Simulation of perceptions of ecological innovations by respondents in Slovakia

The KANO model was used in order to detect requirements of respondents on the ecological innovations within the determined monitored age categories.

The customer's value (Table 1) was figured out as the sum of points which have been assigned to the individual categories of the questionnaire. The outcomes signify various attitudes towards ecological innovation of products according to the age.

Ecological innovations report the most substantial value for respondents aged from 27 to 40 years (as it is presented by the total customer value 6).

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Table 1 The comparison analysis of perceptions of ecological innovations in Slovakia

Ages	15-26		27-40		41-60		61 +	
Price of products	I	0	A	2	I	0	A	2
Total Quality of products	X	2	X	4	X	4	X	2
- The brand	O	1	I	0	I	0	I	0
- The origin	I	0	O	1	O	1	O	1
- The standards	O	1	M	3	M	3	O	1
Total Ecological innovations	X	0	X	0	X	0	X	0
- Environmental product safety	I	0	I	0	I	0	I	0
- The importance of eco-innovation	I	0	I	0	I	0	I	0
- The origin of eco-innovation	I	0	I	0	I	0	I	0
- Slovak products with enviro brand	I	0	O	1	I	0	I	0
- Ecological innovation	I	0	I	0	I	0	I	0
- The concept of eco-innovation	I	0	I	0	I	0	I	0
- Availability of eco-innovation	I	0	I	0	I	0	I	0
- Information on eco-innovation	I	0	I	0	I	0	I	0
- Attractiveness of eco-innovation	I	0	I	0	I	0	I	0
- Advertising of eco-innovation	I	0	O	1	I	0	I	0
- The price of eco-innovation	I	0	R	-1	I	0	I	0
Total	2		6		4		4	

Ecological innovations are the most valuable for the customers at the age of 27 to 40, for whom these innovations represent one-dimensional requirement. It represents those innovation attributes that lead to fulfilment and satisfaction of customers. The higher the degree of compliance with these requirements are, the customers are more satisfied. They appreciate mainly Slovak products with enviro brand, however they perceived exactly oppositely price of ecological innovations of products. That means that price of ecological innovation is perceived negatively.

On the other hand, the younger ones at the age less than 27 and the older generation than at the age less than

41 years are more interested in classic products than in eco-innovations.

The most important thing for respondents is the quality that products must fulfil (must by requirement), respectively age categories 16-26 and 61+ higher. The higher the quality is, the more sufficient they are (one-dimensional requirement).

On the other hand, for ages 61+ and 27-40, price of products belongs among attractive requirements. It has an obvious influence on customer satisfaction because it is a requirement that customers do not expect, but it is attractive for them. Other products prices do not influence them (indifferent requirements), Figure 1.

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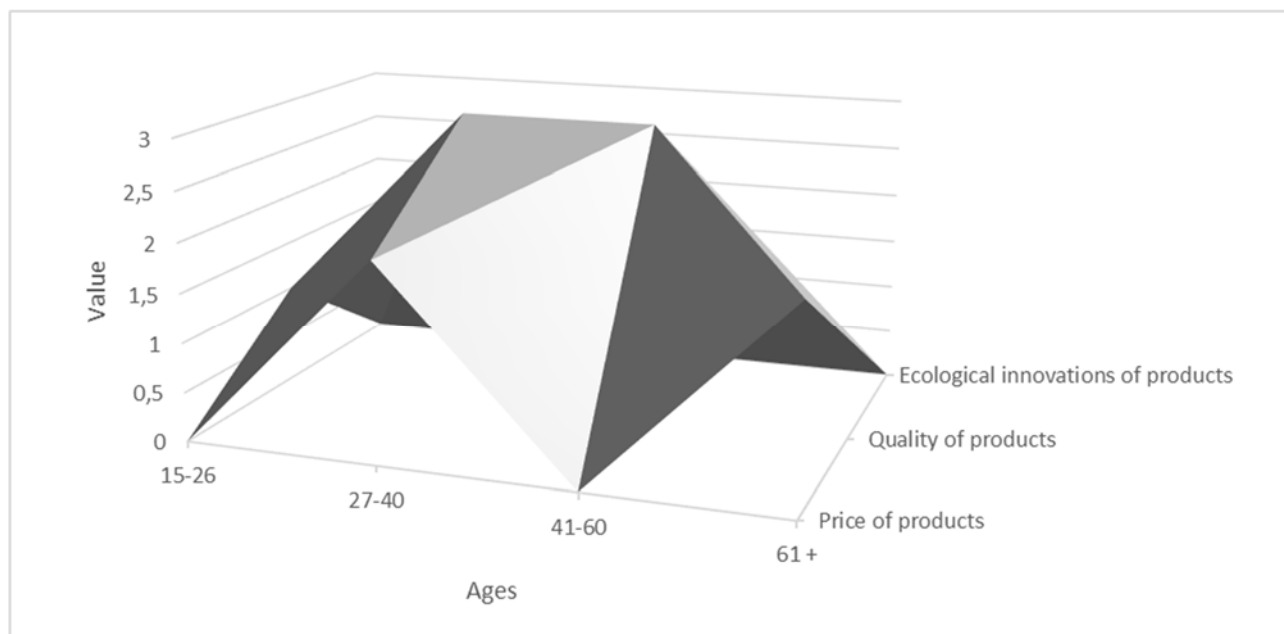


Figure 1 Simulation of perceptions of ecological product and innovations by respondents in Slovakia

Ecological innovations have the least impact on respondents. The respondents are mainly influenced by the price of the product. Following the results, we can state that the quality of the product has the average impact. However, the quality is a mandatory requirement, the price is an attractive requirement and total eco-innovations are an indifferent requirement for respondents. The respondents

perceive the quality of the product based on its standards and origin of the product. Respondents evaluate Slovak products with enviro brand one-dimensionally, but the price of eco-innovation is perceived negatively. These conditions are presented in a simulation in Figure 2: 3D Simulation of perceptions of ecological product and innovations by respondents in Slovakia.

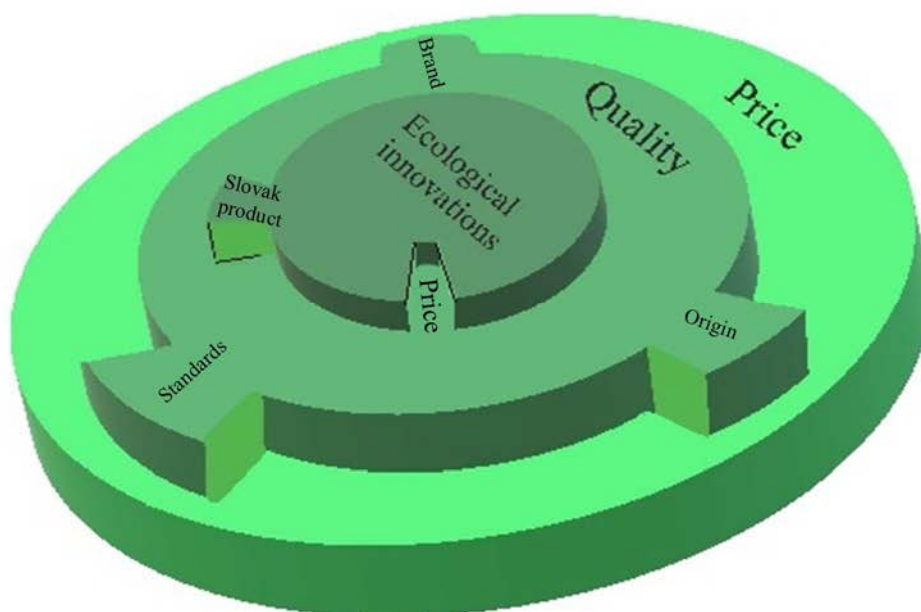


Figure 2 3D Simulation of perceptions of ecological product and innovations by respondents in Slovakia

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4 Conclusion

The importance of ecological innovations is still growing, so it is necessary to monitor the adoption of these innovations by respondents. At present great importance is emphasized in the introduction of eco-innovation. Companies implementing ecological innovations should realize that, it is inevitable not only to implement them, but also to monitor their acceptance by customers. The results just point out that in Slovakia customers place the main emphasis on price and product quality. Eco-innovation does not affect them. Ecological innovations have the most significant impact on respondents at the age from 27 to 40 years. Customers belonging to this age category are more satisfied with Slovak products with enviro brand than customers from other age categories. The results and information about customers' perceptions and preferences in the area of ecological innovations from respondents of different age can be subsequently used during communication and innovation of ecological products.

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SIMULATION OF ECOLOGICAL INNOVATIONS PERCEPTIONS IN SLOVAKIA

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A MODEL TO STUDY DYNAMIC EFFECTS OF THE FORMATION OF DEFECTIVE ITEMS IN MANUFACTURING

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Abstract: In this work, a tool is developed to study operational aspects of manufacturing/production processes. Most studies of operations systems are concerned with waiting times, queue lengths, servers' utilization, etc. This work, on the other hand, is concerned with the yield of production/manufacturing processes with assembly operations in intermittent production environments. A novel approach is proposed to study operational effects of processes' imperfectness. Specifically, effects of the formation of defective items. The number of defective items and, hence, the number of conforming items that are formed in each execution of each activity in a process are random variables. The number of units of each component type in each (sub)-assembly is, however, dictated by the assembly ratios. Consequently, the actual numbers may not fit the planned targets or each other. These differences might be small but suffice to generate chaos in the system. A generic model is proposed, which enables to investigate and analyse these effects and evaluate tactics to handle them.

1 Introduction

This work is in the production/manufacturing domain. It is concerned with operational aspects of production/manufacturing processes, which involve assembly operations, in intermittent production environments; e.g., batch processing. No specific system is studied but a generic model is developed to study operational effects of processes' imperfection. Specifically, the ramifications of the formation of defective items. To illustrate, consider a carmaker who receives a delivery of n wheels. Suppose $n = 4 \cdot k + m$ and $m < 4$. Then, since there are four wheels in a car, at least m wheels will remain unused, more, if k is greater than the desired number of cars. Further, if k is smaller than the desired number, a shortage is created despite the fact that at least m wheels remain unused. These miss-matches are created because the numbers of conforming units in production processes are random variables. The model proposed here is aimed at studying these miss-matches and their effects on systems' performances. This work differs from other studies in several manners. First, most stochastic models of operations systems, as defined below, are concerned with waiting times, queue lengths, servers' utilization, etc.; e.g., [1]. Second, serial processes are considered in most studies where inspections are included; e.g., the works reviewed in [2]. Third, long-range averages are examined; e.g. [3] and [4]. This study, on the other hand, is concerned with quantities – numbers of conforming and defective units in processes, which involve assembly operations, and is aimed at system dynamics and the examination of run-to-run relationships. Simulation is used because the quantities are random variables with complex relationships among them.

Widely used to define simulation is the term 'system'. Robinson [5], for instance, defines simulation, basically as "an imitation of a system" and many others; e.g., [6-8] also use this term. Law and Kelton [7] define a system "to be a collection of entities; e.g., people or machines that act and interact together towards the accomplishment of some logical end." Checkland [9] identified four main classes of systems: natural systems, designed physical systems, designed abstract systems and human activity systems. When people and machines interact, both human activity system and designed physical system are involved, and there are many examples of other combinations of Checkland's system types. Robinson [5] adopted Wild's [10] term *operations systems* or *operating systems* for systems where human activities are applied to physical entities, including production systems, service systems and supply chains.

As an imitation, any simulation builds on a model of the system it imitates and there are also distinctions between various types of models. In the context of this study, the relevant distinction is between static and dynamic (simulation) models. "A static simulation model is a representation of a system at a particular time, or one that may be used to represent a system in which time simply plays no role," while "a dynamic simulation model represents a system as it evolves over time." [7]

In operations systems time usually plays a primary role, either directly – the throughput time in manufacturing systems, waiting and service times in service systems, or indirectly by averaging over time – inventories, work in process, queue lengths, utilizations of servers, etc. Consequently, the vast majority of simulation studies of operations systems "track the system as it evolves

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continuously over time." ([8], p.3). The model developed in this study is different since it tracks the progress of units via the steps of the production process and through repeated executions the process. Although time passes as the units move forward and between process's executions, the proposed model is concerned with the numbers of units, the division between conforming and defective units and how these numbers are changed. Consequently, not times are sampled and the simulations are not discrete events simulations. Rather, the term Monte Carlo simulation, as defined by Law and Kelton [7], suits the present model. However, while Law and Kelton conclude that "Monte Carlo simulations are generally static rather than dynamic", the systems considered here have a dynamic nature because in an intermittent production environment distinct executions of a process are interrelated.

The model is generic in the sense that it models only the production process to which many other functions can be added; e.g., information management regarding residual quantities that are generated and can be used for future needs. Additionally, while production environments are considered here, the principle behaviour also suits service systems. In medicine, for example, erroneous diagnosis or imperfect treatment may result in the return(s) of the patient. Similarly, the failure of a student in a course forces her/him to repeat the course. In these cases, the patient or the student are, in many senses, analog to defective units in production systems.

2 The Skeleton of the Model

The model proposed here is built on an old tool – the *operations process chart* (OPC). Process charts were introduced by Frank and Lillian Gilbreth in 1921 [11]. From this early presentation emerged the OPC, which "is one of the most useful techniques in manufacturing planning. Actually, it is a 'diagram' of the manufacturing process. It has been used in many ways as a planning and control device. With the addition of other data, it can be extremely useful in manufacturing management." [12] The American Society of Mechanical Engineers established a standard for the OPC [13], of which the following symbols are used here: cycles represent operations and square boxes inspections, while arrows represent flows of material(s). Each task – operation, inspection, and so on, has an identification (ID) code. Usually, a list of all the tasks accompanies each OPC and provides additional information as proposed by Apple [12]: each task is briefly described, the performing station is identified, process and set-up times are specified, etc. This list is, called 'route sheet' and the tasks' IDs refer the OPC to the route sheet and vice versa. In this study, other additions, which are not included in the route sheet, are also considered.

An example OPC is illustrated in Figure 1. The operations in the figure are numbered from 0 to 15, while the inspections are numbered separately and in an opposite order to distinguish between the two groups. The arrows

follow the direction of the process – from the elementary components to the end-item. The operations can be divided into two sub-sets: those that have a single entrance and those that have two or more entrances. A sequence of operations, each with a single entrance, represents a component – elementary or sub-assembly, of the final product. Operations with multiple entrances, on the other hand, represent assembly operations – the entering arrows correspond to the components of the assembly while the single leaving arrow is the assembled item – a sub-assembly or a final assembly. Operation #0 is the final assembly in Figure 1. Consequently, an OPC has a tree structure – at least one but maybe more arrows are directed to each cycle or square box, while only one arrow is directed away from any such entity. Any OPC with more than one end-item can be decomposed – one chart with a tree structure for each end-item. The activity in an arrowhead is the immediate successor of the activity in the arrow's tail.

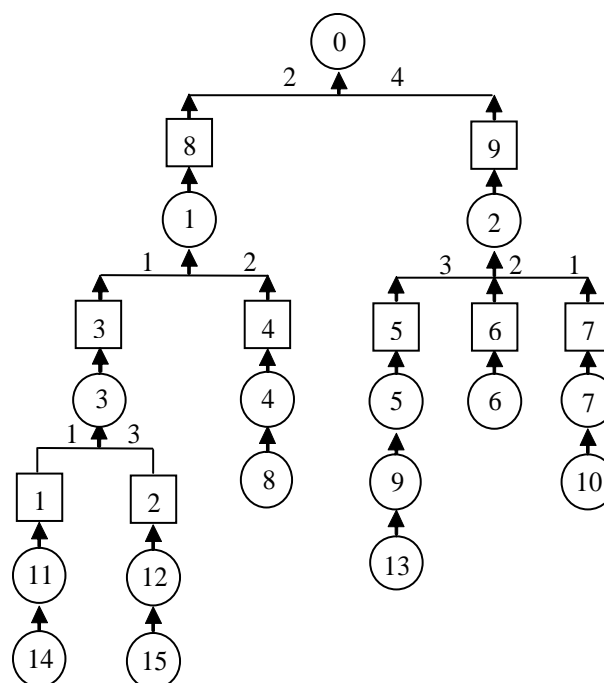


Figure 1 An Operations process chart with assembly ratios

Frequently, several units of the same component type are assembled in a single unit of the (sub) assembly; e.g., four wheels in a car, several processors in a multi-processor computer, etc. The number of units of a component type in its immediate (sub)assembly is its *assembly ratio*, which is the core input to material requirements planning (MRP). The assembly ratios are provided by the bill-of-materials (BOM); e.g., [14], and can easily be added to the OPC – on each link, which enters assembly operation, the corresponding assembly ratio is marked, as in Figure 1.

Another type of information is the corresponding probabilistic data: the defect rate of each operation and the

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error rates – of type I and type II errors, of each inspection. This information is necessary for many types of analyses as illustrated in the sequel, but has never been associated with the OPCs until the recent study of Eben-Chaime [15]. Once this information is added, the number of defective units that are generated in every pass through an operation and the resulting numbers of the inspections – type I and type II errors, can be sampled. Then, each process can be tracked step-by-step as explained in the following sections. Obviously, parallel execution of multiple processes can also be simulated, whenever desired.

3 Sampling

The novelty of the approach proposed here is to sample the required numbers individually and use the OPC to calculate the final outcome. These samplings are based on the following assumptions:

- 1) Independence between operations and inspections.
- 2) Independence between different operations.
- 3) Independence between item's units.

The first assumption is rather common; e.g. [16]. The second assumption is justified by the fact that each operation is performed in either a different station or on a different part and the third assumption follows the implicit assumption that the process is in control. Thus, defective units are formed only due to random causes; e.g., [17]. These three assumptions justify the applicability of the binomial distribution for all numbers and the use of the inverse transform algorithm; e.g., [8], p.56, for sampling. This method requires the number of trials, the success rate and a random number from a uniform (0,1) distribution, for each execution. The derivation of the numbers of trials and the success rates is the new component of the proposed approach and is detailed in the following sub-sections while the calculations of the final outcome are considered in the next section.

As noted, two types of entities are considered – operations and inspections and there is an inherent difference between these types. In inspections, units can be removed from the flow. A unit that is rejected does not continue with the other units – even if not wasted, a rejected unit should be repaired or reworked. The numbers of units is changed in operations, too, but not by removal. In any assembly, at least two component types or two units of the same type are assembled. Thus, the number of units that leave an assembly operation is no larger than any of the entering numbers.

3.1 Non-assembly Operations

Let d_i denote the mean defect rate of operation i and Q_{ij}^{in} are the numbers of conforming units that arrive to operation i in the j^{th} pass through it. Then, the number of new defective units, which are formed in this operation in this pass, x_{ij} is a binomial random variable with a success rate d_i and Q_{ij}^{in} trials. The number of conforming units that leave operation i in the j^{th} pass through it is: $Q_{ij}^{out} = Q_{ij}^{in} -$

x_{ij} . Note that many more units that are defective can flow through operation i in the j^{th} pass because the numbers for each task depend also on previous tasks and the model keeps track of these numbers.

3.2 Assembly Operations

The defect rate of an assembly operation is not only its own defect rate, but of the arriving components, too, due to the mutual effects among the components, as demonstrated in [15]. Suppose an assembly consists of K component types, with assembly ratios m_k , $k = 1, \dots, K$. Suppose also that Q_{ijk} conforming units and x_{ijk} defective units of component type k arrive to assembly operation i in the j^{th} pass through it. Then, the mean defect rate of assembly operation i in the j^{th} pass through it is:

$$1 - (1 - d_A) \cdot \prod_k [Q_{ijk} / (Q_{ijk} + x_{ijk})]^{m_k} \quad (1)$$

This is the binomial success rate for the sampling. Moreover, the number of trials for the sampling equals the number of units that can be assembled:

$$N_{ij} = \min_k \{ \lfloor Q_{ijk} + x_{ijk} / m_k \rfloor \} \quad (2)$$

where $\lfloor x \rfloor$ denotes the integer part of x . The generated binomial number, x_{ij} is the number of defective (sub) assemblies while $\min \{ (Q_{ijk} + x_{ijk}) / m_k \} - x_{ij}$ is the number of conforming (sub) assemblies that are assembled. However, all assembled units including the defective units continue to the next step in the process.

Note that $(Q_{ijk} + x_{ijk}) - m_k \cdot N_{ij} \geq 0$ units of any component type are not used by assembly operation i in the j^{th} pass through it. What happened to these units is influential on system's performance and the analysis of these effects motivated the development of the proposed model, as discussed in Sections 4 and 5.

3.3 Inspections

In inspections, as noted, units are removed from the flow. The removed units are of two types: defective units and conforming units, which are falsely rejected – error type I. On the other hand, not all defective units are detected and some slip through – error type II. Consequently, two numbers should be sampled and hence two (0,1) uniform random numbers – one for each error type are required. The rate of type I error, α , is the success rate and Q_{ij}^{in} , the number of conforming units that enter inspection i in the j^{th} pass through it, is the number of trials to determine the number of false rejections, f_{ij} , while $Q_{ij}^{out} = Q_{ij}^{in} - f_{ij}$ conforming units pass the inspection. In addition, x_{ij} defective units also pass the inspection. The type II error rate β and the number of defective units that enter inspection i in the j^{th} pass through it are used to sample this number, in a similar manner.

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In Sum, both the number of conforming units and the number of defective units that travel each arrow in each pass through the OPC can be tracked as described above. This enables to determine the output – the number of conforming units of the end item that is produced from the specified input for each pass through the OPC.

4 System's Dynamics

Had only a single pass or a series of independent passes through the OPC been executed it would have been a static Monte Carlo simulation as defined by; e.g., Law and Kelton [7], but here, the execution of many passes is a key. A simulation which consists of a series of independent executions of the process – passes through the OPC would be very similar to stochastic analyses of projects where activities' durations are sampled to determine the project's critical path in each run; e.g., [18]. However, in intermittent production environments distinct process executions are not independent. Residual inventories might be constructed, as noted above, during each execution of the process due to the stochastic nature of the yields – the ratios of conforming units in production processes. These inventories turn the system into a dynamic system by interrelating distinct executions of the process as in each execution, units that were produced in earlier executions can be used and units that are produced now might not be used now and left for future use. Formally: $I_{i,j} = I_{i,j-1} + P_{i,j} - C_{i,j}$, where $I_{i,j}$ is the inventory at the end of the j^{th} execution of operation i , $P_{i,j}$ is the amount processed in operation i in its j^{th} execution and $C_{i,j}$ is the amount of units processed in operation i and consumed by subsequent operations. This is, actually, a well-known equation, which is used in dynamic production planning; e.g., [6, 10], but in production planning an index t for time periods is used instead of j , and here, the time intervals between successive executions of the process might be of different lengths.

Moreover, the inventories considered here can be constructed around assembly operations only: either before the assembly operations of sub-assemblies or after the final assembly. Production plans take into account the defect rate of each operation. Yet, the actual quantities are random numbers. Aiming at averages in long term planning, the maximal number of final assemblies should be assembled in each path. In some cases more than planned would be produced – adding to the inventory, while in other cases less than planned would be produced and the inventory can be used to fill the gap, keeping the average around the target. Maximal numbers should also be assembled of each sub-assembly, but miss-match between component types, as indicated above, can result in residual inventories. This includes cases where the number of arriving units is not an integer multiple of the assembly ratio of the corresponding component type. For example, of 23 wheels only 5 cars can be made with a residue of three.

Following this discussion, the number of units of each item which are not used in each pass through the process

are rather small and vary from pass to pass. This creates a challenging inventory management task – where to keep, record keeping, etc., as illustrated in the next section.

5 Illustrative Runs

The purpose of this section is two-fold. First to illustrate the operation of the model and then to demonstrate some possible applications.

5.1 Model's operation

Table 1 portrays a single pass through the process of Figure 1 with no initial inventories. In the left column, the activities are identified: 'o' indicates operation, while 'i' indicates inspection and the numbers match the numbers in Figure 1. A mean defect rate of 1% is assumed for each operation, while mean rates of 3% for type I error and 2.5% for type II error are assumed for each inspection. (Obviously, the rates are equal just for simplification and different rates can be used just the same.) The second column lists the immediate successor of each activity and the assembly ratios are specified, were relevant, in the third column from the left.

Table 1 A single pass through the process

Ac. ID	Imm. succ.	Asse- m- bly ratio	Number of defective units	Number of conform- ing units	Number of units not used
o0	--		11	994	5
i9	o0	4	1	4050	31
i8	o0	2	1	2009	0
o2	i9		49	4175	
o1	i8		31	2064	
i7	o2	1	4	4220	0
i6	o2	2	0	8458	10
i5	o2	3	15	12664	7
i4	o1	2	3	4188	1
i3	o1	1	1	2120	26
o7	i7		98	4352	
o6	i6	0	89	8722	
o5	i5		411	13089	
o4	i4		90	4360	
o3	i3		34	2180	
o10	o7	0	45	4405	
o9	o5		263	13237	
o8	o4	0	54	4396	
i2	o3	3	4	6654	16
i1	o3	1	1	2213	0
o13	o9	0	127	13373	
o12	i2		127	6873	
o11	i1		43	2277	
o15	o12	0	64	6936	
o14	o11	0	19	2301	

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The three columns on the right side of the table are numbers of units, which were set aiming at the assembly of 1,000 conforming units of the end item, on average and accounting for both: the assembly ratios and the defect rates. (see [15]). Operations 6, 8, 10, 13, 14 and 15 are leaves in the *OPC* of Figure 1 – each has no arrow pointing into it. This is indicated by the '0' values in the assembly ratios of these operations, which thus serve as the starting points for the calculations. Material for 7,000 units enters operation 15, which constitutes the number of trials for this operation in this pass. Consequently, 64 defective units were sampled from the binomial distribution with 1% success rate (the mean defect rate), 7,000 trials and a cumulative probability which was sampled from the uniform (0,1) distribution. 2,320 trials were used for operation 14, 13,500 trials for operation 13, 4,450 trials for operations 8 and 10 and 8,811 trials for operation 6. The immediate successor of operation o15 is o12. The number of conforming units which enters this operation is $6,936 = 7,000 - 64$ = the number of trials for sampling. 63 defective new units from this operation join the previous 64, 127 units together, leaving 6,873 conforming units. The numbers for o11, o9, o7 and o4 – the successors of o14, o13, o10 and o8 are determined in exactly the same way. The successor of o9 is o5. Hence, the number of trials for o5 are the 13,237 conforming units, which arrive to o5 from o9. Of these, 148 units turn defective, joining the 263 defective units that arrive from o9, too. The successors of o12, o11, o7, o6, o5 and o4 are all inspections.

For each inspection, two numbers should be sampled: the number of defective units that are missed and slip through the inspection and the number of false rejections. The details of o12 are used for the sampling for i2. False rejections are of conforming units. Hence, 6,873 trials are used for sampling with a success rate of 3% – the rate of type I errors. 219 conforming units are falsely rejected, leaving 6,654 to continue, with another 4 defective units, out of 127, which slipped through the inspection. Similarly, only 2,213 of the 2,277 conforming units that arrive to i1 continue, with the addition of a single defective unit. These principles are used also for the sampling of i4, i5, i6, and i7. The successors of all these inspections are assembly operations.

Recall the difference between operations and inspections, which is noted in the beginning of the third section. The total number of units is not changed while moving from o15 to o12, from o14 to o11, or in the other routes. In contrast, in the inspections the numbers are changed, due to the removal of units which are deemed defective.

In assemblies, the assembly ratios should also be taken into account. Going bottom-up, o3 needs to be considered first. In this operation, a single unit that arrives from i1 is assembled with 3 units from i2. The numbers of arriving units are 2,214 from i1 and 6,658 from i2 and since $2,214 < 6,658/3$, only 2,214 units will be assembled and this is

the number of trials for the sampling for operation o3. This also leaves $16 = 6,658 - 3 \cdot 2,214$ unused units at i2. The defect rates are $1/2,213$ and $4/6,654$, respectively for the arriving units from i1 and i2. Consequently, the defect rate of o3 is $1 - 0.99 \cdot (2,213/2,214) \cdot (6,654/6,658)^3$, were $0.99 = 1 -$ the self-defect rate of o3. The sampling resulted in 34 defective units and 2,180 conforming units. In o2, three component types are involved, which arrive from i5, i6 and i7. The number of trials is $4,224 = \min \{4,224, [8,458/2], [12,679/3]\}$. Ten unused units are left in i6 and 7 units in i5. No defective unit arrive from i6. Hence, the defect rate of o2 is $1 - 0.99 \cdot (2,213/2,214) \cdot (8,458/8,458)^2 \cdot (12,664/12,679)^3$. Notice the numbers of residual units. 1 unit in i4 because the total number of units: $4,188 + 3$ is odd and 26 units in i3, which suffice for additional 26 sub-assemblies, but have no matching components.

Table 2 A single pass through the process with final inspection

Ac. ID	Imm. succ.	Asse- mbl ratio	Number of defective units	Number of conform- ing units	Number of units not used
FI		1	0	996	0
o0	FI		11	1028	
i9	o0	4	1	4188	33
i8	o0	2	1	2077	0
o2	i9		50	4317	
o1	i8		32	2134	
i7	o2	1	4	4363	0
i6	o2	2	0	8735	1
i5	o2	3	15	13134	48
i4	o1	2	3	4330	1
i3	o1	1	1	2185	20
o7	i7		101	4499	
o6	i6	0	92	9008	
o5	i5		426	13574	
o4	i4		93	4507	
o3	i3		35	2247	
o10	o7	0	47	4553	
o9	o5		273	13727	
o8	o4	0	56	4544	
i2	o3	3	4	6844	2
i1	o3	1	1	2289	8
o13	o9	0	132	13868	
o12	i2		130	7070	
o11	i1		44	2356	
o15	o12	0	65	7135	
o14	o11	0	20	2380	

All the rules for the calculations have now been presented and the calculations up to the end-item continue in the same way. The final assembly – o0, ends up with 994 conforming units and 11 defective units. The corresponding outgoing quality is $994 / (11 + 994) \sim 98.9\%$

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a bit higher than the mean value of 98.8%. Both values can be improved if a final inspection is added after the final assembly. The mean value of the outgoing quality increases to almost 99.97% and the results of the single pass with final inspection (FI) are listed in Table 2. However, the additional inspection also involves 3% false rejections. Consequently, the input had to be increased by $1/(1-.03) - 1 \sim 3.1\%$ in order to maintain the target of 1,000 conforming units. This is the sole source for the differences between Tables 1 and 2 – the same uniform (0,1) random numbers and the same mean defect rates have been used. Of course, however, with different numbers of units, the numbers of trials are changed and, in addition, the defect rates of the assembly operations. The final results reflects the improvement – while the same number of defective units, 11, have been assembled in o0, none slipped through the final inspection. The number of conforming units is about the same – the difference can be attributed to the modulo operator in the calculations of the assembly operations. This is also related to the different numbers of unused units.

5.2 Systems' dynamics and possible applications of the model

The development of the model was motivated by the desire to study the effects of the residual inventories – the unused units in Tables 1 and 2. To illustrate, a second pass through the process has been executed, with and without final inspection. These executions have been performed in two different settings. First, independent pass – the residues of the first pass have not been used in the second, and the residues of both passes are accumulated. Then, the residues of the first pass have been used in the second pass. The results are presented in Table 3. The passes without final inspections are shown on the top part, while the passes with final inspection are shown in the lower part, of the table. In the bottom of the table, the column titles are put in words. Non-assembly operations are excluded from the table since, as noted in the beginning of Section 3, the number of units is not changed in these operations.

Table 3 System's Dynamics

	ID	IS	AR	First pass			2 nd pass without residues				2 nd pass with residues		
				#D	#Conf.	I1	#D	#Conf.	I2	I1+I2	#D	#Conf.	I2
Without final inspection	o0			11	994	5	7	1002	9	14	7	1003	15
	i9	o0	4	1	4050	31	2	4035	1	32	2	4035	28
	i8	o0	2	1	2009	0	0	2020	2	2	0	2020	0
	o2	i9		49	4175		51	4165			51	4165	
	o1	i8		31	2064		23	2094			23	2094	
	i7	o2	1	4	4220	0	3	4213	0	0	3	4213	0
	i6	o2	2	0	8458	10	5	8478	51	61	5	8478	61
	i5	o2	3	15	12664	7	8	12734	94	101	8	12734	101
	i4	o1	2	3	4188	1	1	4233	0	1	1	4233	1
	i3	o1	1	1	2120	26	0	2119	2	28	0	2119	28
	o3	i3		34	2180		20	2178			20	2178	
	i2	o3	3	4	6654	16	3	6639	48	64	3	6639	64
	i1	o3	1	1	2213	0	2	2196	0	0	2	2196	0
With final inspection	FI			0	996	-4	0	1006	6	2	0	1008	4
	o0	FI		11	1028		7	1036			7	1038	
	i9	o0	4	1	4188	33	2	4172	2	35	2	4172	27
	i8	o0	2	1	2077	0	0	2089	3	3	0	2090	0
	o2	i9		50	4317		53	4306			53	4306	
	o1	i8		32	2134		23	2165			23	2166	
	i7	o2	1	4	4363	0	3	4356	0	0	3	4356	0
	i6	o2	2	0	8735	1	5	8756	43	44	5	8756	44
	i5	o2	3	15	13134	48	8	13204	5	183	8	13204	183
	i4	o1	2	3	4330	1	1	4376	1	2	1	4376	0
	i3	o1	1	1	2185	20	0	2193	5	25	0	2197	28
	o3	i3		35	2247		20	2254			20	2258	
	i2	o3	3	4	6844	2	3	6830	11	13	3	6830	1
	i1	o3	1	1	2289	8	2	2272	0	8	2	2272	4
ID – activity identification IS – immediate successor AR – assembly ratio							#D – number of defective units #Conf. – number of conforming units Ix – residual inventory at the end of the x th pass						

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System dynamics is manifested by the differences in the number of units; e.g., the differences between the column I2 of the independent passes – without residues, with I2 when the residues are used in the second pass. The most important consequence of the use of the residues is the increase in the yield of the second pass. With no final inspection one additional unit, while with final inspection two additional units of the end item are assembled. This also results in smaller inventories of the sub-assemblies – the total inventory at the end of the second pass in the rows of i8 and i9. No general conclusions can be drawn from a couple of passes, but the dynamic pattern is demonstrated and the model can be executed as many times as needed.

Noteworthy is the fact that the first pass, with or without final inspection ended with less than planned conforming units. Without final inspection, the 11 defective units, which continue to the next destination of this product, hide the problem, while the final inspection exposes this shortage, which may or may not be fulfilled by the surplus of the second pass. This type of behaviour, however, is certainly expected in reality and the proposed model enables to analyse its pattern and consequences.

6 Summary

Manufacturing/production processes are imperfect and produce defective items in a random manner. The introduction of inspections for quality assurance adds randomness to the system due to inspection errors of both types. The facts that product design dictates specific assembly ratios while the actual number of units that arrive to assembly operations are random numbers create miss-matches in production systems, which involve assembly operations. This might be less prominent when a single product is manufactured with rare interruptions for maintenance, but in a multiple-products-resource-sharing environment, which forces intermittent production, these miss-matches can result in chaos – quotas are not fulfilled and ordered are delivered either late or incomplete.

In this study, a dynamic simulation model has been developed to analyse these phenomena. It is dynamic because it enables to follow the interrelationships between different executions of production processes, focusing on residual quantities of items, which result from miss-matches, either surpluses or shortages. The operation of the model is described in details and its merit is demonstrated with few examples.

Since the magnitudes of these residual quantities are (often very) small compared to the total quantities, it is not even clear if they are managed in any form. The numerical examples show that even in two executions of a process using the residues of the first pass during the second makes differences. Much more significant differences are expected when processes are executed in the high frequency of industrial plants. The proposed model enables to better understand the behaviour of production systems

and forms a basis for the evaluation of various approaches and tactics to improve system's performance.

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