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Neuro-mechanistic model for cutting force prediction in helical end milling of metal materials layered in multiple directions

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A B S T R A C T

In machining of multi-layer metal materials used frequently for the manufacture of transfer sheet-metal forming tools, the cutting edge is often damaged because of cutting force peaks. Therefore, a neuro-mechanistic model, presented in this paper, has been created for accurate prediction of cutting forces in helical end milling of multidirectional layered materials. The generalized model created takes into account the complex geometry of the helical end milling cutter, the instantaneous chip thickness and the direction of depositing of the individual layer of the multidirectional layered material considered in the calculation through predicted specific cutting forces. For the prediction of specific cutting forces for individual layers a neural network is incorporated in the model. The comparison with experimental data shows that the model predicts accurately the flow of cutting force in milling of multidirectional layered metal materials for any combination of cutting parameters, tool engagement angle and directions of depositing three layers of material. The predicted cutting force values agree well with the values obtained, the maximum error of predicted cutting forces is 16.1 % for all comparison tests performed.

A R T I C L E I N F O

Keywords:
Helical end milling;
Multidirectional layered metal material;
Cutting forces;
Specific cutting forces;
Neuro-mechanistic model;
Modelling;
Prediction;
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1. Introduction

Tool shops making resistant transfer sheet-metal forming tools use the most up-to-date multi-layer metal materials. The materials are made layer after layer by the LENS (laser engineered net shaping) process [1].

In the multi-layer material, the individual layers are deposited in different directions, therefore the machinability of the layered material is changing from layer to layer. Machinability also depends on the angle between the feeding axis of the tool and direction of layer depositing.

Machining of such materials is a demanding operation requiring continuous adaption of machining parameters to momentary cutting conditions. A review of literature identifies no researches in the field of machinability of multidirectional layered metal materials. There are a few researches on machinability of difficult-to-machine nickel-based alloys [2], titanium alloys [3] and composite materials [4]. M'Saoubi *et al.* [5] presented an overview of the recent advances in high performance cutting of aerospace alloys and composite used in aeroengine and aero structure applications.

Hojati *et al*. [6] and Bonati *et al*. [7] examined the machinability of additively manufactured Ti6Al4V alloy parts in the micro-milling with a particular emphasis on cutting forces. They found out that the microstructure of the material, in addition to the hardness of the material, has a significant impact on the cutting forces. Furthermore, the cutting forces for additively manufactured part are lower than those of standard manufactured part despite of their higher hardness. Montevecchi *et al*. [8] analysed cutting forces in order to examine the machinability of AISI H13 alloy. Mechanistic approach was employed to identify cutting force coefficients and to investigate the behaviour of the cutting force for laser deposition (LENS). Results outlined that the additively manufactured AISI H13 material had reduced machinability compared to the same standard material at wrought state.

In machining multi-layer metal materials high cutting force peaks and excessive wear and extensive damages of the cutting tool occur because of the non-uniform shape of chips [5]. The cutting force frequencies measured in milling can be directly associated with the manner of chip formation [9]. Also the roughness of the machined surface depends strongly on the manner of chip formation and is in correlation with cutting force. The tool wear and damages are directly associated with cutting forces, therefore accurate prediction and monitoring of cutting forces is a key factor assuring quality of machining. By the cutting forces, accurately predicted, the quality of machining can be evaluated and undesirable effects on the cutting tool reduced [10].

Literature comprises a lot of researches on modeling of cutting forces in oblique cutting. The majority of cutting force models for oblique cutting are created by the mechanistic modelling technique [9]. The developed mechanistic models for oblique cutting in predicting of cutting forces take into account: radial cutter runout [11]; tool deflection [12]; system dynamics and flank wear [9]; indentation of the cutting edge into the work material [13]; dynamic chip thickness, chip forming and friction forces [14]; radius of curvature for sculptured surface machining [15]; Johnson-Cook constitutive equation [16].

In the mechanistic models, the cutting forces are associated with instantaneous uncut chip thickness through experimentally defined specific cutting forces [17]. The principal challenge in creating of those models is the work-intensive acquisition of specific cutting forces for oblique cutting. Further, the acquisition of specific cutting forces for different tool and workpiece combinations requires a great number of cutting experiments and much analytical work. In modeling of multidirectional layered materials also the non-homogeneities in materials must be considered making the determination of specific cutting forces even more exacting.

Models for simulating of cutting forces in orthogonal cutting of layered laminates with different directions of fibres [4, 18, 19] and quite a few models for prediction of cutting forces in helical end milling of metals are available. For example, Kline [20] created a cutting force model by dividing the helical end mill in axial direction into differentially thin elements. For each element, he calculated the differential cutting force as the product of specific cutting force and uncut chip cross-section area. With the sum of differential cutting forces for the entire cutting edge he then determined the total cutting force on the tool.

Zhang *et al*. [21] developed a stochastic model of cutting forces in milling of fibre-reinforced ceramic matrix composites. In this model, the cutting forces are modeled by combining the simultaneous influences of randomly distributed carbon fibres and stochastic deterioration of tool wear. Grdisek *et al*. [22] created a generalized prediction model considering the chip and tool geometry, cutting parameters and specific cutting forces determined by a special method from orthogonal cutting data. Wang *et al*. [23] developed a novel analytic cutting force model of helical milling of titanium alloy. Liu *et al*. [24] developed a cutting force model to predict the cutting forces and torque during helical milling of AISI D2 steel. In the recent years, the artificial neural networks (ANN) for modelling of the milling process have become popular. Zuperl *et al*. [25] used backpropagation ANN for modelling of cutting forces in ball-end milling based on a set of input cutting conditions. Aykut *et al*. [26] applied ANN for predicting cutting forces in face milling of satellite Co-based alloy under dry conditions. El-Mounayri *et al*. [27] introduced a radial basis model for predicting cutting forces in a ball-end milling process. Al-Zubaidi *et al.* in his paper [28] reviewed the previous studies and investigations on the application of artificial neural network in modeling of milling processes.

Balasubramanian *et al.* [29] performed analysis of cutting forces in helical ball end milling of Ti-6Al-4V alloys using deep neural network. On the basis of the results obtained, he concluded that the accuracy of the predicted forces was more than sufficient for any practical purpose.

The models based on neural networks prove to be very accurate in predicting by searching for correlations between cutting parameters and cutting forces, whereas they are not successful in predicting cutting forces on the basis of different properties of workpiece material. Our paper discusses the generalized neuro-mechanistic model for accurate prediction of cutting forces in helical end-milling of multidirectional layered materials. The generalized model consists of a mechanistic prediction model of cutting forces for complex cutting tool geometry and an artificial neural network for prediction of specific cutting forces of a particular layer.

The relevant scientific contribution of this paper is the presented methodology to build a predictive cutting force model for edge milling of multidirectional layered materials with complex cutting tool geometries. The methodology is not limited to one cutting tool; it can be extended to all other complex cutting tools where the instantaneous uncut chip thickness and direction of the layer deposition can be determined.

The paper is organized as follows: Section 2 presents the methodology of creating of combined neuro-mechanistic model for prediction of cutting forces in helical end-milling of multidirectional layered material. Subection 2.1 outlines an overview of the proposed cutting force model. Subection 2.2 presents the developed mechanistic model for prediction of cutting forces by considering the geometry of the helical end milling cutter, instantaneous chip thickness and direction of depositing of individual layers of multi-layer material. Subsection 2.3 describes the artificial neural network based modeling and predicting of specific cutting forces for each direction of deposition of individual layer of layered material. Subsection 2.4 outlines the experimental set-up. In Section 3 the results of comparison of the model prediction with experimental data are analyzed. Section 4 gives the concluding remarks.

2. Materials and methods

A quantitative study design was undertaken in three phases. In the first phase, edge milling of metal materials layered in different directions was executed in order to obtain orthogonal data base (milling force data) for determining specific cutting forces. Mechanistic technique was employed to predict specific cutting forces. In the second phase, an artificial neural network was built to estimate specific cutting forces. In the third phase, a generalized cutting force model was developed based on mechanistic modeling technique [17, 24]. The model was verified by comparing predicted and experimentally acquired values. The average percentage error (APE) was employed to evaluate the accuracy of the neural and cutting force model.

2.1 Overview of proposed cutting force model for multidirectional layered material

Hereinafter, a combined neural-mechanistic model for prediction of cutting forces in helical end-milling of multidirectional layered metal material is presented. The model is capable of predicting the cutting forces for selected combination of cutting parameters, immersion angle and direction of deposition of individual workpiece layers. For creation of the model, the mechanistic modeling technique of complex tool geometry, dividing the helical tool cutting edge in axial direction into a great number of equal differential elements with angle offset, is used. By the use of trained artificial neural network the radial and tangential cutting force coefficients (K_r, K_t) are evaluated for each element. Based on evaluated instantaneous coefficients K_r and K_t the radial dF_r and tangential dF_t differential forces for each individual differential element are calculated. In the end, the total force on the cutting tooth is calculated by integrating differential forces on all elements of the cutting edge. The force on tool is determined by the sum of cutting forces on all tool cutting edges.

2.2 Creation of cutting force model for helical end mill

Cutting forces are calculated for the end mill with helix angle β, diameter D and number of cutting edges N. The milling cutter with designated cutting force direction and differential segments is shown in Fig. 1. The two elementary forces dF_t and dF_r on the differential element L are determined on the basic of instantaneous values K_r and K_t, instantaneous uncut chip thickness h_L and milling width. Tangential force dF_t and radial force dF_r acting on the differential element L of dz height are calculated according to Eqs. 1 and 2:

$$dF_r(\phi_L, z) = \left[K_{re} + K_r \cdot h_L(\phi_L, z)\right] \cdot dz \tag{1}$$

$$dF_t(\phi_L, z) = \left[K_{te} + K_t \cdot h_L(\phi_L, z)\right] \cdot dz \tag{2}$$

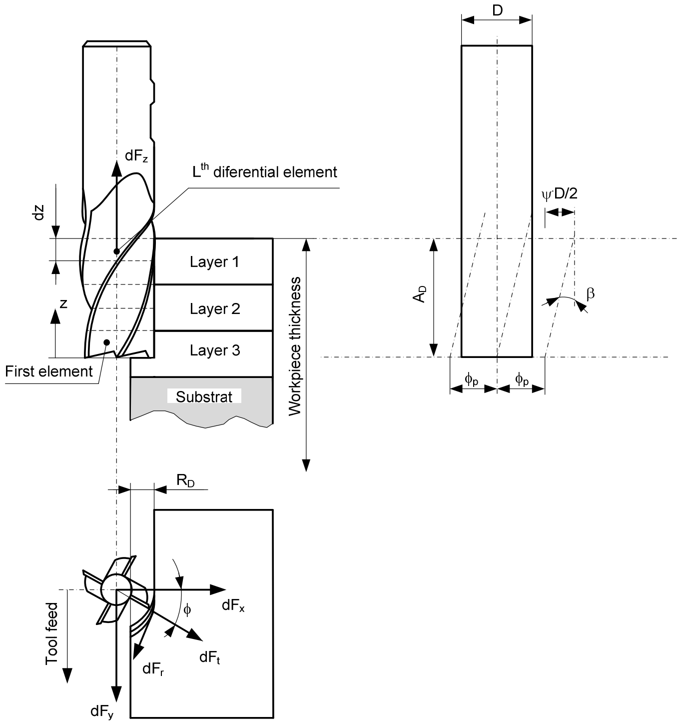

Fig. 1 Geometry of helical end milling of multidirectional layered material with relevant cutting forces and tool dissection into differential elements

The immersion (engagement) angle for differential element L on tooth j at an axial depth of cut z is calculated according to:

$$\phi_L(z) = \phi + j\phi_p - \lambda \tag{3}$$

In the calculation, it is assumed that the bottom part of the cutting edge $j = 0$ has reference immersion angle ϕ. The bottom end points of the other cutting edges are offset from reference cutting edge by angle $\phi_p = 2\pi/N$. This relation is written with Eq. 4:

$$\phi_j(z = 0) = \phi + j\phi_p; \quad j = 0, 1, \ldots, (N - 1) \tag{4}$$

where ϕ_p is the angular pitch of cutting edge. Lag angle for differential element L for axial cut depth z is calculated Eq. 5:

$$\lambda = \frac{2 \tan \beta}{D} \cdot z \tag{5}$$

h_L for the differential element is calculated according to Eq. 6.

$$h_L(\phi_L, z) = f_z \cdot \sin\phi_L; \quad f_z = \frac{f}{n \cdot N} \tag{6}$$

where f is the feed rate and n is the rotational tool speed.

The cutting force components with zero chip thickness are designated as K_{te} and K_{re}.

The effect of cutting tool wear is not considered because sharpened tool is used for each pass.

By considering the cutting trigonometry the differential axial cutting force dF_a for L-th differential element is determined on the basis of dF_t and dF_r according to Eq. 7:

$$h_L(\varphi_L, z) = f_z \cdot \sin \phi_L dF_a(\varphi_L, z) = \frac{dF_r(\sin\beta - \cos\beta \cdot \sin\alpha_n \cdot \tan\eta) - dF_t \cdot \cos\alpha_n \cdot \tan\eta}{\sin\beta \cdot \sin\alpha_n \cdot \tan\eta + \cos\beta} \quad (7)$$

where β is the inclination angle of cutting edge, α_n the relief angle and η is the rake angle.
The radial and tangential coefficient of cutting force depend on the direction of layer deposition of layered material and uncut chip thickness determined for the instantaneous engagement angle ϕ_L according to Eq. 6.

The angle of instantaneous direction of deposition of layers of layered material for differential element L is determined according to Eq. 8:

$$\theta_L = \begin{cases} \psi - \phi_L & 0 \le \phi_L < \psi \\ 180 - (\phi_L - \psi) & \phi_L > \psi \\ 180 - \psi & \psi = 0 \end{cases} \quad (8)$$

The angle of deposition of a gradient layer of material is designated ψ.

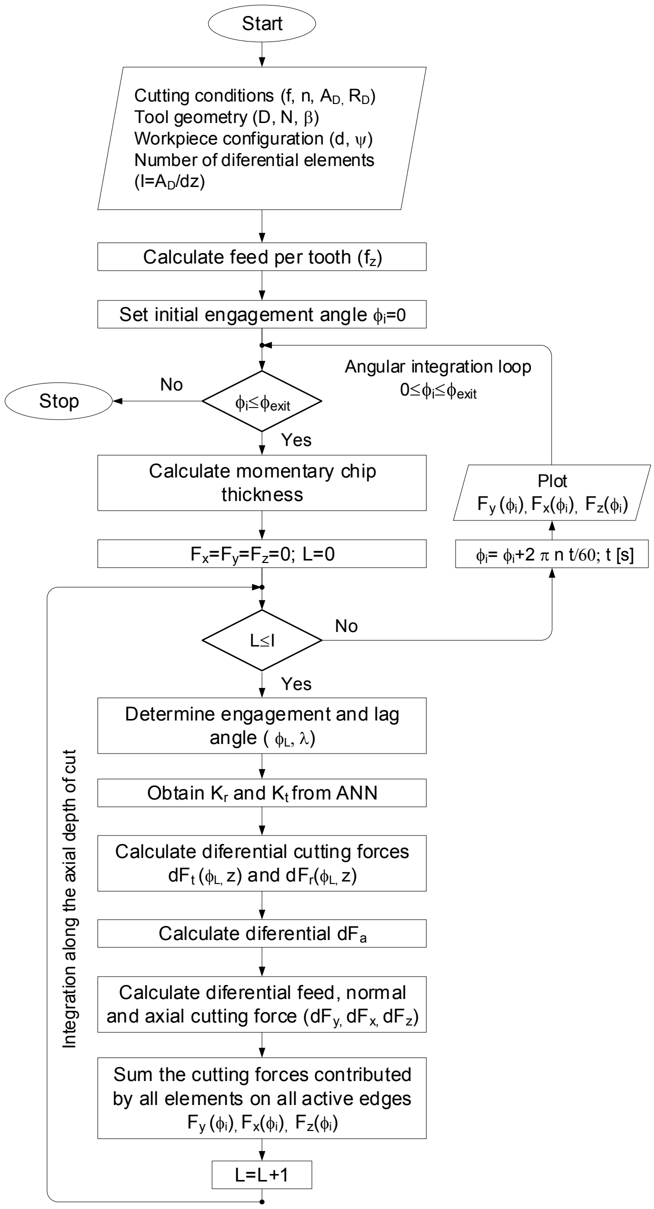

Fig. 2 Algorithm for prediction of cutting forces in helical end milling

Transformation of elementary force dF_r and dF_t into differential feeding force dF_y and normal force dF_x by taking into account the cutting trigonometry is determined according to following equations:

$$dF_x(\phi_L, z) = dF_t \cdot \cos\phi_L(z) - dF_r \cdot \sin\phi_L(z) \tag{9}$$

$$dF_y(\phi_L, z) = dF_t \cdot \sin\phi_L(z) + dF_r \cdot \cos\phi_L(z) \tag{10}$$

$$dF_z(\phi_L, z) = dF_a \tag{11}$$

By integrating the differential forces on the active part of cutting edge (from 0 to A_D) the total cutting force of one cutting edge j is determined. Total cutting forces generated by the tool are determined by the addition of cutting forces on all differential elements of cutting edges. The following expressions are used:

$$F_x(\phi_i) = \sum_{j=0}^{N-1} \sum_{z=0}^{A_D} dF_x; \quad F_y(\phi_i) = \sum_{j=0}^{N-1} \sum_{z=0}^{A_D} dF_y; \quad F_z(\phi_i) = \sum_{j=0}^{N-1} \sum_{z=0}^{A_D} dF_z; \qquad 0 \leq \phi_i \leq \phi_{exit} \tag{12}$$

Fig. 2 shows the algorithm for prediction of cutting forces in milling with helical end milling cutter.

2.3 Neural model of specific cutting forces for unidirectional layered material

This chapter presents the methodology of modelling and predicting of specific cutting forces for unidirectional layered metal material by the use of ANN. Specific cutting force in milling of multilayer materials depends on the direction of deposition of individual layers, instantaneous chip thickness, cutting speed and tool wear. For a certain pair tool-workpiece the specific cutting force links the cutting parameters to relevant radial and tangential cutting force.

For the individual deposited metal layer of material with defined instantaneous direction of deposition θ its amplitude is calculated according to the following expressions:

$$K_r(n, f, \theta, h) = \frac{F_r(n,f,\theta,h)}{A_D \cdot h(\phi)}; \qquad K_t(n, f, \theta, h) = \frac{F_t(n,f,\theta,h)}{A_D \cdot h(\phi)} \tag{13}$$

In the equation, F_r and F_t are measured cutting forces, the expression in the denominator is the calculated uncut chip area. The experimental data set for calculation of specific cutting forces is obtained by measurement of cutting forces in milling of multi-layer metal workpieces. All layers of the individual workpieces were made with equal direction of deposition.

To train, validate and test the neural model, a total of 54 cutting experiments with three spindle speed levels, three feed rate levels, two axial depth of cutting levels and three different workpiece configurations were conducted.

The data set used for training, validating and testing the neural model consists of 1890 data points. The total data set was split into input and output subsets. The input subset consists of spindle speed n, feed rate f, axial depth of cutting A_D, radial depth of cutting R_D, the direction of the material layer deposition ψ, uncut chip thickness h and hardness of the machined material HV. The output set consists of radial and tangential specific cutting forces.

Further, the total data was randomly divided into training/validation (1260 data points) and testing data subsets (630 data points). A ten-fold cross-validation is used to validate the ANN model. Therefore, 1260 data points were randomly partitioned into 10 equal blocks (folds). Then, ANN models were systematically trained on 9 folds and validated on the remaining fold; the cross-validation process was repeated 10 times. The prediction errors of the trained ANN models were averaged and 95 % confidence interval was determined. After the validation process, a subset of 1260 data points was used to train a new ANN model. Finally, a testing data subset (630 data points) was used to test the developed ANN model.

To evaluate the accuracy of the created models, the average percentage error (APE) calculated according to Eq. 14 is used:

$$APE = \left(\sum_{i=1}^{n} \frac{\left| K_{\text{target},i} - K_{predicted,i} \right|}{K_{\text{target},i}} \cdot 100\ \% \right) / n \tag{14}$$

where $K_{\text{target},i}$ is the experimentally determined specific cutting force component, $K_{predicted,i}$ is predicted specific cutting force component in radial and tangential direction generated by ANN and n is the number of testing data points.

For modeling, a four-layer feed forward ANN with backpropagation learning algorithm is used. The rate of training 0.12 and the momentum rate 0.08 are selected for training, while for the transfer of signals between neurons the arctan transfer function is chosen. The input vector of neural network consists of spindle speed n, feed rate f, axial depth of cutting A_D, radial depth of cutting R_D, the direction of the material layer deposition ψ, uncut chip thickness h and hardness of the machined material HV. The value HV did not change in the machining experiment. The output vector ANN consists of radial and tangential specific cutting forces. The ANN architecture shown in Fig. 3 and the optimum training parameters were determined through simulations. The ANN training process was completed, when 8500 iterations of training had been performed or when the prediction error has fallen below the pre-defined limit value (0.01).

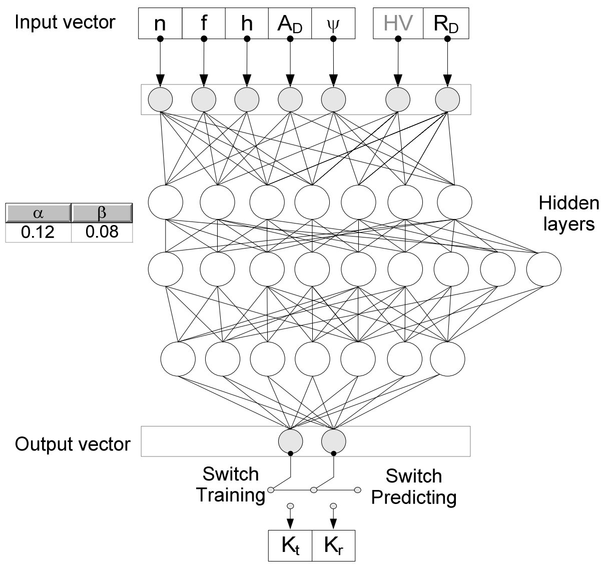

Fig. 3 Detailed structure of ANN used for prediction of components of specific cutting forces depending on material layer deposition direction

2.4 Experimental set-up

To build the cutting force model, a set of machining experiments was performed on the Heller BEA01 milling machine according to the experimental plan. Cutting conditions of performed expriments are described in Table 1.

The orthogonal milling experiments with cutting conditions described in Table 1 have been carried out in order to train and test the ANN model. For determinig the specific cutting forces the stright one tooth cutting tool with a diameter of 16 mm was used. The carbide tool had 3.8° rake angle. Cooling-lubricating agents were not used.

Four complex milling experiments with the same cutting conditions have been carried out in order to obtain the data for verifying the developed generalized neuro-mechanistic model. The model was verified for a segmented helical cutting tool in edge milling of unidirectional and multidirectional workpieces. In these experiments the carbide helical cutting tools with a diameter of 8.5 mm and two flutes were used. The tool from sintered tungsten carbide had 27.3° helix angle and 4.28° rake angle. Cutting edges had PVD-TiAlN coating and hardness of 1820 HV. Cooling-lubricating agents were not used. In all helical milling experiments the same tool rotational frequency 3800 min^{-1} and the same feed rate 200 m/min were selected. The cut depth A_D was adjusted to 1.8 mm and the radial cut depth R_D to 0.5 mm.

Table 1 Cutting conditions of performed machining experiments and material layer deposition directions

Parameter	Orthogonal milling	Helical milling
n [min^{-1}]	3500, 3800, 4100	3800
f [m/min]	200, 250, 300	200
R_D [mm]	1	0.5
A_D [mm]	1.6, 1.8	1.8
D [mm]	16	5.5
Layer depositing direction ψ [°]	90, 180, 135	90, 180, 135, 90/135/180
Number of teeth	1	2
Helix angle [°]	0	27.3
Radial angle [°]	3.8	4.28

Three cutting force components were measured with Kistler piezo-electric dynamometer. The signals of the measured forces were processed with dual mode charge amplifier and low pass filter of 2 kHz cut-off frequency to eliminate noises induced by vibrations of adjacent systems. Adequacy of frequency Bandwidth of dynamometer for all cutting force frequencies in the experiment was confirmed by calculations. Dynamic compensation of measured cutting forces was not employed at low tooth frequencies. Measured signals were transferred to data acquisition with Labview software.

Workpiece of 50 mm length, 15 mm width and 21.8 mm height was clamped to the dynamometer. Two types of workpieces shown in Fig. 4 were used in machining experiments. The first, i.e. unidirectional workpiece type (Fig. 4a) was made from 16MnCr5 basic substrate and several stainless steel (316L) layers with a singular 0.6 mm thickness. All gradient layers were deposited in the same direction. Identical workpieces, properly machined and rotated on Z axis in respect to feed direction for 90°, 135° and 180°, were used in orthogonal milling experiments.

The other, i.e. multidirectional workpiece type (Fig. 4b) was used only in complex helical milling experiment. It was made from a 16MnCr5 basic substrate and three stainless steel (316L) layers deposited in different directions. Each new layer was deposited at 45° angle with respect to the direction of deposition of previous layer. Thus, individual layers were deposited at 90°, 135° and 180° angles. Thickness of individual layers made was 0.6 mm with measured hardness 288 HV. Overlapping of laser trajectories was adjusted to 40 %. Diameter of the effective laser beam was 0.9 mm.

Fig. 4 shows the structure and orientation of used test workpieces in machining experiments.

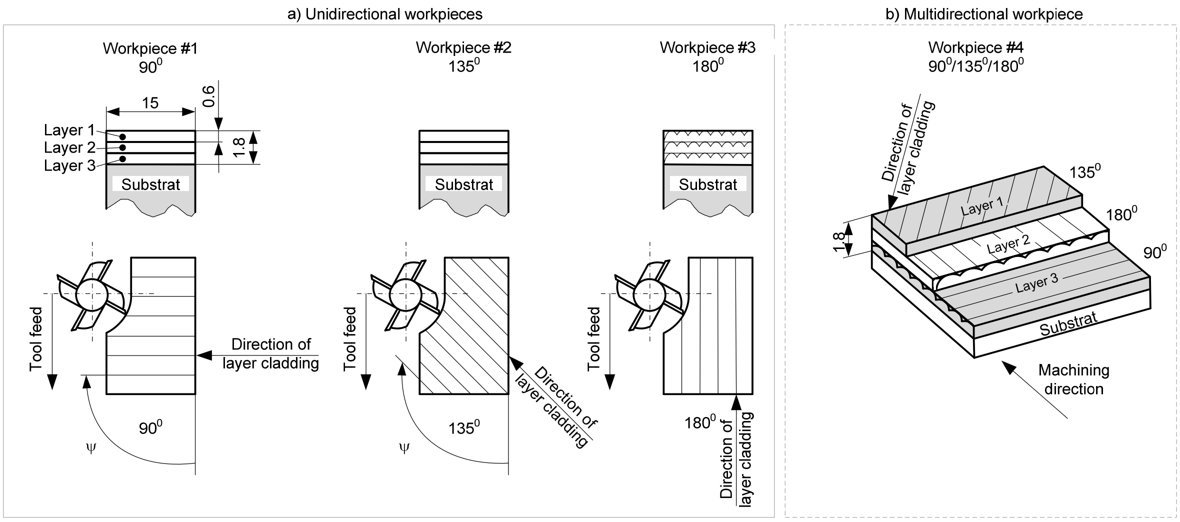

Fig. 4 Structure and position of used unidirectional and/or multidirectional multi-layer workpieces in machining experiments

3. Results and discussion

Many experimental tests with different cutting conditions have been carried out in order to validate the developed generalized neuro-mechanistic model.

A sample of predicted and measured cutting forces in helical milling of unidirectional and multidirectional layered metal material is shown in Figs. 5 and 6. Samples of force values in normal, feed and axial direction are shown diagrammatically depending on the engagement angle. The measured signals of cutting forces, representing the average value of 3 measurements, are represented with full line and predicted values with dashed line. From the flow of cutting force signals it is possible to discern an obvious peak of the cutting force with the tip corresponding to one cutting-off cycle of one cutting tool edge. The cutting force peak results from the increase of chip cross-sectional area on the cutting edge from 0 upon the entry of the cutting edge into material up to maximum value upon the exit of the cutting edge from workpiece. The value and form of the cutting force signal are affected by the layer deposition on the multi-layer material. The instantaneous deposition direction relative to the tool cutting edge changes with the engagement angle.

From the flow of cutting force signals in Fig. 5 it can be discerned that the cutting force values in milling of multi-layer stainless steel with 90° deposition direction are greater than when milling the material with 180° deposition direction. Also a smoother flow of cutting force signals with fewer fluctuations can be discerned. Contacts between deposited layers contribute to formation of very small broken chips. The increase of the deposition direction angle from 90° toward 135° results in strong increase of cutting force fluctuations and magnitude. Most unfavourable cutting forces occur in machining the material with deposition direction 135° (Fig. 6a), where a slightly greater chip cross sectional area of incorrect shapes and from time to time partly continuous appear. Bad cutting conditions might be ascribed to sticking of the cutting edge tip between individual deposited layers. The cutting force magnitudes in milling of unidirectional multi-layer material with deposition direction from 135° towards 180° and partly also fluctuations are decreasing. Greater fluctuations of axial force F_z can be observed in machining the material with 180° deposition direction (Fig. 5a). More favourable, somewhat larger, broken chips appear. When milling a multidirectional three-layer workpiece (90°/180°/135°) two distinct cutting force tops (Fig. 6b) can be observed. They result from great changes of instantaneous directions of deposited layers on the tool cutting edge, when it passes between individual stainless steel layers. Because of the low $R_{D,}$ only one cutting edge cuts at a time. At the beginning of tool rotation, the tool cutting edge moves vertically on the entire thickness of layer 3. Afterwards, it passes over the layer 2 and, in the end, it gets out of the layer 1 at engagement angle 25°. During gradual cutting of the lowest layer 3 with 90° deposition direction the first peak of all three cutting force components (Fig. 6b) occurs.

A decrease of cutting forces, coinciding with cutting of the middle layer with 180° deposition direction, follows. During cutting of the highest layer with 135° deposition direction the second, somewhat smaller, peak of the cutting force component occurs. The greatest magnitudes and fluctuations of cutting force values occur when machining this layer particularly because of greater cross and unfavourable form of the chip and rough tearing of the chip from workpiece. Machining of the highest layer with 130° deposition direction contributes most to the total cutting force shown in Fig. 6b and machining of the middle layer with 180° deposition direction contributes least. The sizes, sequences and distances of peaks of measures cutting forces depend on the sequence and thicknesses of deposited layers constituting the multidirectional multi-layer metal material.

Comparison between measured and predicted forces for helical end milling of unidirectional multi-layer material is shown in Figs. 5a, 5b and 6a. Fig. 6b shows the comparison between measured and predicted forces for milling of multi-layer material with layer deposition directions (90°/180°/135°). Results in Figs. 5 and 6 witness that the predicted force values agree well with experimentally obtained values in milling of 180° and 135° unidirectional multi-layer workpiece. A slightly smaller agreement of predicted and measured forces is discerned in milling of unidirectional workpiece with 90° direction of laser-deposited layers.

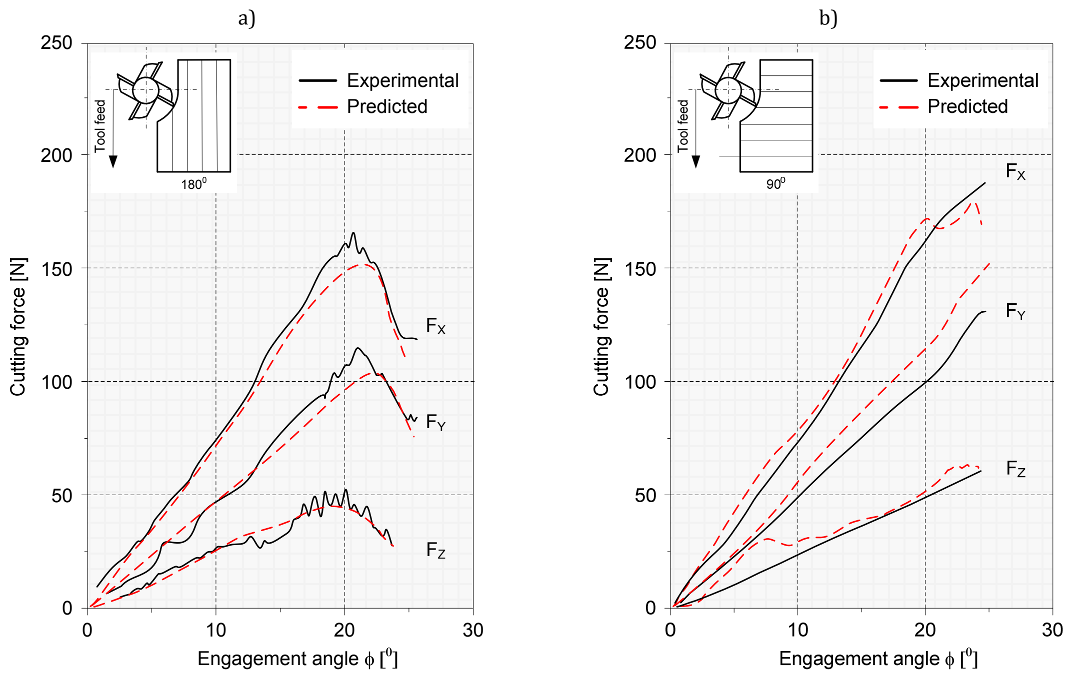

Fig. 5 Comparison between experimental and predicted cutting forces for unidirectional three-layer metal material with: a) with 180⁰ direction of layer deposition b) with 90⁰ direction of layer deposition

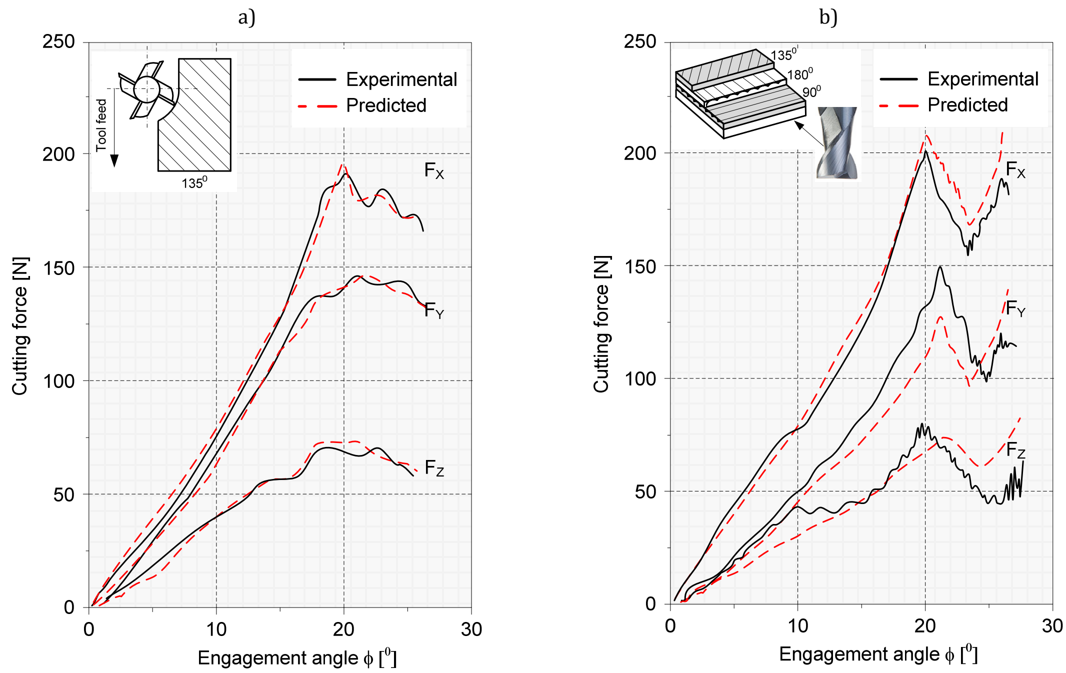

Fig. 6 Comparison between experimental and predicted cutting forces for unidirectional and multidirectional three-layer metal material: a) with 135⁰ direction of layer deposition b) with 90⁰/180⁰/135⁰ directions of layers deposition

The greatest deviation between the model predictions and experimental values of forces occurs in milling of multidirectional workpiece with layer deposition directions (90°/180°/135°). The results differ as follows: from 2.9 % to 8.6 % for F_x, from 3.6 % to 11.7 % for F_y and from 3.6 % to 16.1 % for F_z.

The results in Figs. 5 and 6 show that the developed model appropriately predicts the general course of cutting forces in milling of multi-layer materials.

Table 2 Accuracy of ANN prediction model

ANN	K_r	K_t
APE [%]; Training set	4.29	4.25
APE [%]; Testing set	5.21	3.55

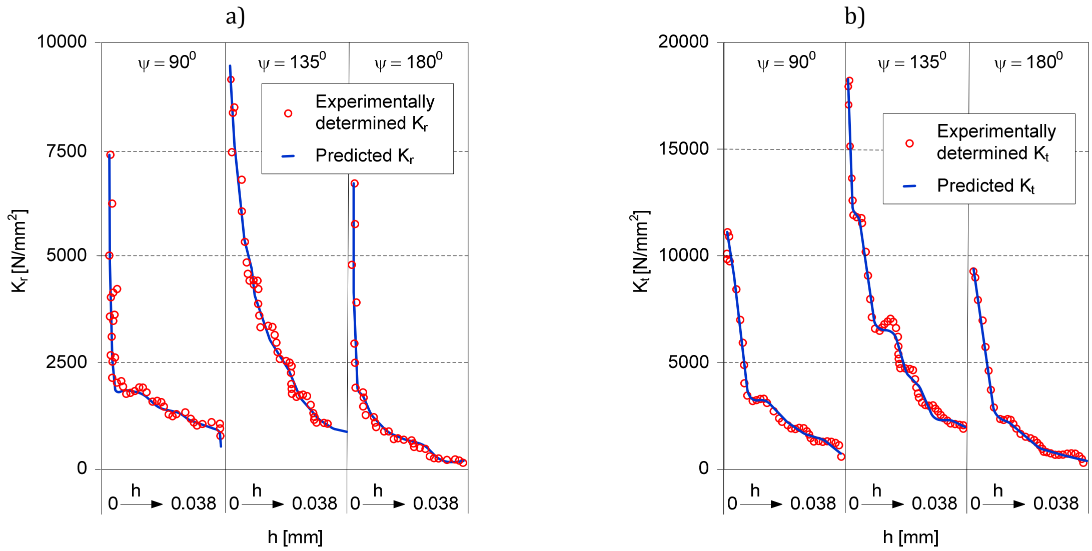

Fig. 7 Comparison of K_r and/or K_t predicted by neural model and obtained experimentally with four different directions of layer deposition; $f = 200$ m/min, $n = 3800$ min-1

The accuracy of the ANN model for predicting specific cutting forces was analysed using the APE method. The results of analysis of the model capacity are given in Table 2. The uncertainty of the predicted results, obtained from the ten-fold cross-validation, can be characterized as small, consequently it was concluded that the ANN adequately predicted K_r and K_t. The maximal prediction error of the ANN model is 5.21 % for K_r, and 3.55 % for K_t with a 95 % confidence interval. A part of predicted values K_t and K_r depending on the layer deposition angle and uncut chip thickness is presented in two graphs in Fig. 7. Both graphs show that the predicted values of specific components of cutting forces in radial and tangential direction strongly agree with experimentally obtained values. The two specific cutting forces decrease with the increase of the engagement angle and/or instantaneous uncut chip thickness. The greatest values are reached with layer deposition angle 135°.

4. Conclusion

The paper presents a combined neural-mechanistic model of the process of helical milling of multidirectional layered metal materials.

For creation of model the mechanistic technique of cutting force prediction was used by dividing the helical end mill into a series of differentially thin axial elements with oblique cutting edges and calculating the differential cutting force for each element. To that end, it uses specific cutting forces predicted by the artificial neural network and incorporates in the calculation the deposition direction of individual layer of multidirectional layered metal material. The total cutting force for any immersion tool angle is calculated by integrating the differential cutting forces on the height of the tool cutting edge in contact with the multi-layer workpiece.

The model is capable of predicting the cutting forces in milling of multidirectional and unidirectional metal materials with complex geometry tools.

Many cutting experiments have been carried out to validate the developed model. The following conclusions can be drawn from these experiments:

- The magnitude of cutting forces in milling of multidirectional layered metal material is affected by the layer deposition direction and immersion angle of cutting tool determining the instantaneous cross-section of the chip.
- The developed model appropriately predicts the general course of cutting forces during milling of multidirectional metal materials. It can be recapitulated that the model created is generally efficient (valid) for any combination of cutting parameters and direction of workpiece layer deposition.
- Accuracy of the model prepared is high in milling of unidirectional metal materials and slightly worse in milling of the workpiece with multidirectional laser deposited layers.
- The neural network incorporated in the model predicts the specific cutting forces for any instantaneous direction of deposition of material layers, therefore the proposed model is widely applicable and capable of simulating the cutting forces on the helical milling tool for multidirectional layered metal material.
- The predicted cutting force values agree well with experimentally obtained values in milling 180° and 135° unidirectional multi-layer workpiece. A slightly smaller agreement between predicted and measured forces is found in milling unidirectional workpiece with 90° direction of layer deposition. These minor errors are not random. They might appear due to the failure to take into account the entire cutting tool geometry when calculating the specific cutting forces.
- The results differ as follows: from 2.9 % to 8.6 % for F_x, from 3.6 % to 11.7 % for F_y and from 3.6 % to 16.1 % for F_z.
- The maximum percentage prediction cutting force is found to be less than 16.1 % for all the cases tested.

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Improvement of logistics in manufacturing system by the use of simulation modelling: A real industrial case study

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A B S T R A C T

The current practice and the requirements of industrial enterprises in all industrial areas require a detailed display of manufacturing systems course of events. In this paper, we studied the effects and impacts of computer simulation to improve the actual industrial production. We also verified whether the proposed simulation model and its intervention in the logistics of concrete production in a concrete manufacturing enterprise will correspond to reality. The EXTENDSIM simulation software was used. The simulation results utilization in practice has increased the actual production several times. The simulation results indicated that it is necessary to double the intensity of company supply, i.e. a frequency of entry set to 0.15 days for each timber type. This adjustment increased the performance of unutilized devices and the whole manufacturing system several times, up to 54,475 produced building timber elements, which represents an increase of production by about 199.6 % while maintaining company flexibility.

A R T I C L E   I N F O

Keywords:
Manufacturing;
Logistics;
Simulation;
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EXTENDSIM

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1. Introduction

The solution of manufacturing logistics problems in specific market area requires the utilization of the means of algorithmization, heuristics, mathematical statistics, modelling and computer simulation. A combination of the defined approaches is possible for the designing, and it solves the problems of any manufacturing system. The objective of the logistics solutions is to influence and manage material flows in the right way. The execution of a concrete manufacturing system from a complex point of view of all types of flows is possible only by taking advantage of computer simulation. The application of mathematical modelling for the designing of material, information and financial flows together is practically impossible (and what about the effect of the human factor, in determination, haphazard and so on). All these facts make computer simulation the perfect facility (in many tasks, the only possible one) for the solution of specific problems of manufacturing systems. The foregoing results clearly show the importance of computer simulation for improving the efficiency of logistics in manufacturing. The problem relates to an effective utilization of the computer simulation with EXTENDSIM simulation system to improve the efficiency of logistics in manufacturing of concrete production company, engaged in the processing of raw timber and the production of building timber in the form of beams, planks, and boards from different types of wood, such as oak, beech, spruce and pine.

Timber production, in general, belongs to the most common types of industrial productions. Timber as a building material is equally popular in all the continents of the world. The methods of processing raw timber are identical, and they work on the same, respectively similar devices under the same, respectively similar conditions. This implies the importance of tackling this issue for the industrial sector in question and the universal character of the usage of this approach to increase the efficiency of logistics in manufacturing by means of computer simulation and the EXTENDSIM simulation system.

The aim of this paper is to clearly define a procedure which must be followed to solve equal or similar types of tasks through the utilization of concrete EXTENDSIM simulation system serving the needs of industrial practice. The tasks that must be executed are related to some given resolution procedures that are generally applicable to streamline the logistics in manufacturing using computer simulation. The quality of the solutions and their impacts on the manufacturing system depend on the quality of the performed analysis, quality and accuracy of data acquired for the purpose of the simulation model, and the knowledge and experience of the creator of the simulation model with the work with a concrete simulation system. The subsequent correct evaluation of the results and the definition of conclusions for the implementation of measures in practice are equally important as well.

2. Literature review

In order to be able to understand the essence of the functioning of the means of simulation, it is necessary to define and understand the basic principles and relations of simulation and modelling and the parts concerned. The goal of a simulation is to obtain information about the system and its elements according to presumed or defined change of characteristics of the elements and their connection.

A simulation of the systems makes it possible to experiment besides real objects, resp. these objects do not have to exist. Simulation as a term means an imitation of some real situation, thing, condition, action, event of process [1, 2]. Simulation is a research method, the essence of which consists of the replacement of an essential dynamic system by its model, simulator, and we perform experiments with the purpose of getting the information about the essential system. Using a simulation, it is possible to obtain answers to some very important questions, such as: "How is the system going to behave when the following (any) changes happen? Which part of the system contains critical points? How long is the distance the conveyor must overcome if two more stations are added in the system? How long will it take to run the production? How many people are needed to meet the deadline of the project?". In a simplified way, it is possible to characterize simulation by three steps:

- design of the simulation model of a real system,
- carrying out the experiments with the simulation model,
- reversed use of the obtained results to improve the system.

In our view, the objects of the simulation will be production processes representing the processes in the group of aggregates, machines and devices, on which the production processes are progressing. The amount of the production operations depends on the type of product and on the used devices, on which the production operations are taking place. Continuous production processes are the processes leading to a smooth, continuous change of the state of the production process (work of the breaker, mills, and conveyor belts). Discrete (discontinuous) production processes are the processes leading to a change of the state of the production process at certain time moments (transport of material by cars, wagons, loading of materials by an excavator). Combined production processes are characterized by combining the discrete and continuous production processes (transport of material by cars from quarry into a ball crusher).

The origins of the creation of simulation models goes back to the 1950's, when universal, general programming systems were used to create simulation models. A gradual development and progress is every area of production, science and practice required increasingly difficult

simulation models and applications. General programming systems proved to be maladroit and not dynamic enough to create fast changes in the simulation models. A special category of programming systems has gradually been invented. These systems are called simulation systems.
Simulation systems are adapted for the purposes of simulation. They allow us to create program simulation models in such form to create models representing the simulated systems [3-5]. The simulation models allow us to perform quick changes in the created models, in case they are needed, in such a way that the created models correspond to the changes that can occur in a real system.

The evolutional phases of the simulation systems change in time and naturally evolve [6]. The recent state is characterized by object and realistically oriented simulation with the support of 3D animations and video on a professional level. According to the functional aspects of the simulation, simulation systems are oriented to activities, events and processes, wherein a change of state can occur continuously, discretely or in a combined form [6-8].
Each area of problem solving relating to logistics combines and uses the required methodology, methods, procedures and tools specific to the given area, but also the methods of other areas. The variability of some solutions within the logistics clearly predetermines the usage of methods based on the principle of multi-criteria decision-making, statistics, modelling, the principles of heuristics and computer simulation [9-11].
To achieve the highest performance with maximum production efficiency, logistics, from the strategic, tactical and operational levels, defines respectively proposes actions that lead to achievement of the required results by using all the available means of science and technology, economics and computer science [12, 13].

The aim of logistics is to create a united, integrated, optimized material flow, which is arisen from different parts of the system in the way to ensure a continuous exchange of goods and services [14]. Logistics has gradually been developing and many definitions have also been developed together with it, while new perspectives on its scope and its level of activity are still being formed. According to Hesket, Glaskowsky and Ivie [15], logistics is the management of all activities that facilitate the movement and coordination of offer and demand in creating of time and place benefits. According to Schulte [16], logistics is an integrated, market-oriented planning, creation, implementation and control of flows of material, goods, information from suppliers to enterprises, in enterprises and from enterprises to clients at optimal costs. According to Malindzak [17], logistics is the way, philosophy of flows management (material, information and financial), at which there are applied systematic approach, methods of planning, algorithmic thinking and coordination in order to achieve the global optimization. According to Straka [18], logistics is a system in which there is an affect to elements in order to set coordinated material, information and finance flow, resulting in, respectively, aiming at satisfying customer requirements and respective economic effect. According to Merkuyev, Merjuyeva, Piera and Guasch Petit [19], simulation models have proved to be useful for examining the performance of different system configurations and/or alternative operating procedures for complex logistic and manufacturing systems. It is widely acknowledged that simulation is a powerful computer-based tool enabling decision-makers in business and industry to improve their organisational and operational efficiency. Combining simulation with experimental design or intelligent search has been successfully adopted for simulation optimization [20, 21].

Logistics as a scientific discipline was first defined back in the 50s. Subsequently, there was the development of the MRP I – Material Requirements Planning system. Later in the 60's, the MRP II – Manufacturing Resources Planning system was created, where the original MRP was supplemented by the algorithms for capacity calculations [22]. In the 70s, the method called Just-in-time was discovered for the first time. During the 80's, the advancements in computer technology helped to accelerate the information flows. Later, fully integrated logistics systems gradually started to emerge, which resulted in cost savings and gradual replacement of manual work by mechanisation [23, 24]. The area of logistics covers a variety of technical means, such as the elements of conventional transport, the elements of production facilities, robots [25-27] and, recently, also modern drones [28].

3. Presentation of the problem

The investigated company is focused on timber processing of production of building timber products, such as beams, planks and boards. They are currently very popular for the construction of low cost houses the core of which is formed from beams, planks and boards. That is why there is a high demand for the products of the company for the needs of the building industry. The basic element of the products of the company is timber. The company produces beams, planks and boards of the required dimensions and types by means of timber cutting, edging, planning, milling and trimming. The raw material is supplied from various sources and the main types of woods are oak, beech, spruce and pine. All the types of raw timber for the production companies are represented in the same volume. The supply the production company is carried out by the contracted transport companies supplying one truck of timber of each timber type once a week.

The described production company has its headquarters in the south-east of Slovakia in the vicinity of Košice city. The company provides a complex timber processing, i.e. from the inputs of raw timber through its storage, cutting and drying, to manufacturing of beams, planks and boards. The waste generated during the production is processed in a contracting company to produce pellets and wood chips used for heating.

As there is an increasing demand for the products of the company, which is demonstrated by the increase in the building activities within the region, there are situations during which the company is not able to meet all the requirements of the market in the short term. This is also the reason why the company is interested in identifying the bottlenecks [29] in production and design of the logistics in manufacturing in order to produce and purchase new devices that could increase their production with a minimum investment [30-32]. The entire production process of raw timber processing was developed to its present form only based on the experience of the company operators and workers. Since wood drying is the longest stage in the processing of raw timber in terms of the technological progress, the company bought a drying kiln for the batch drying of wood material. The capacity of the kiln drying device is 40 m^3. Drying in this device takes 50 days on average, according to the type and thickness of the wooden elements. Within the technological process, the raw timber material is gradually shifting through the workplaces: receiving raw timber material and its storage – cutting head saw – edging saw – wood drying – crosscut saw – planning, milling, trimming – products despatch (Fig. 1). Cuttings waste is packed into sacks at special workplace for the disposal of waste.

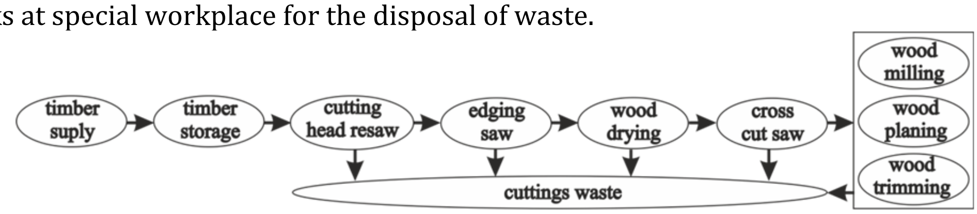

Fig. 1 Schema of the company logistics in the manufacturing system

Capacity utilization of the devices is performed by means of the preparation of raw timber, its drying and the crowdedness of the system in advance. The passage time through the timber manufacturing system depends on the capacity of the individual devices, their cadence and the time necessary for the execution of the manufacturing operation and overloading of the manufacturing system as a whole unit (Table 1). Statistically, most of the time in real operation is required for drying of the raw timber material. The company provides transport of the products to customers by means of outsourcing companies.

Each workstation is equipped with its own buffer necessary for the regulation of different production capacities and to ensure the fluency of production. In each part of the technological process, it is necessary to have an enough semi-finished timber element. That is why a significant amount of semi-finished products and unfinished timber elements is bound in each part of the system and a significant amount of capital is bound in warehousing, resources and in semi-finished products.

Table 1 Parameters of workstations delay, and devices delay in logistics in manufacturing

Timber	Timber entry	Cutting head resaw	Edging saw	Kiln drying	Air seasoning	Cross cut saw	Wood planning	Wood milling	Wood trimming	Packing cuttings waste
Oak	3 pieces / day / type	60 min	3.5 min	75 days	6 months	2 min	5 min	15 min	5 min	5-8 min
Beech		60 min	3.5 min	75 days						
Spruce		40 min	3.0 min	25 days						
Pine		40 min	3.0 min	25 days						

4. Materials and methods

The next step is a prepared comprehensive simulation model of all the activities within the timber material processing, which required a thorough analysis and compliance with the steps formalized scheme: description of production units, block diagram, simulation model, simulation runs, improvement of efficiency of logistics in manufacturing.

4.1 The creation of a formalized scheme

To make the computer simulation model, the first right step is to create a formalized scheme that represents the exact sequence of production operations, interconnecting facilities with the technical resources of the company. This step also involves retrieving the information about the parameters of the material flows in terms of volume distributions. Such a formalized scheme then represents the overall system with its features and links. In this case, the system consists of the individual elements represented by the operations with timber material. Between the operations, there are links formed by the elements of flow management of semi-finished products and of timber waste. A formalized structure (Fig. 2) is a very important basis for the creation of an actual simulation model. The limitations and capacity of the production facilities are important for correct understanding of whole system activity and the elements of logistics in manufacturing. During the subsequent simulation modelling, the individual parts of a formalized scheme will be replaced by a respective block of specific simulation software. Delay parameters (Table 1) are crucial for the setting of the simulation model blocks and for the control and solution of the critical production bottlenecks of the whole manufacturing system.

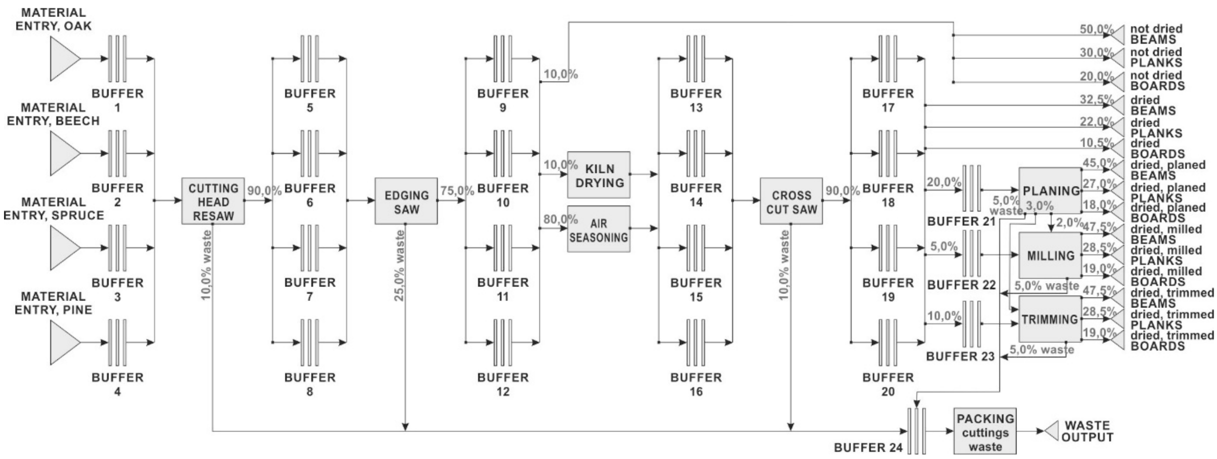

Fig. 2 The formalized scheme of building timber elements production

4.2 The logistics in manufacturing units

The entire manufacturing system and logistics in manufacturing is composed of parts that are arranged in sequence according to the technological procedure. The system is mainly series oriented with the final processing of products according to the required processes. The sequence of production technology is determined by the arrangement of specialized workplaces, which are created by workplace for income and storage of raw timber material, workplace for cutting head resaw, workplace for edging saw, workplace for drying timber, workplace for cross cut saw, workplaces of products finalization as wood planning, wood milling, wood trimming and with workplace for packing of cuttings waste.

The workplace of income and storage of raw timber material ensures the supply of the company with raw timber material, and its primary storage by the type of timber before processing. The company supply is carried out on a weekly basis with a frequency of one truck for each timber type, which represents about 20-24 units of one timber type per week, i.e. approximately 1 piece of timber material per 0.33 day.

The workplace of cutting head resaw involves raw timber material cutting (depending on the thickness and length of timber) to beams, planks and boards. The output of the cutting is represented by unedged timber elements. The processing time of the elements depends on the type of timber. The cutting process of one timber piece of oak and beech requires about 60 minutes and the cutting process of one timber piece of spruce and pine requires about 40 minutes. The average output after cutting is 20 pieces of various wooden elements in the form of beams, planks and boards. The cutting generates 10 % of cuttings waste and 90 % of wooden elements continuing to the next workplace.

The workplace of edging saw is used for adapting and edging of unedged wooden elements. The time for edging of wooden elements depends on the type of timber, but an average time for oaks and beeches edging is about 3.5 minutes, and for spruce and pine edging, the time is about 3 minutes for one piece of wood element. The edging of wooden elements produces 25 % of cuttings waste. After edging of the wooden elements, 10 % is sold in the raw state and 90 % of the elements will be moved to the workplace of wood drying. 10 % goes to the kiln drying, and 80 % is dried in the open stock in natural conditions.

The kiln drying device has a capacity of 40 m^3 for a drying batch. The cut raw timber is dried according to the requirements for the percentage of moisture and for the type of material. In general, the raw timber materials of the oak and beech types are drying for about 75 days and the spruce and pine types are drying form about 25 days. Drying of the raw timber material at the open stock in natural conditions takes about six months for all the types of timber.
After drying, the timber elements are cut to the required lengths at the workplace of crosscut saw. The time for timber elements cutting to the required lengths is about 2 minutes per one piece of timber element. The cutting process generates cuttings waste, which represents 10 % of the timber material capacity.

After cutting, 65 % of the timber elements are ready for sale and export, and 35 % of the timber elements are treated according to special requirements of customers at the workplaces of wood planning, wood milling and wood trimming. The workplaces of wood planning, wood milling and wood trimming provide a service for customers and their requirements for the final machining. The processing time of the wood planning and wood trimming is about 5 minutes for a one piece of any type of timber element. The processing time of wood milling is about 15 minutes for a one piece of any type of timber element. All the final activities produce 5 % of cuttings waste.

All the timber waste is situated in the stock of the packing of cuttings waste workplace. The packing of one waste unit requires about 5-8 minutes. Waste taking is carried out by a contracting firm and its own means of transport. Cuttings waste is used for the secondary recovery and for heating.

4.3 The model of logistics in manufacturing represented by a block diagram

To create a block diagram (Fig. 3) as a basis for the actual simulation model, it is important to prepare the data and the information that are essential for the setting of the individual blocks within the simulation model [33]. From the statistical data obtained from observation and measurement in the field as well as from the technical documentation data [34], it appears that the input of the timber material into system occurs each 0.33 day, when another piece of timber material enters the system. In the simulation model, this is modelled by the four entry blocks "create" for each type of timber with a constant distribution setting of 0.33 day. Just before the first production facility, which is the cutting head resaw, there is an unprocessed timber storage which balances the cadence delays within production and the capacity of the control unit. In the simulation model, this is represented by four blocks "queue" with the setting of "last in first out (LIFO)", material is put on itself. After that, there is a cutting head resaw type of device, where the processing of a single piece of timber ranges from 40 to 60 minutes. In the simulation model, this delay is modelled by a “lookup table” with constant distribution with delay parameters set to 40 minutes or 60 minutes for the processing of one piece and type of timber.

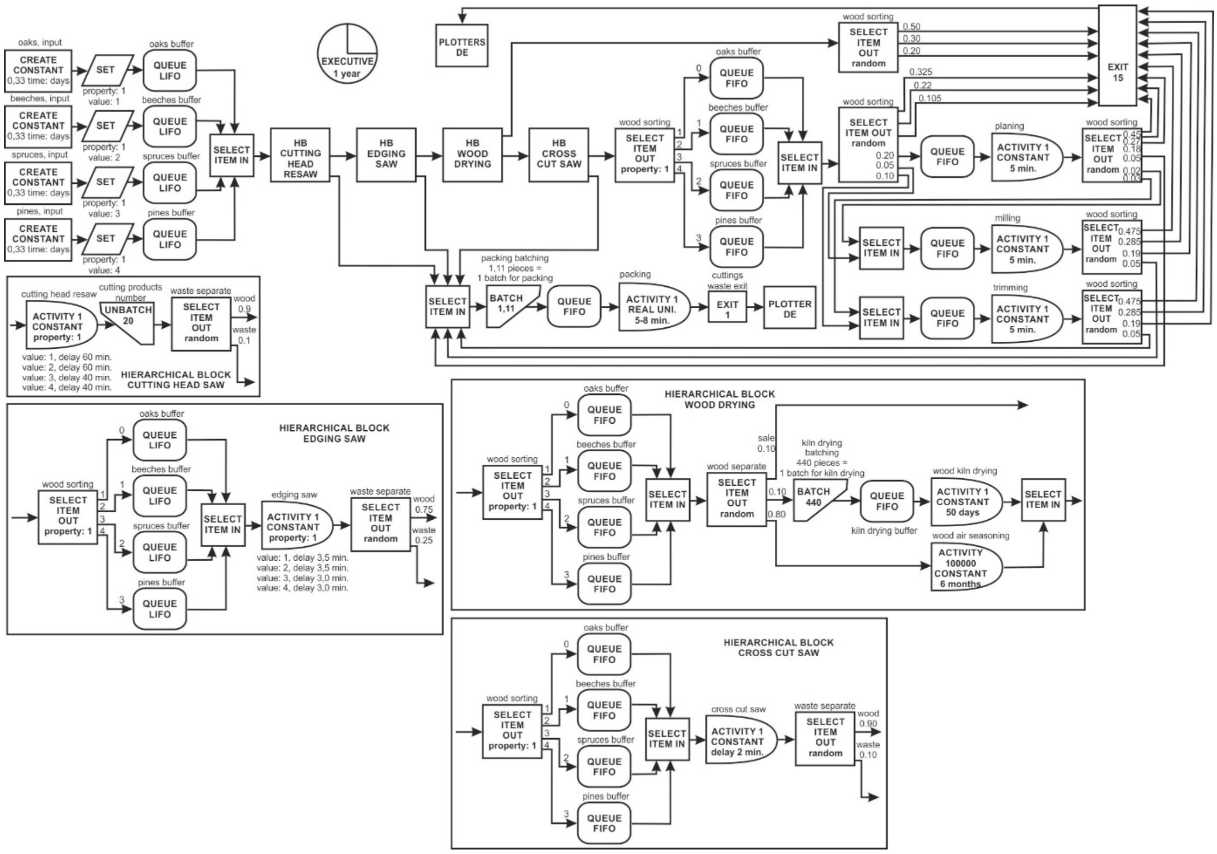

Fig. 3 Block diagram of the building timber elements production

4.4 The logistics in manufacturing of the concrete company designed by the EXTENDSIM

Each real activity, and all the processes and operations of the manufacturing system are necessary to transform and design by the blocks of concrete simulation system EXTENDSIM. Parts of the formal and block diagrams will be translated step by step, block by block to EXTENDSIM simulation model. The entry of timber into the production company, the identification of timber types and the storage of logs are represented by the blocks of "create", “set” and "queue" (Fig. 4). el blocks and for the control and solution of the critical production bottlenecks of the whole manufacturing system.

The place of work of “Cutting head resaw” is modelled in the simulation model using the first “hierarchy block”. The hierarchy block for this operation is created using the blocks of “activity” – “batch” – “select item out” (Fig. 5).

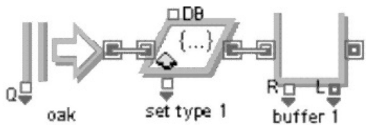

Fig. 4 Blocks "create", “set” and "queue" which represent the entry of timber material into the company, the identification of timber type and the storage of logs

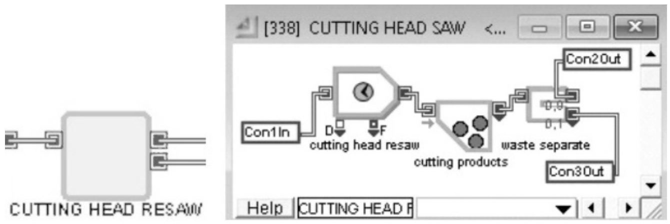

Fig. 5 Blocks of "hierarchy block", “activity”, “batch” and "select item out" which represent the cutting of the timber into semi products such as beams, planks and boards

The place of work of “Edging saw” is modelled in the simulation model using the second “hierarchy block”. The hierarchy block for this operation is created using the blocks of “select item out” – “queue” – “select item in” – “activity” – “select item out” (Fig. 6).

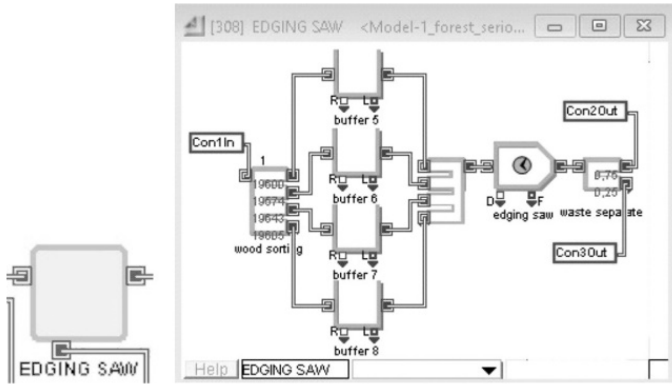

Fig. 6 Blocks of "hierarchy block", “select item out”, “queue”, “select item in”, “activity” and “select item out” which represent the operation edging of the timber

The place of work of “Wood drying” is modelled in the simulation model using the third “hierarchy block”. The hierarchy block for this operation is created using the blocks of “select item out” – “queue” – “select item in” – “select item out” – “batch” – “activity” – “select item in” (Fig. 7).

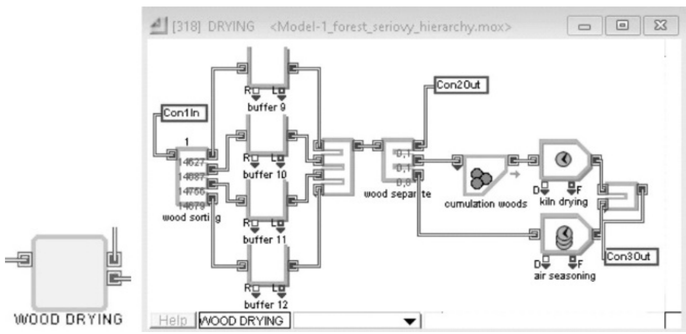

Fig. 7 Blocks of "hierarchy block", “select item out”, “queue”, “select item in”, “select item out”, “batch”, “activity” and “select item in” which represent the operation drying of the timber

The place of work of “Cross cut saw” is modelled in the simulation model using the fourth “hierarchy block”. The hierarchy block for this operation is created using blocks “select item out” – “queue” – “select item in” – “activity” – “select item out” (Fig. 8).

By combining the above described simulation model elements, several selected production processes were modelled, and they represent the actual real-life manufacturing system within the investigated company (Fig. 9).

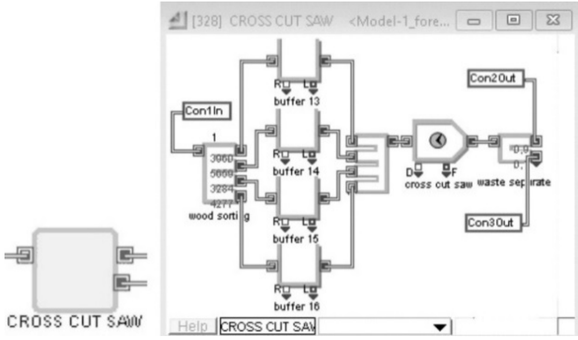

Fig. 8 Blocks of "hierarchy block", "select item out", "queue", "select item in", "activity" and "select item out" which represent the operation cross cutting of the timber

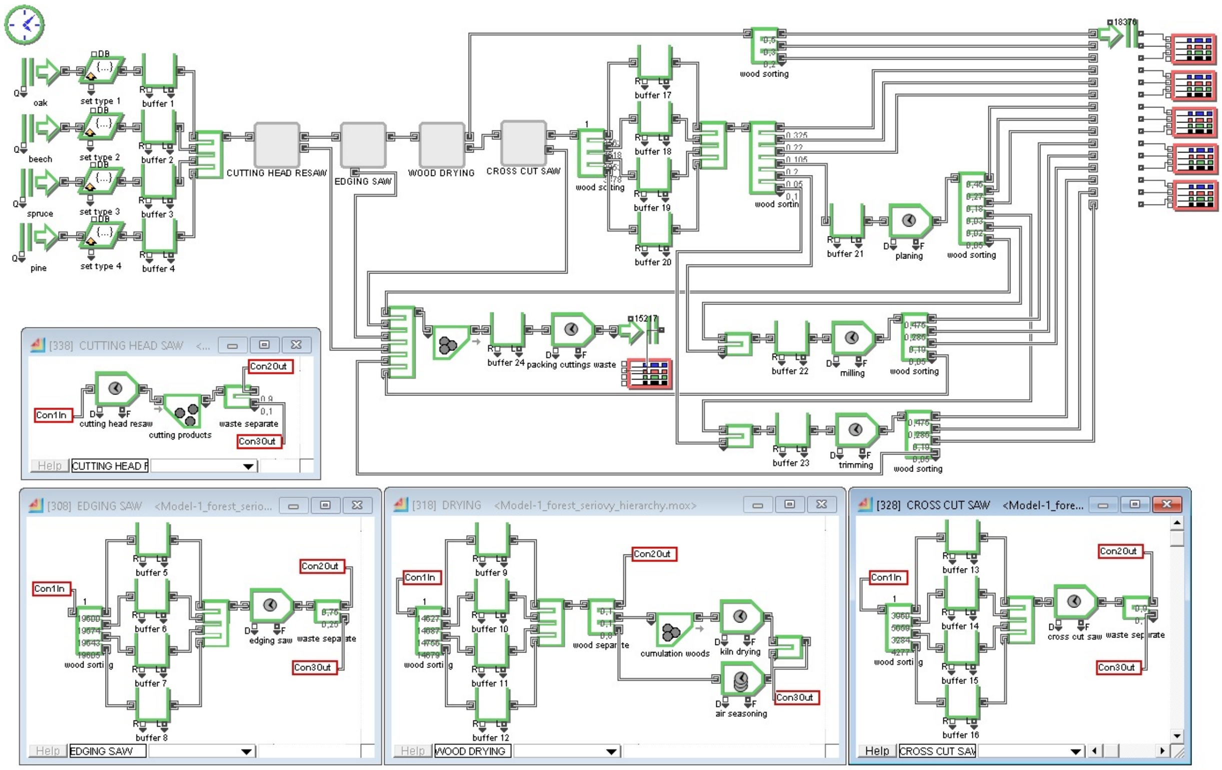

Fig. 9 The simulation model of the researched company building timber production

5. Results

As the simulation results indicate, the drying place of work, namely the facility for drying of timber material is the actual bottleneck. The given state is derived from the simulation analysis and has been verified by the technology management of the company. The findings indicate that this place of work is not sufficiently efficient to process the timber material entering the drying process, which results in an accumulation of unprocessed material (Fig. 10). This stage is solved by means of drying the timber material by air seasoning. This process of drying is extending the time necessary for processing of timber in the manufacturing system and possibly results in gradual degradation of quality timber material and of the company resources.

The simulation results indicate that the company produced a total of approximately 18,000 building timber elements for one year. The most sold building timber materials of the company during the year are the dried and made to measure beams (4,800 pieces), planks (3,309 pieces) and the dried beams of various sizes (1,734 pieces). The utilization of workstations wood planning, wood milling and wood trimming does not exceed 10%, even after the optimization. To increase the utilization of the planning, milling and trimming equipment, the production company must offer these processes used for the finalization of wood elements as a service provided to its customers. This activity can attract new customers for production.

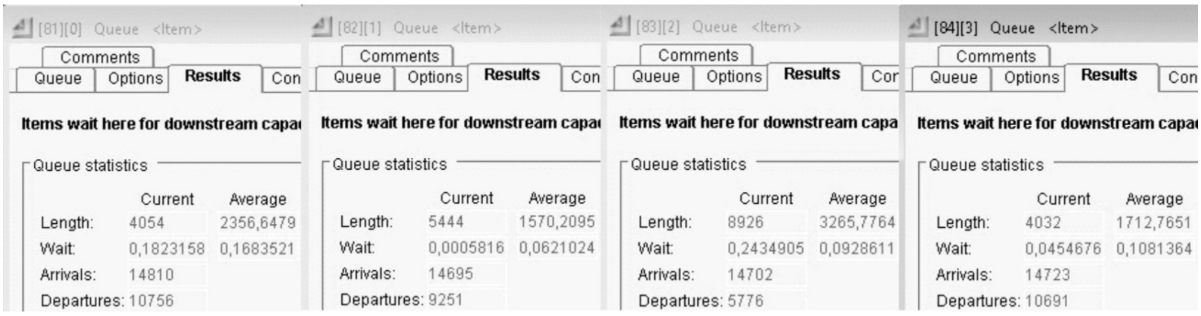

Fig. 10 Length of timber material in blocks of "queue" before processing at kiln drying facility

The researched manufacturing system generates approximately 15,000 pieces of packed cuttings waste units per year. The production of cuttings waste depends on the numbers of processed timber materials and the utilization of production devices. The ratio between the quantity of the incoming material to the manufacturing system and the cuttings waste is approximately 5:1. The ratio between the quantity of the finished products and the cuttings waste is approximately 1.2:1. Other building timber materials are scattered throughout the manufacturing system. This fact makes it possible to state that the store and buffers of the whole manufacturing system contain many unfinished products. The number of elements of unfinished products can be reduced by means of thorough planning of production and by increasing the utilization of the production devices.

The simulation output data show that part of the manufacturing system is overloaded, while other parts of the system have substantial reserves. We have the following possibilities in order to streamline the production:

The streamlining of the manufacturing system activity does not depend on the purchase of new and expensive devices, but only on the change of the logistics in manufacturing and the management of flows. All the workstations of the company have reserves for further development. By changing the management of the company logistics in manufacturing, we will increase the performance of timber drying in the drying device, thereby also increasing the performance of the entire manufacturing system. The company has enough storage capacity and it is therefore possible to increase the intensity of company supply. The simulation results indicate that it is necessary to double the intensity of company supply, i.e. a frequency of entry set to 0.15 days for each timber type. This adjustment increases the performance of unutilized devices and the whole manufacturing system several times, up to 54,475 produced building timber elements, which represents an increase of production by about 199.6 % while maintaining company flexibility (Fig. 11).

This adjustment increases the resources at the input to the system, but the performance of the devices will increase several times and thus the whole manufacturing system. This implies that the intensity of the input material to the system also represents a bottleneck for the produc-

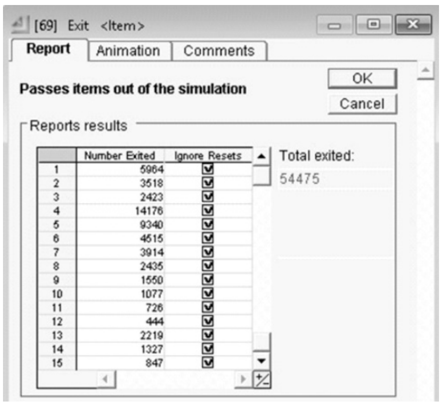

Fig. 11 The increasing utilization of the whole manufacturing system by means of timber supply reorganization

tion. An additional adjustment is related to the preparation of the entry batch for drying in advance, which was described above. The changes in the organization of logistics in manufacturing and the supply of enough input of resources increase the system performance without any necessary investment in new expensive production facilities.

6. Conclusion and questions for discussion

Computer simulation allows users to create simulation models of complex manufacturing systems, detailed orientation in devices, as well as orientation in operations and processes. The utilization of computer simulation, as a scientific method, is very widespread in the area of science, research and practice. The financial, time, material and energy savings and efficiency of the operation in practice are the benefits of the utilization of computer simulation. Simulation software EXTENDSIM, Simul8, Witness, Tecnomatix and other belong to the modern means of simulation, where simulation models are created from blocks, which are kept in libraries, and they are used to build the entire simulation model, similar to building a house from bricks, because their use is easy and intuitive.

In terms of the complexity of technological processes, the creation of their mathematical models is very difficult or even impossible. The conversion itself is protracted and inefficient. The experiments in real operating system are very rare and the main reasons why this experimenting in not used are: experiments with real systems are expensive and lengthy, it is impossible to investigate more variations and more options, important variables are fixed in real operation and it is hard to change them for the purpose of the experiment, experimenting can cause serious system failures, the investigated object does not exist in reality and operation experiments can be dangerous for people or machines, the state changes of the system are too rapid or slow to record the necessary information. Computer simulation of the systems can be executed outside the real objects, without affecting the actual operation, resp. without the existence of the actual investigated system.

The result of a simulation is information about the investigated system and its elements according to the defined parameters. Experimenting with a simulation model sets apart the simulation of systems from other forms of the cognition process. That is why this method is considered as simulation in the narrower sense of the word. The conclusions derived from its usage are applied in all the phases of interactively running simulation process.

The above described case study, where the simulation modelling has been successfully implemented for the needs of a company producing building timber, demonstrates the capabilities of simulation modelling and the advantages of such approach for the advancement of science, as well as for the application in the solution of everyday problems in general practice. The individual parts of the simulated system are described by the sequence of blocks in the model. These blocks are connected by the flow lines with arrows that set the direction of the flows. The recommendations for the above described company, supported by the simulation results, were subsequently applied in practice. The practice has verified the simulation outputs from the EXTENDSIM simulation system and has confirmed the validation of the proposed recommendations. Thanks to the application of EXTENDSIM simulation system, the production capacities have increased in the case study company, which demonstrates the importance of computer simulation use to solve this type of tasks. The assignment goal that was defined in the introduction to this article has been achieved.

In terms of further research, the following questions remain open for consideration:

- How will the increased production performance affect the business position of the company in the market?
- How will the increased production performance affect the whole system and human resources management?

In general, it can be said that computer simulation is an important means for solving problems in the field of logistics in manufacturing, in production and in manufacturing systems [35].

Acknowledgement

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Estimating the position and orientation of a mobile robot using neural network framework based on combined square-root cubature Kalman filter and simultaneous localization and mapping

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ABSTRACT

The real-time performance of target tracking, detection, and positioning behaves not well for non-Gaussian and nonlinear model with circumstance uncertainty. The weak observability of the system under large noise causes the algorithm unstable and slow to converge. A new estimation algorithm combining square-root cubature Kalman filter (SRCKF) with simultaneous localization and mapping (SLAM) is proposed. By connecting neural network weights, network input, functional types and ideal output network, the algorithm firstly update iteratively the SRCKF-SLAM state model and observation model, then conduct the cubature point estimate (weights) neural network framework. Thus, a point set better representing the target state and a more accurate state estimation are achieved, which can improve the filtering accuracy. This paper also estimates robot and characteristic states by filtering in groups. The simulation results showed that the proposed algorithm is feasible and effective. Compared with other filtering algorithms such as SRUKF and SRCDKF, it improves the estimation accuracy. Applying the new algorithm to the position filtering estimation of mobile robot can effectively reduce the positioning error, achieve high-precision tracking detection, and improve the accuracy of robot target detection.

ARTICLE INFO

Keywords:
Robot;
Mobile robot;
Square-root cubature Kalman filter;
Simultaneous localization and mapping;
Sensors;
Artificial neural networks;
Iteration update;
Filter estimate

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1. Introduction

During the navigation process, robot carries various navigation sensors to track and detect the target, and there is a certain error between true value and estimated position of target observed by the sensors. How to improve navigation and positioning accuracy, use appropriate system state models and observation models, and use more appropriate positioning estimation algorithms to reduce navigation errors and other issues have become the core issues in robot navigation and positioning. In the 1988s, foreign scholars proposed simultaneous localization and mapping technology [1], which uses a carrier to carry sensors to complete navigation and localization. This technology has successfully broken the traditional constraints of a priori maps and has been widely concerned and studied. The models in practical engineering applications are mostly non-linear models. The discrete observations of sensors are often used to estimate the continuous state of the target, random noise is filtered out, then state parameters of robot and position information of the target are solved. The method used is the extended Kalman filter algorithm(EKF)[2-3], which expands the Taylor series of non-linear function, and then ignores the higher-order part, and successfully performs the non-linear problem. Linearization, but at the same time introduces a cut-off error, which increases the estimation error. Juliear, Umhlman, Durrant-Whyte, etc. proposed an Unscented Kalman Filtering (UKF) algorithm[4-5]. Based on UT transformation, state quantity and covariance matrix of the system were estimated by weighted average. Then the time update and measurement update obtain the filtered system state quantity equation and its covariance matrix. However, due to the cumbersome matrix decomposition and inversion of the UKF algorithm, the positive definiteness of the state estimation covariance is difficult to guarantee. The cubature Kalman filter(CKF) [6] algorithm generates a new set of $2N$ point sets on the unit sphere after a set of N sampling points with weights undergoes a non-linear cubature spherical radial transformation. The set of points on the heavy unit sphere is then iteratively updated by the state equation to capture the relevant parameters such as the mean and variance of the state quantities. The cubature radial criterion is used to approximate the nonlinear model to integrate the probability density and finally obtain a higher-precision nonlinearity filter effect.

When the standard CKF algorithm solves the SLAM problem, the numerical value is unstable during the recursion process due to the large amount of calculation. Reference [7] proposed a Strong Tracking Filter (STF) cubature Kalman filter algorithm. The introduction of a fading factor realized the online adjustment of the gain matrix, thereby maintaining the high tracking and positioning ability when the system dimension suddenly changed, but also increased computational complexity. In this regard, covariance matrices of a series of adaptive high-order cubature Kalman filtering (HCKF), CDKF and other algorithms also introduce a fading factor to improve the strong tracking ability, but all have their own numerical calculation and filtering accuracy problems. On the other hand, with the growing of intelligent algorithms, in solving the problem of measurement noise uncertainty in navigation, reference [8] proposed a fuzzy iterative cubature Kalman filter algorithm (FISCKF), which uses fuzzy control to adjust model parameters to improve to a certain degree of accuracy. In view of the large calculation amount and numerical problems of the above algorithms, and under large initial error or large observation noise, the observability of the system is weak, leading to problems such as unstable filtering algorithms and slow convergence speed [9]. This paper follows the filter of square-root form. By recursively updating square-root form of covariance matrix, it can not only reduce the computational complexity, but also ensure the symmetry and semipositive definiteness of covariance matrix and improve accuracy and stability of the filtering . The learning and training of neural networks can be regarded as seeking the best weight parameter through optimal estimation [10-11]. The weight matrix and network output values can be regarded as state quantities and measured values, respectively, and described by state space training. Since neural networks do not need accurate mathematical models, and have good convergence and robustness, so a SRCKF-SLAM with neural network framework algorithm is proposed. The weights of neural network are associated with network input, function type and ideal network output respectively, and neural network framework is performed on the weights of SRCKF to obtain a cubature point set that can better characterize the state of the target. In order to more clearly analyze the superiority of SRCKF neural network framework for non-linear filtering estimation problem of target tracking, this paper carried out comparative experiments of SRCKF, SRUCF, and SRCDKF, and carried out corresponding experimental analysis.

2. Materials and methods

2.1 Proposed SRCKF-SLAM algorithm

In the cubature transformation, the numerical integration of a set of cubature points with equal weight is used to approximate the Gaussian integral of the above formula, that is,

$$I = \int_{U_n} f(y)p(y;\mu,\Sigma)dy \approx \frac{1}{2n_y}\sum f\left(\sqrt{\Sigma}\xi_i + \mu\right) \quad (1)$$

Where, y is n_y dimension vector; The non-linear function is $f(\cdot)$; p is the probability density under a Gaussian distribution. cubature points that are orthogonal to each other at the coordinates $\xi_i = \sqrt{n}\{[1]_i\}, i = 1,2,\cdots,2n$ in the i dimensional coordinate system. When $n = 2$, the cubature point base in a 2-dimensional coordinate system is $\sqrt{2}\left\{\begin{bmatrix}1\\0\end{bmatrix},\begin{bmatrix}0\\1\end{bmatrix},\begin{bmatrix}-1\\0\end{bmatrix},\begin{bmatrix}0\\-1\end{bmatrix}\right\}$.

The SLAM problem is decomattituded into robot and feature map state quantities x_v and x_m.

$$x_m = [\mu_{k,1}, \mu_{k,2}, \cdots, \mu_{k,m}] \tag{2}$$

Feature map state quantity, including the specific state of each feature in the map, where $\mu_{k,i}, i = 1,2,\cdots,m$ represents the state of the the i-th feature point at k moment and is added to the map database.

Synthesis of two parts of state quantities, namely:

$$s_k = [x_{k,v}, x_{k,m}]^T = [x_{k,v}, \mu_{k,1}, \mu_{k,2}, \cdots, \mu_{k,i}, \cdots, \mu_{k,m}]^T, i = 1,2,\cdots,m \tag{3}$$

Where, $\mu_{k,i}$ representing state value in the i-th feature point at k moment.

Then describe the SLAM problem as a Bayesian model as

$$p(s_k|z^{1:k}, u^{1:k}) \sim N(s_k; \hat{s}_k, P_k) \tag{4}$$

Where, $z^{1:k}$ is observed by the sensor from 1 to k; $u^{1:k}$ is robot motion control information from time 1 to k. Then the SLAM filtering problem is the process of solving the optimal estimate $\hat{s}_k$ of the system state quantity s_k and its covariance P_k and then updating it. Assuming that robot state model and the map feature model obey the Gaussian normal distribution, the SLAM Bayesian model of the above formula is expressed as a prior estimation form:

$$p(s_k|z^{1:k-1}, u^{1:k}) \sim N(s_k; \hat{s}_{k|k-1}, P_{k|k-1}) \tag{5}$$

From Markov chain hypothesis, the formula (5) is simplified to the following form:

$$p(s_k|z^{1:k-1}, u^{1:k}) = \int p(\hat{x}_k|\hat{x}_{k-1}, u^{1:k}) \cdot p(s_k|z^{1:k-1}, u^{:k-1}) ds_{k-1} \tag{6}$$

The prior estimation model is expressed as the system joint posterior probability density form:

$$p(x_{v,k}, x_{m,k}|z^k, u^k) = p(z_k|x_{v,k}, x_{m,k}) \int p(x_{v,k}|x_{v,k-1}, u^k) \cdot p(x_{v,k}, x_{m,k}|u^k, z_{k-1}) dx_{v,k-1} \tag{7}$$

Where, u_k is control input, drive $x_{v,k-1}$ to $x_{v,k}$; z_k is characteristic measurement of robot at position $x_{v,k}$ at time k. $p(x_{v,k}|x_{v,k-1}, u_k)$ is motion model which is the probability of downloading robot posture $x_{v,k}$ at time k, on the premise that control input u_k at time k and robot posture $x_{v,k-1}$ at time $k-1$ are known; $p(z_k|x_{v,k}, x_{m,k})$ is observation model which is the conditional probability of obtaining observation z_k under premise of $x_{v,k}$ and $x_{m,k}$.

For nonlinear motion models:

$$\begin{cases} x_{v,k} = f(x_{v,k-1}, u_k + \delta u) \\ z_k = h(x_{v,k}) + \delta z \end{cases} \tag{8}$$

Where, $f(\cdot)$ and $h(\cdot)$ are system nonlinear function and observation function, respectively. System noise and observation noise are represented here by $\delta u \sim N(0, Q)$ and $\delta z \sim N(0, R)$. u_k represents robot motion control information; let system dimension be n_s; the feature dimension be n_m; then system joint state quantity is:

$$s_k = [x_{k,v}, x_{k,m}]^T = [x_{k,v}, \mu_{k,1}, \mu_{k,2}, \cdots, \mu_{k,i}, \cdots, \mu_{k,m}]^T, i = 1,2,\cdots,m \tag{9}$$

Then robot state vector at two neighboring moments can be expressed as the attitude information of robot itself and extended state vector of system's input control information, that is, $\chi_k = [s_k u_k]^T$ decomposing the covariance matrix into $P_k = \zeta_k \zeta_k^T$, then the extended square-root covariance matrix is $S_k = diag[\zeta_k \sqrt{Q}]$. When the algorithm is updated, the object of action is square-root covariance subformula, so here it is square-root covariance subformula ζ_k and its extended subformula S_k.

SRCKF algorithm includes the following steps:

(1) Time update phase

① Calculate the cubature point set from state system dimension $(n_s + n_m)$ to $2(n_s + n_m)$ dimension of the joint system:

$$\hat{x}_{k-1}^{i} = S_{k-1}\xi_i + \chi_{k-1}, i = 1,2,\cdots,2(n_s + n_m) \tag{10}$$

Where, i-th joint cubature point state quantity includes i-th robot attitude information cubature point and i-th map characteristic cubature point, that is,

$$\hat{x}_{k-1}^{i} = \left[x_{k-1,v}^{i}, x_{k-1,u}^{i}, x_{k-1,m}^{i}\right]^T = \left[x_{k-1,v}^{i}, x_{k-1,u}^{i}, \mu_{k-1,1}^{i}, \mu_{k-1,2}^{i}, \cdots, \mu_{k-1,j}^{i}, \cdots, \mu_{k-1,m}^{i}\right]^T, j = 1,2,\cdots,m \tag{11}$$

Where, $x_{k-1,v}^{i}$ and $x_{k-1,m}^{i}$ are robot and characteristic position information, respectively; $x_{k-1,u}^{i}$ is control input amount to robot.

② Cubature points are propagated through equation of state, and the prior estimates (weights) are calculated as:

$$\hat{x}_{k|k-1}^{*i} = f\left(x_{k-1,v}^{i}, x_{k,u}^{i}\right) \tag{12}$$

③ According to cubature seeking rule, square-root covariance of robot attitude estimation can be calculated:

$$S_{k|k-1} = qr\left(S_{k|k-1}^{*} S_{Q,k-1}\right), Q_{k-1} = S_{Q,k-1} S_{Q,k-1}^{T} \tag{13}$$

④ Apply cubature transformation to approximate the third-order state of robot.

$$\chi_{k|k-1,v}^{i} = \frac{1}{2(n_s+n_m)} \sum_{i=1}^{2(n_s+n_m)} \hat{x}_{k|k-1,v}^{*,i} \tag{14}$$

Where, qr means the matrix is decomposed into lower triangle and upper triangle forms; and covariance prediction value is:

$$P_{k|k-1} = \frac{1}{2(n_s+n_m)} \sum_{i=1}^{2(n_s+n_m)} \hat{x}_{k|k-1}^{*,i} \left(\hat{x}_{k|k-1}^{*,i}\right)^T - \hat{x}_{k|k-1}\hat{x}_{k|k-1}^{T} + Q_k \tag{15}$$

⑤ Estimation (weight) and state error innovation are represented by $S_{k|k-1}^{*}$.

$$S_{k|k-1}^{*} = \frac{1}{\sqrt{2(n_s+n_m)}} \left[\hat{x}_{k|k-1}^{*,1} - \chi_{k|k-1}^{1}, \hat{x}_{k|k-1}^{*,2} - \chi_{k|k-1}^{2}, \cdots, \hat{x}_{k|k-1}^{*,2(n_s+n_u)} - \chi_{k|k-1}^{2(n_s+n_u)}\right] \tag{16}$$

(2) Measurement update phase

The i-th feature point observation generalized from the nonlinear observation model is expressed as the posterior estimation formula:

$$z_{k|k-1}^{i} = h\left(x_{k|k-1,v}, x_{k|k-1,m}^{i}\right) + \delta z = h\left(x_{k|k-1,v}, \mu_{k|k-1}^{i}\right) + \delta z \tag{17}$$

Where, $x_{k|k-1,v}$ is attitude information of robot in the prior estimation, which does not change with observation of a certain feature point; $\mu_{k|k-1}^{i}$ is estimated value of i-th feature point at time $k-1$; Observation noise is $\delta z \sim N(0, R)$.

① First calculate the i-th cubature point.

$$\hat{x}_{k-1}^{i} = \zeta_{k|k-1}\xi_i + x_{k|k-1}, i = 1,2,\cdots,2(n_s + n_u) \tag{18}$$

$$\hat{x}_{k-1}^{i} = \left[x_{k|k-1,v}^{i}, \upsilon_{k|k-1,1}^{i}, \upsilon_{k|k-1,2}^{i}, \cdots, \upsilon_{k|k-1,m}^{i}\right] \tag{19}$$

is cubature point set of i-th cubature point $x_{k|k-1,v}^{i}$ of robot's own state and i-th cubature point $\upsilon_{k|k-1,j}^{i}$ of j-th characteristic state quantity, $j = 1,2,\cdots,m$.

② Propagation cubature point

$$z_{k|k-1}^{i,j} = h\left(x_{k|k-1}^{i}, v_{k|k-1,j}^{i}\right) \tag{20}$$

③ According to the rule for finding the cubature, calculate the observation and prediction values:

$$\hat{z}_{k|k-1}^{i} = \frac{1}{2n_s}\sum_{j=1}^{2n_s} z_{k|k-1}^{i,j} \tag{21}$$

④ Calculate observation and forecast estimate (weight) covariance error innovation square-root formula:

$$S_{zz,k|k-1} = qr\left\{\left[\varepsilon_{k|k-1}^{i}\sqrt{R}\right]^{T}\right\} \tag{22}$$

Where, $R_k = S_{R,k}S_{R,k}^{T}$. Innovation error is:

$$\varepsilon_{k|k-1}^{i} = \frac{1}{\sqrt{2n_s}}\left[z_{k|k-1}^{i} - \hat{z}_{k|k-1}^{i}\right],\ i = 1,2,\cdots,2n_s \tag{23}$$

$$\varepsilon_{k|k-1}^{i} = \frac{1}{\sqrt{m}}\left[z_{k|k-1}^{i} - \hat{z}_{k|k-1}^{i}\right],\ i = 1,2,\cdots,m \tag{24}$$

⑤ Square-root of estimated (weight) cross-covariance is:

$$P_{xz,k|k-1} = \zeta_{k|k-1}\left(\varepsilon_{k|k-1}^{i}\right)^{T} \tag{25}$$

$$\zeta_{k|k-1} = \frac{1}{\sqrt{2n_s}}\left[\hat{x}_{k|k-1}^{*,1} - \hat{x}_{k|k-1,v}, \hat{x}_{k|k-1}^{*,2} - \hat{x}_{k|k-1,v}, \cdots, \hat{x}_{k|k-1}^{*,2n_s} - \hat{x}_{k|k-1,v}\right]^{T} \tag{26}$$

Kalman gain is:

$$W_k = \left(P_{xz,k|k-1}/S_{zz,k|k-1}^{T}\right)S_{zz,k|k-1} \tag{27}$$

According to Kalman gain expression in CKF algorithm, square-root of correlation error covariance can be obtained:

$$S_{k|k} = qr\left[\zeta_{k|k-1} - W_k\varepsilon_{k|k-1}, W_kS_{R,k}\right] \tag{28}$$

Under the given initial conditions, after the state prediction update iteration of SRCKF-SLAM algorithm, system's state estimation is obtained, and robot's navigation in the environment and positioning and observation of target are achieved. However, with the creation of SLAM map database, the cubature point set and its weights have been continuously updated and expanded, which has led to a reduction in the algorithm's filtering estimation accuracy. A neural network framework based on SRCKF-SLAM algorithm is proposed to reduce square-root cubature points. The weight matrix of set and the output value of network are regarded as state quantities and measured values, respectively, and state space is used to describe training.

2.2 Neural network structure model

Let the number of nodes in input layer of neural network be n, the number of nodes in hidden layer be m, and output layer be a non-time-varying neuron node. Then network model is shown in the Fig. 1 [12]:

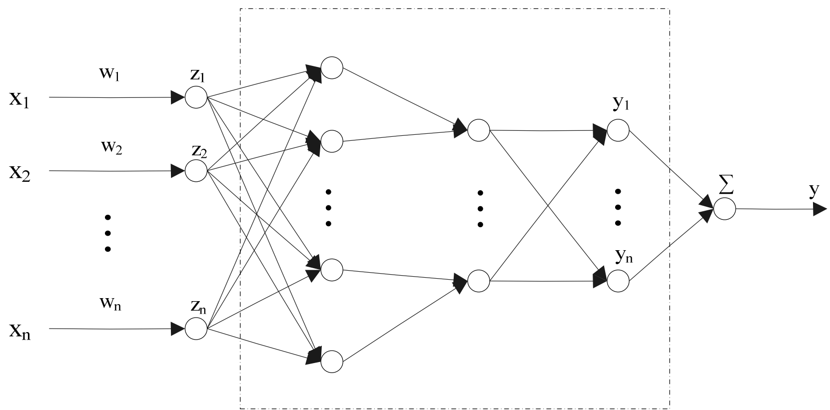

Fig. 1 The model of neural network

Let dimension of input signal be n, so the number of samples is the same as the dimension of input signal. In Fig. 1, $x_1, x_2, \cdots, x_n$ is input signal to be trained, and its corresponding weight is: $w_1, w_2, \cdots, w_n$. The function at each input node of hidden layer is $z_i = x_i w_i$.

Input signal of output layer is:

$$z = \sum_{i=1}^{n} x_i w_i = x^T w \tag{29}$$

The general formula for nonlinear relationship between output of neural network and input is:

$$y = f\left(\sum_{j=1}^{m} v_j \psi\left(\frac{\int_0^T \sum_{i=1}^{n} x_i(t) w_{ij}(t) dt - b_j}{a_j}\right)\right) \tag{30}$$

Where, x_i and y are network input and output. $\psi(\cdot)$ is hidden layer excitation function. $a_j$is the scaling function factor. b_j is translation function factor. $f(\cdot)$ is activation function of output layer. $w_{ij}(t)$ is the weight between j-th neuron in hidden layer and the i-th neuron in input layer, and v_j is the weight between output layer and the j-th neuron in hidden layer.

It is generally believed that increasing the number of hidden layers can reduce network errors, but also complicate network. Generally, the design of neural networks should give priority to 3-layer networks. When accuracy allows, reduce the number of nodes in hidden layer as much as possible [13-15]. State space of network consists of a weight matrix, network input and output, weight update functions, and parameterized non-linear functions. Assuming that there are I and J neurons in each of the two adjacent network layers, the weight matrix between the two layers is W_{IJ} and the weight space of neural network is $W = \{\sum W_{IJ}\}$.

Let W_{IJ} be the weight matrix between layer I and layer J consisting of $w_{ij}(i = 1...I; j = 1...J)$. Unitized weight matrix is W_{IJ}:

$$W_{IJ} = F_1(w_{ij}) = \frac{w_{IJ}}{\sqrt{\sum_{i=1}^{I} \sum_{j=1}^{J} w_{ij}^2}} \tag{31}$$

The optimal estimate of the cubature point weights (state quantities) of SRCKF is obtained through neural network framework. State space model of neural network with weight as state quantity can be expressed as:

$$\begin{cases} w_{k+1} = F_k w_k + q_k \\ z_k = \psi_k(w_k, \tilde{x}_k) + r_k \end{cases} \tag{32}$$

Where, two kinds of Gaussian noise obey $q_k \sim N(0, \tilde{Q})$ and $r_k \sim N(0, \tilde{R})$, respectively. Output of neural network at time $k + 1$ is the iterative training result of the observation equation of network, which is determined by network weights and network observation noise at time k; F_k and ψ_k represent the linear state mapping and observation nonlinear mapping of network. Article selection is $F_k = I_k$.

3.Results and discussion

3.1 Neural network framework based on proposed SRCKF-SLAM algorithm

Establish a neural network framework and tracking algorithm based on SRCKF-SLAM. The process includes:

(1) Update iterative formula according to the state of SRCKF-SLAM, generate and propagate cubature points, solve the prior estimates of the attitude of robot and calculate robot's attitude information and square-root covariance.

(2) Set the initial weight for the innovation error (weight) between the observation and estimation of the cubature point state with the new square-root sub-form in SRCKF in step (1) as the input of neural network. Hermit function is selected as excitation function, a network state space

model is established to train the SRCKF state quantity, and the filtered new optimal estimate and gain are obtained as output of neural network, which together serve as the next state parameter update.

The result of the expected output vector is that the position error of the feature point is required to be minimal, so network output layer node is set to 3 (Observe coordinates in the x-direction and y-direction, and observation angle of robot heading angle φ), so network input layer vector is constrained, and the number of nodes is set to 5 (Coordinates in the x-direction, coordinates in the y-direction, the size of robot's heading angle φ, and controls input noise and observation noise), hidden layer is first set to 10 nodes and is automatically adjusted by Matlab software after network training programming.

(3) Bring the trained estimates (weights) into the SRCKF algorithm to iterate, propagate cubature points and calculate state update parameters.

Square-root of the estimated cross-covariance in step (1) is improved to a neural network framework state model as:

$$\tilde{P}_{xz,k|k-1} = \sum_{i=1}^{m} w_i \zeta_{k|k-1} \left(\varepsilon_{k|k-1}^{i}\right)^T \tag{33}$$

Kalman gain is:

$$\widetilde{W}_k = \left(\tilde{P}_{xz,k|k-1} / S_{zz,k|k-1}^T\right) S_{zz,k|k-1} \tag{34}$$

According to Kalman gain expression in CKF algorithm, square-root of correlation error covariance can be obtained:

$$S_{k|k} = qr\left[\zeta_{k|k-1} - \widetilde{W} \varepsilon_{k|k-1}, \widetilde{W} S_{k|k}\right] \tag{35}$$

3.2 Verification and analysis of feature map simulation experiments based on SLAM

Let initial state of robot be zero. Initial values of robot and feature covariance are $P_{v0} = \text{diag}[330]^T$ and $P_{m0} = \text{diag}[0.20.20]^T$, so sensor sampling frequency is $T = 0.02s$. System noise and observation noise are $Q = \begin{bmatrix} 0.2^2 & 0 \\ \left(\frac{2\pi}{180}\right)^2 & \left(\frac{3\pi}{180}\right)^2 \end{bmatrix}$, $R = \begin{bmatrix} 0.1^2 0 \\ 0 \left(\frac{\pi}{180}\right)^2 \end{bmatrix}$. Robot motion parameters are as follows: speed $v = 2$ m/s, speed error $\sigma_v = 0.2$ m/s, angular velocity $\alpha = 15$ °/s, ranging error 0.25 m, angle error $\sigma_\alpha = 1°/s$. In the experimental environment (Fig. 2), SRCKF-SLAM, SRUKF-SLAM, SCDKF-SLAM were subjected to 50 independent repeated simulation experiments, so the estimation errors in the x-direction and y-direction of robot path were analyzed and compared.

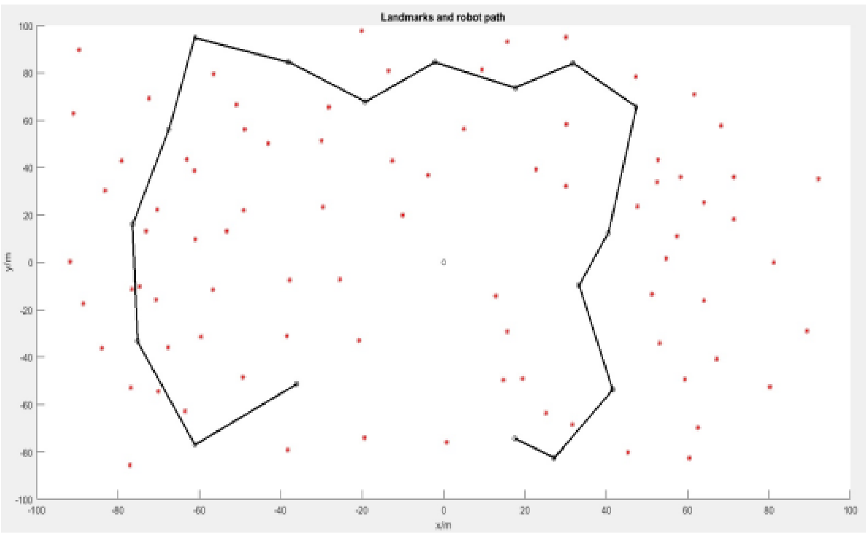

Fig. 2 Simulation area

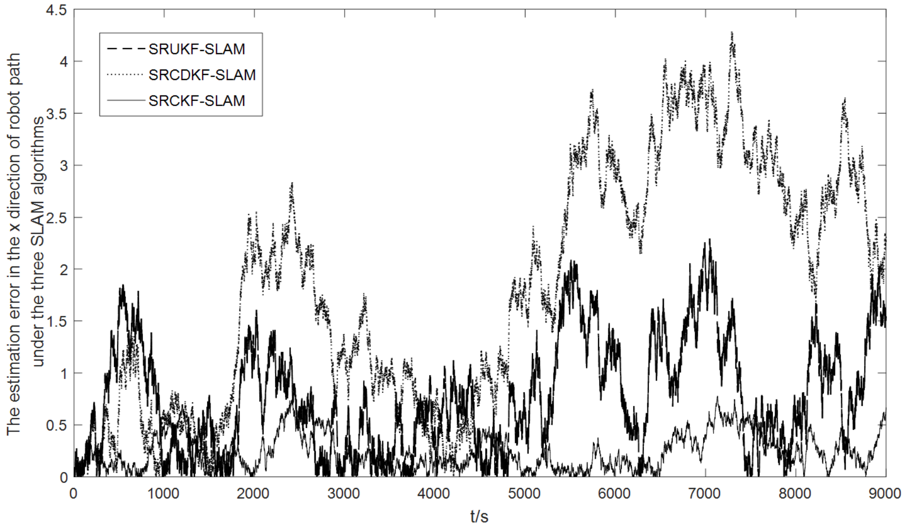

Fig. 3 The estimation error in the x-direction of robot path under the three SLAM algorithms

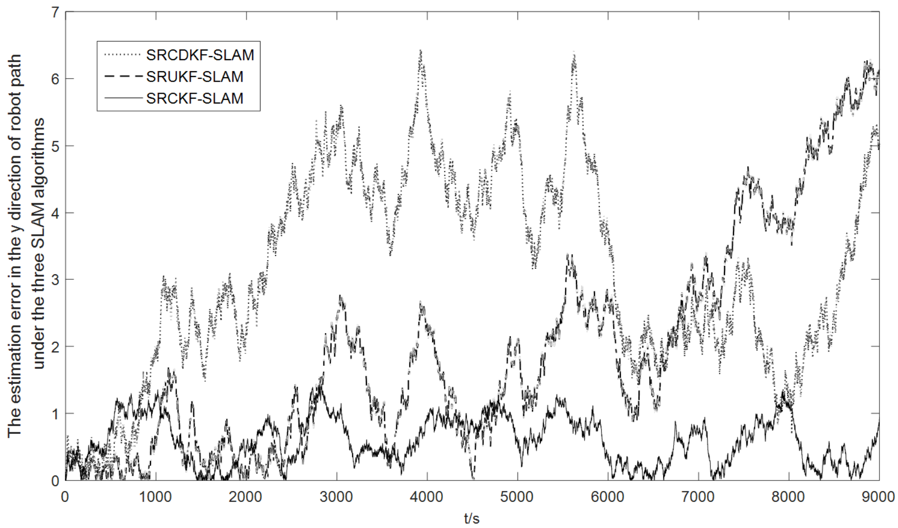

Fig. 4 The estimation error in the y-direction of robot path under the three SLAM algorithms

It can be seen from Figs. 3 and 4 that the position estimation error in the x-direction of robot path obtained using SRCKF-SLAM algorithm is [0, 0.8] m, and position estimation error in the y-direction is [0, 1.2] m. Compared with SRUCF-SLAM and SRCDKF-SLAM filter estimation errors, the filter estimation error is the smallest, and the filter estimation accuracy is superior to them. The experimental data fully proves that using SRCKF-SLAM algorithm for mobile robot navigation and positioning estimation can achieve high accuracy and good stability. Then compare the superiority of the target feature position of cubature point estimation (weight) under neural network framework based on the new and traditional SRCKF-SLAM algorithm.

3.3 Experimental verification and analysis of neural network frameworks based on SRCKF-SLAM

- *Simulation experiment and analysis of feature position estimation*

Hermit function is selected as excitation function, and the expression is:

$$f(x) = \frac{1.1(1-x+2x^2)\exp\left(-\frac{x^2}{2}\right)}{2} \tag{36}$$

Initialization algorithm can effectively reduce overshoot and shorten the convergence time of algorithm. Network itself has a certain good weight, so this difference can effectively reduce the possibility of divergence during network learning process. In this paper, initial network weight w is a random number between $[-1,1]$, and the noise follows normal distribution[0,0.1], the learning rate is 0.4, the momentum term coefficient is 0.6, and the number of learning times is 800. According to the function expression, P0 is 0.55, a = 0.2, b = 0.01.

In order to better compare the filtering estimation accuracy of SRCKF-SLAM filtering estimation algorithm of the cubature point weights and the traditional SRCKF-SLAM algorithm after neural network, increase the system noise and observation noise, set

$$Q = \begin{bmatrix} 0.2^2 & 0 \\ \left(\frac{2\pi}{180}\right)^2 & \left(\frac{3\pi}{180}\right)^2 \end{bmatrix}, R = \begin{bmatrix} 0.1^2 \left(\frac{\pi}{180}\right)^2 \\ 0 & \left(\frac{\pi}{180}\right)^2 \end{bmatrix}.$$

Other initial conditions remain unchanged, and 50 independent repeated simulation experiments are performed, and the estimated errors in the x-direction and y-direction of the target feature position are analyzed and compared.

From Figs. 5 and 6, it can be seen that under the conditions of increasing system noise and observation noise, as the simulation progresses, due to the setting of the reference path, the walking direction of robot is constantly changing, so the position estimation error has fluctuations during the simulation. The traditional SRCKF-SLAM algorithm's position estimation errors in the x-direction and y-direction are respectively [0, 1.8] m and [0, 2.6] m. The filtering algorithm based on SRCKF-SLAM's cubature point estimation (weight) after neural network framework, the position estimation errors in the feature x-direction and y-direction are respectively [0, 1.2] m, [0, 1.7] m. The filtering estimation accuracy is higher than the former, which is consistent with the theoretical analysis.

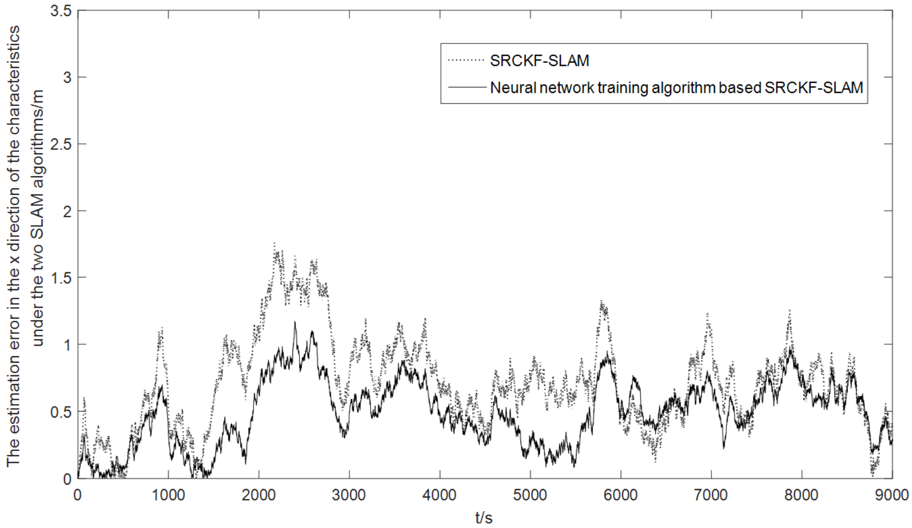

Fig. 5 The estimation error in the x-direction of the characteristics under the two SLAM algorithms

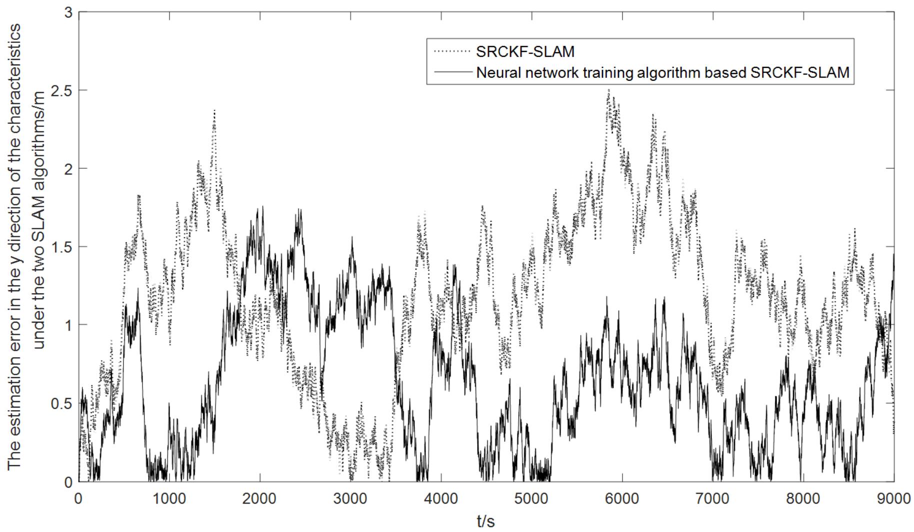

Fig. 6 The estimation error in the y-direction of the characteristics under the two SLAM algorithms

- *Observation of features under different SLAM algorithms*

Based on SLAM filtering algorithm, the position error observations in the x-direction and y-direction of features are collected.

Observe the characteristics in Fig. 2 of the simulation area. The three filtering algorithms using the SRUCF-SLAM, SRCKF-SLAM and SRCKF-SLAM cubature point weight training algorithms all observe 82 feature points, indicating that the new algorithm is feasible for SLAM feature target observation. It can be seen from Figs. 7 and 8 that the above-mentioned three algorithms reduce the position error in the x-direction and the y-direction of the features in turn, indicating that the SRCKF-SLAM algorithm after the cubature point weights are trained by network has the highest accuracy. And the algorithm error is convergent and stable, which is consistent with the theoretical analysis.

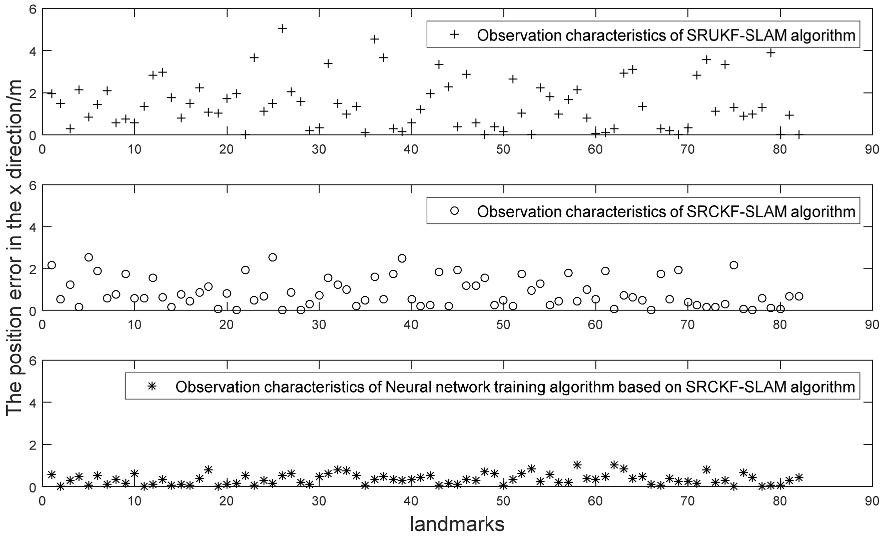

Fig. 7 The position error in the x-direction of landmarks

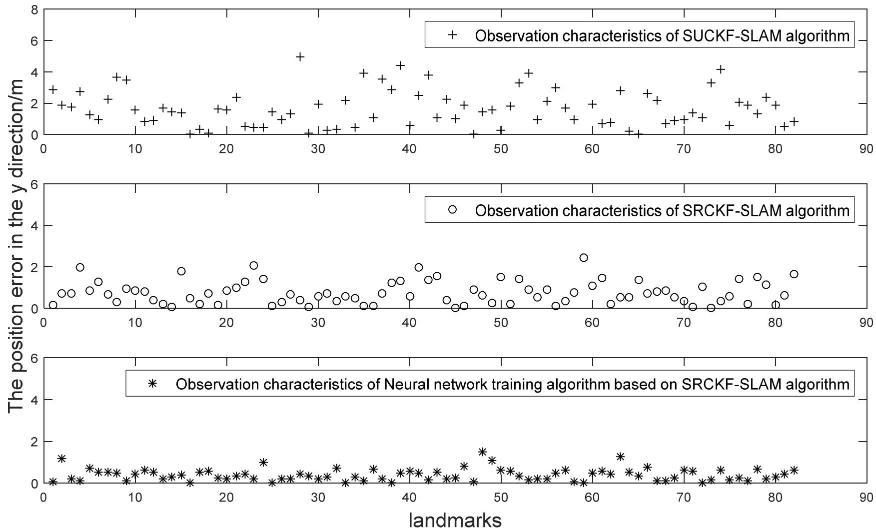

Fig. 8 The position error in the y-direction of landmarks

3.4 Possible practical implementation of the proposed SRCKF-SLAM algorithm

At present, single non-linear filtering algorithms used to deal with SLAM problems mainly includes EKF, UKF, CDKF, CKF, etc. Later, scholars further improved above several algorithms and proposed their derivative algorithms such as SRCDKF, SRUKF and SRCKF, then their accuracy are mainly discussed below.

In reference [16], accuracy of EKF, UKF and CDKF are compared, and it is concluded that when EKF algorithm was used to deal with nonlinear model, Jacobian matrix was needed to be solved, and Taylor expansion and high-order terms were needed to be eliminated, and larger truncation error was introduced, which led to larger algorithm error. UKF is a method that uses weighted statistical linear regression to achieve random linearization, which can approximate the Gaussian distribution. In theory, UT transformation could approach the posterior mean and covariance of the nonlinear Gaussian system with three times of Taylor precision. However, when UKF algorithm generated a set of random Sigma points with a large number, it would lead to more complicated calculation of state quantity parameters.

The Central Difference Kalman filter (CDKF) belongs to a suboptimal Gaussian filter. This algorithm uses polynomial interpolation to calculate multidimensional integrals. It uses a function sequence to approximate the integrand, which is similar to UT transform in UKF. It is just that the sampling point weights and calculation of prediction covariance expressions are different from the UKF algorithm in the form. The calculation of this algorithm is simple and easy to implement, but it is different from the selection of sigma points of UKF. In theory, the accuracy of CDKF and UKF algorithms is equivalent or slightly higher. According to references [17-18], it can be known that when using the CDKF algorithm to process non-linear models, the solution of the complex Jacobian matrix is avoided, the shortcomings of EKF algorithm are overcome, the linearization error is smaller than of EKF. The experiments have shown that it is less sensitive to state covariance and has a faster approximation speed than UKF.

Later scholars collectively referred to the UKF / CDKF as the sigma point Kalman filter (SPKF).

Then we discuss the accuracy problems of UKF, CDKF and CKF algorithms: the basic idea of the three filtering algorithms is to generate several groups of weight points through different methods, then calculate the parameters such as the mean value and covariance of propagation, and update state and measurement of algorithm. A large number of references, such as [19-20], have proved that the accuracy of filter estimation of the three algorithms is equivalent, and can reach the second order. For similar algorithms, another performance indicator that needs to be considered is computational complexity. According to the literature [20], it is verified that the computational complexity of the three algorithms is reduced in order, so that their filtering performance is sequentially enhanced.

However, for the SPKF filter and ordinary CKF filter, there is still a problem of computational divergence. Later, students introduced SR ideas into these methods. According to reference [9], Square-root can not only propagate square-root of state covariance, but also ensure the symmetry and semi positive setting of covariance matrix, and improve the accuracy, robustness and stability of filtering algorithm. So combining with SR idea, this paper applied three groups of filtering algorithms SRUKF, SRCDKF and SRCKF to SLAM nonlinear model, compared the filtering performance, and got the conclusion in this section. That is, SRCKF-SLAM algorithm had the highest filtering accuracy and the best stability. However, in order to get higher accuracy, this paper established a more suitable state model for engineering application after training the state quantity of SRCKF algorithm with neural network, and compared it with SRUKF and SRCKF algorithms without neural network framework, and obtained another group of experimental conclusions in this section.

It can be seen from the introduction and the theory of filtering in this paper, square-root cubature Kalman filter algorithm uses numerical integration to calculate the mean and covariance of the nonlinear random model, which avoids the derivative operation and reduces the computational complexity. Moreover, the algorithm propagates square-root of the state covariance, ensures the symmetry and semi positive finalization of the covariance matrix, and improves the accuracy, robustness and stability of the filtering. If the new algorithm is applied to the mobile robot, for example, in the practical application system of the aviation strategic missile in military field, when the tracked target encounters air resistance in the course of navigation, its state equation and observation equation become highly nonlinear. While in the estimation of the tracking state of the reentry ballistic target with unknown ballistic coefficient, the new algorithm can greatly reduce the tracked target state estimation error and improve the estimation accuracy. Therefore, the time to solve the its position and speed information is short, and the navigation operation speed is fast.

4. Conclusion

Aiming at the problems of weak observability of system under non-Gaussian, non-linear, and large noise, leading to unstable filtering algorithms and slow convergence, a SRCKF-SLAM filtering algorithm was used to estimate the position of robot and target. Since the learning and training of neural network could be regarded as seeking the best weight parameter through optimal estimation, and weight matrix and network output value could be regarded as state quantities and measured values, respectively, the training was described by state space. Moreover, neural network could have good convergence and robustness without an accurate mathematical model. An SRCKF-SLAM filtering algorithm based on neural network framework with cubature point estimates (weights) was proposed. Simulation experiments showed that the new filter algorithm was feasible and effective for feature observation after training with neural network. Under the conditions of increasing system noise and observation noise, position estimation errors of feature in the x-direction and in the y-direction were respectively [0, 1.2] m and [0, 1.7] m, which improved estimation accuracy compared to other traditional filtering algorithms such as SRCCK-SLAM, SRUCF-SLAM and SRCDKF-SLAM. If the new algorithm is applied to mobile robot, for example, in the practical application system of aviation strategic missile model in military field, it can greatly reduce tracked target state estimation error and improve estimation accuracy. The time to solve its position information is short, so the navigation operation speed is fast.

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A comparison of the tolerance analysis methods in the open-loop assembly

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A B S T R A C T

Dimensional and geometric tolerances affect both the cost and the functionality of a given product. Finding the acceptable trade-off between the two is among the common engineering tasks. Thus, many tolerance analysis methods are developed to help engineers and assist in the decision-making process. In this article, the authors have assessed four tolerance analysis methods by applying them to the open-loop assembly. The results obtained by the tolerance chart (worst-case) method, Monte-Carlo simulation, vector-loop analysis, and the Unified Jacobian-torsor model were analysed and compared. Additionally, the overview and application guidelines are included for each of the methods, aiming to help both researchers and practitioners. The results have confirmed that there are significant variations in the outputs across the observed methods, implying the need for informed method selection.

A R T I C L E I N F O

Keywords:
Assembly;
Open-loop assembly;
Tolerance analysis;
Computer aided tolerancing;
Tolerance chart analysis;
Unified Jacobian-torsor model;
Monte Carlo method;
Vector-loop analysis

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1. Introduction

During the design phase, tolerances are assigned to nominal dimensions, ensuring successful assembly while retaining the manufacturing costs at an acceptable level. As the complexity of mechanical design increases, keeping track of the tolerances becomes harder. To mitigate the problem, tolerance analysis methods of various complexity are available. The methods range from simple, 1D tolerance chart analysis, to advanced procedures requiring the use of advanced mathematical models. Examples include vector loop, Unified Jacobian-torsor, T-maps, and Skin model Shapes. Furthermore, tolerance analysis methods can be divided by several criteria: an approach to the analysis, identification process, and the calculation procedure of dependent dimensions [1].

Before analysing, tolerances are assigned to assembly features and are organised into stacks, easing the variation analysis. Stacks are then used to analyse the assembly by reading the drawings or by assigning tolerances on computer-aided drawing (CAD). The tolerances are then stacked into loops using points, surfaces, vectors, or joints, among others – depending on the method [1]. Manual charting is frequently used when solving simple problems consisting of few dimensions. As the number of dimensions increases, its reliability decreases – it is error-prone and tiresome. Additionally, manual analysis is hard to perform in 2D and 3D tolerancing problems.

The tolerancing problem complexity further increases when the geometric tolerances are necessary [2]. Geometric tolerances are defined by 3D tolerance zones, rendering most of the simpler methods unusable. Thus, computer-aided tools (CAT) were developed, increasing the capabilities in terms of the number of available approaches and mathematical models. Many such tools are developed and successfully applied (VisVSA, 3DCS, CETOL, OpTol) [3] in the industrial environment. Unfortunately, various proprietary CAT tools use different mathematical models to define and analyse tolerances, meaning that the obtained results may differ [4].

State-of-the-art CAT tools allow users to model assembly stacks with point-to-point features. The contributing tolerances are identified and arranged into suitable stacks or loops [5] as each method is compatible with a specific stacking procedure to build the stacking equation. In recent papers, many researchers have studied differences and similarities of tolerance analysis methods. Studies considered the contributing tolerances from multiple directions [6], the angular deviation of the adjustable element, or a critical assembly feature (functional requirement) [6]. Also, the form [1] and interaction of the multiple tolerances in the 3D context is defined by the geometric drawing and tolerancing (GD&T) standards [1, 10]. Due to frequent changes in GD&T standards [7] such as ISO 8015 [2] and ASME Y14.5 [8, 9], continuous support of the tolerance analysis methods is needed.

Various assembly applications are described as a system of open-loop or closed-loop that must be solved together. The open-loop describes a dimension stack terminated with a gap or a critical assembly feature. The closed-loop defines a closure constraint for the assembly, implying that adjustable elements are in the assembly. Thus, the critical difference between the open-loop and closed-loop assemblies is the existence of gap; in the open-loop assemblies, we anticipate that gap dimension must be properly toleranced to allow us to form an engineering fit with another part (for the schema of the open-loop assembly, (please see Fig. 3). Those elements, gap or functional requirement, are the result of part tolerance accumulation. If there are no adjustable components, there is no need for closed-loops – the assembly model is composed only of open-loops [2].

In recent studies, methods for tolerance analysis were compared using the closed-loop examples. The aim was to determine the advantages and shortcomings of each method, along with the differences in output (e.g. [10-15]). To the best of our knowledge, mentioned research studies have not considered the open-loop assemblies. Hence, the contribution of the article at hand is the evaluation of the tolerance analysis methods on open-loop problems. Furthermore, besides the scientific contribution, this article aims to provide the practitioners with a simple review and guidelines for the application of each method. To achieve this, we have compared four different methods: tolerance chart method, Monte Carlo method, vector loop model, and Unified Jacobian-torsor model. Each method was applied to an open-loop assembly, allowing for comparison in performances and outcomes.

2. Methods and materials

In this research study, four tolerancing methods were compared: tolerance chart method [16], Monte Carlo method, vector-loop model [15], and Unified Jacobian-torsor (see Section 2.1). Each method is described, along with the steps necessary to apply it. Those include tolerancing problem identification, mathematical modelling, and calculation procedures.

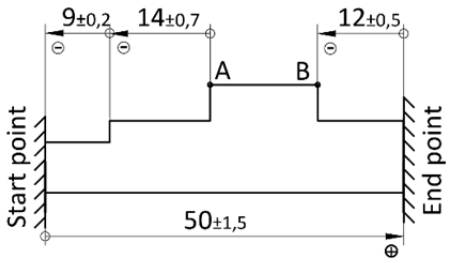
2.1 Used tolerance analysis methods

Tolerance chart method is the most frequently used tolerance analysis method in the industry [16], mostly due to its simplicity. It is widely used for solving problems concerned with dimensional tolerances, although the recent improvements enabled its application to geometric tolerances [15]. The method is one-dimensional; in order to apply it to the multi-dimensional geometric tolerances, they must be converted to 1D space [15].

Tolerance chart method can be performed on both the part and assembly level. For assembly level, parts included in the tolerance chain represent one of the tolerance end-points (maximum or minimum). Each part is placed against its mating part in one of its tolerance end-points. As a result, the worst-case tolerance chart method illustrates the minimal and maximal variation of a functional requirement based on the values in the tolerance chain [9].

When performing the tolerance chart method analysis, the first step is to set a goal by labelling the chain starting and ending points [16]. The starting point is selected on one edge and the ending point on the opposite edge of the analysed feature (see Fig. 1). The chain indicator is placed to determine the direction of the dimension vector and is either positive or negative [17]. The vector pointing toward the chain end-point is marked "⊕", and the vector pointing opposite of the end-point is marked "⊖". The indicator shows whether to add or subtract dimensions and tolerances during the stack calculation. Additionally, it simplifies the interpretation of tolerance chart results [16]. The resulting dimension chain is the shortest possible and consists only of known dimensions - dimensions set by designers.

Tolerance chart method was used in recent studies [5, 6, 9, 15-17], mostly as a reference for the comparison of advanced tolerance analysis methods. Its most important advantage is simplicity; no computational tools are needed as it can be carried out by hand. The downside is that the user has to keep in mind all the standard rules [2, 8] for creating the stacks, making the process error-prone. Besides, the tolerance chart method creates stacks in one direction and ignores the contributions of others, possibly providing unsatisfactory results.



Description	⍰	⍰	TOL
Dimension 1	50		±1.5
Dimension 2		12	±0.5
Dimension 3		14	±0.7
Dimension 4		9	±0.2
Sum	50	35	±2.9

$$DIM = \sum_{i=1}^{m} \oplus_{\mathrm{i}} - \sum_{j=1}^{n} \ominus_{\mathrm{j}} = $$
$$= 50 - 35 = 15$$

$$TOL = \sum_{i=1}^{n} TOL_{\mathrm{i}} = \pm 2.9$$

Final dimension:
15 ± 2.9

Fig. 1 Tolerance chart method

A plethora of statistical approaches was introduced to conduct non-linear statistical tolerance analysis. A typical example is the ***Monte Carlo simulation (MCS)*** based on the algorithm of the same name. It utilises random sampling input values to calculate the output results. For a given input vector $\boldsymbol{x}$, the number of sampling values n is determined $\{x_1, x_2, \dots, x_n\}$. By using the mathematical model (transfer function) $\boldsymbol{y} = f(\boldsymbol{x})$ new output vector of same length is found $\{y_1, y_2, \dots, y_n\}$. Finally, the output results $\boldsymbol{y}$ are analysed by calculating statistical data such as mean, standard deviation, or range.

Monte Carlo simulation (MCS) is a beneficial tool for tolerance analysis of mechanical assemblies. Its main advantage is flexibility and ability to use various non-normal input or output distributions [18]. A large set of sample parts is created by randomly assigning a tolerance value to each nominal dimension. Values are selected within the tolerance interval to simulate the manufacturing variation [18]. The process is repeated until enough output data is acquired to enable the use of statistical techniques. It allows the calculation of the mean value, standard deviation, range, upper and lower specification limit, and share of rejected samples [19].

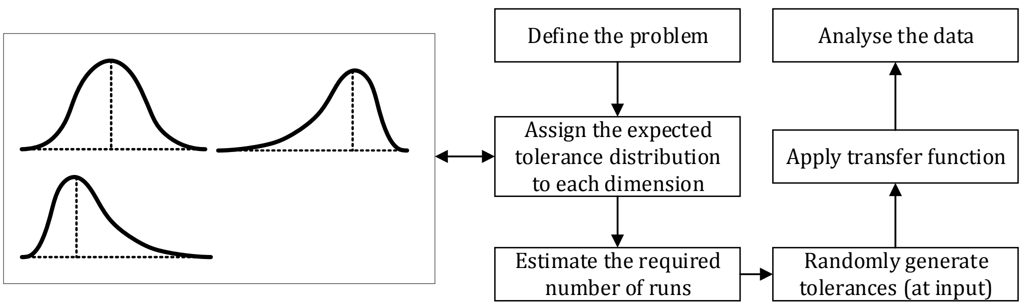


Fig. 2 Monte Carlo simulation for implicit assembly constraints

In this article, MCS is applied as an extension to the Tolerance chart method. A modified form of MCS (McCATS) accounting for the implicit assembly variations was used, as suggested in [20]. In the modified simulation, the random parts are sent to the assembly function, which iteratively solves the tolerance chart equations for the dependent assembly variations [20]. The process is repeated until a sample of a suitable size to produce the assembly histogram is created. The steps necessary to carry out the tolerance analysis using the MCS are shown in Fig. 2.

The vector loop model is a stack-up technique used to extend the stack analysis to two and three-dimensional assemblies [1]. The idea of the vector loop method is to use vectors to describe the dimensions and associated tolerances. Vectors are arranged in loops to determine the assembly deviations. Tolerance analysis problems are solved using the kinematic concept; contact points are set as kinematic joints. A number of possible motions is defined for each joint (i.e. degrees of freedom), along with the local datum reference plane. Three types of variations are described in vector loop model: dimensional variations (lengths and angles), kinematic variations (small adjustments between mating points, joints) and geometric/feature variations (position, roundness, angularity) [1].

Dimensional and geometric tolerances are described as additional degrees of freedom on the kinematic joints [1]. Kinematic simplification is required to represent geometric tolerances in such way. Thus, in the vector loop model, geometric tolerances are included only at mating points, in the direction defined by the type of kinematic joint [1]. They are described as additional translational and rotational transformations (displacement vectors, rotation matrices) – as gaps with zero-length nominal dimension vectors.

The assembly graph is a diagram that represents the analysed assembly, including its parts, dimensions, mating conditions, functional elements, and functional requirements. The graph is used to represent any linear dimension in the assembly as a vector (see Fig. 3). Vectors are connected and form chains or loops, reflecting how assembly parts stack-up together. The associated tolerance is included as a small kinematic adjustment of such a vector (gap) [1, 12]. Such representation allows us to determine the functional requirements of an assembly. Stack-up functions are built by including the vector variations involved in each chain into implicit kinematic equations. As such, they can then be solved using various mathematical approaches [1, 6].

For each part in the tolerance chain, a local datum reference frame (DRF) is added to identify the relevant features of a part for tolerance analysis. DRFs are then connected using datum paths representing geometric layouts, which define the direction and orientation of vectors forming the loop [1]. They are created by stacking and chaining the dimensions that locate the contact point between two parts. After creating datum paths, the vector loops can be created by connecting datums. Loops can be open or closed, depending on the functional requirement of the tolerance analysis. The number of closed loops is calculated as $L = J - P + 1$, where J is the number of the mating points, and P the number of parts.

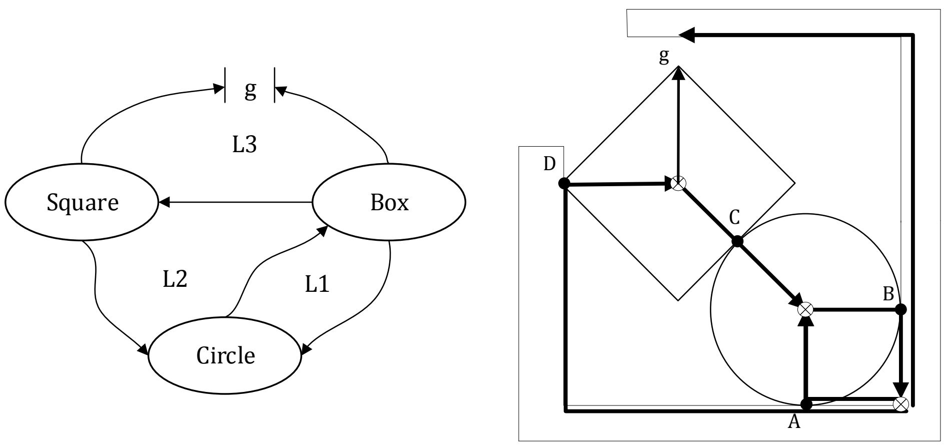


Fig. 3 Assembly graph and the example of vector loops

After defining the vector loops, the calculation is carried out [1, 11]. When considering the closed-loop problem, the equations are often non-linear; they must be linearized using direct linearization method [1, 11], producing approximate results. Thus, vector loop, when using direct linearization, is unable to generate true worst-case results [4, 11]. When the open-loop problem is considered, deviations are calculated directly using explicit equations [11].

Unified Jacobian-torsor (JT) method [21] is a 3D tolerance analysis method. It uses the Jacobian matrix to relate the functional requirement (FR) and virtual joints displacements. JT advances the punctual small-displacement variables of the Jacobian formulation to represent tolerance zones using the torsor model and interval arithmetic. It offers more output information on the FR, reducing the size of the analysed model since it is no longer point-based [21].

Torsor model uses small displacement screws to establish tolerance zones of points, curves, and surfaces [21, 22]. Each real surface is modelled by a substitution surface defined by a set of screw parameters that are modelling the deviations from nominal geometry [23]. Screw parameters are arranged in torsors containing translational components of a point (u, v, w) and α, β, δ as rotational components with respect to the nominal geometry:

$$T = \begin{Bmatrix} \alpha & u \\ \beta & v \\ \delta & w \end{Bmatrix}_R , \tag{1}$$

where R is DRF used to evaluate the screw components. Torsor model can fully define the tolerance zones due to its ability to shape spatial volumes within which the surfaces are deviating [10].

The procedure of Unified Jacobian-torsor method consists of 4 steps [24]. The first step is to identify all functional elements (FEs) affecting the FR by distinguishing kinematic chains involving the functional condition or part under study. Functional element can be any point, curve or surface of a part and creates internal or kinematic pairs [21]. The second step is to associate a torsor or screw parameter to each element (surface, axis) of the kinematic chain. Torsors express the degrees of freedom and the allowable element displacements and their bounds. Small displacements are applied to parts' geometrical features affecting the FR [21], after which the Jacobian matrix is used to determine relative positions and orientations of torsors within the chosen kinematic chain (step three) [22]. The final step is to combine torsor and Jacobian to provide a matrix equation. Solving a resulting matrix using interval algebra provides the functional condition bounds.

2.2 Assembly model for case study

The above-described methods were compared by analysing a 3D tolerancing problem. The assembly consisting of the cantilever and the rotating handle (open loop) was used as an example. Thus, both the dimensional and geometric tolerances were considered. The functional requirement deviations are assessed using each of the methods, while the results are compared in Section 3.5. The nominal dimension (DIM), upper deviation limit (UDL), and lower deviation limit (LDL) were calculated. The comparison is focused on the similarities and differences between results obtained by each method. Differences in procedures and calculation approaches are also observed.

A simple rotating handle assembly consisting of four parts was used to carry out the comparison between the methods (see Fig. 4). The pole (2) is fixed to the bottom plate (1), while the lever (3) is mounted onto the journal located on the pole. The handle (4) is installed into the bore located on the lever. Tolerances were assigned to all the dimensions apart from a distance between the handle (4) and the base plate (1), which is selected as a functional requirement).

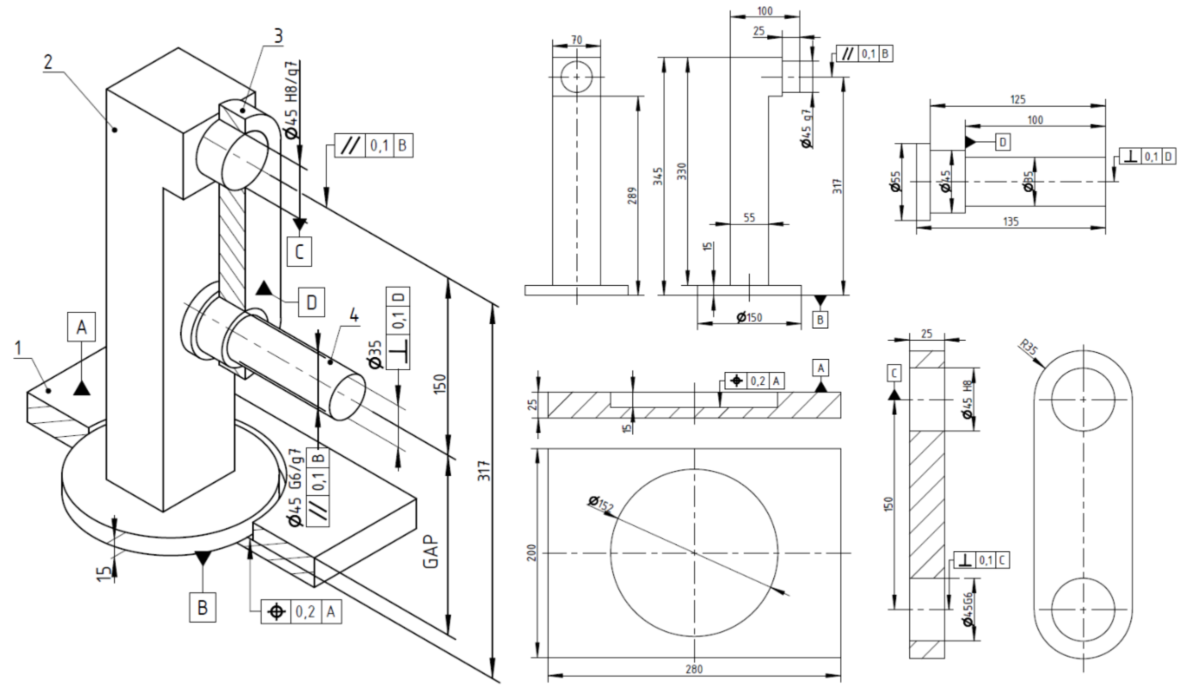


Fig. 4 Case study model

The positional tolerance between the top surface of the base and its cut-out was included. The contact between the base and the cylindrical base of the pole is considered ideal. The parallelism tolerance between the axis of the cylindrical pin located on the pole and the bottom surface of the pole was also included. The lever is mounted onto the pole pin (see Fig. 4) by clearance fit ⌀45 H8/g7. On the opposite side of the lever, the handle is mounted into the bore with a clearance fit ⌀45 G6/h7. Regarding the geometric tolerances, the parallelism between two lever bores and perpendicularity between the handle and the mounting sleeve wall were required.

Each method was then applied to the above-described open-loop assembly. The results were compared according to three criteria:

- identification of the contributing tolerances,
- calculation of the dependent dimension (functional requirement),
- analysis of calculation differences compared to the assemblies with closed loops.

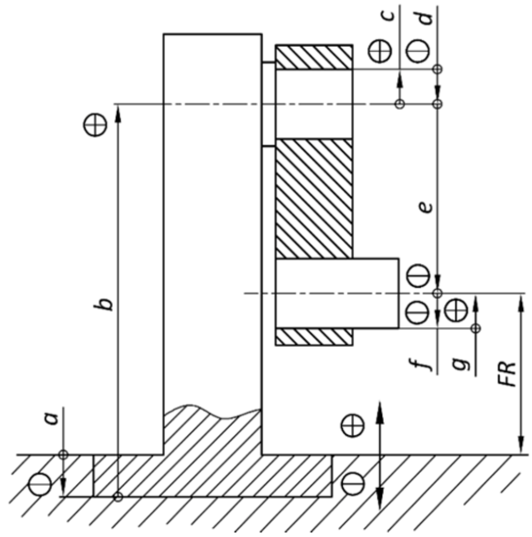
An assembly graph was created for each of the methods except for the Monte Carlo simulation, as it is based on Tolerance chart method.

3. Results and discussion

3.1 Tolerance chart results

Tolerance chart method is mostly used for dimensional tolerances, even though the recent modifications have enabled the analysis of geometric tolerances as well [15]. The geometric tolerances are to be transformed into their dimensional counterparts. Yet, such transformation does not account for the angular surface deviation. In this article, the tolerance chart method is applied only to dimensional tolerances.

Tolerance chain consisting of base plate bore depth (a), length between the pole basis and pole journal axis (b), tolerance fit between pole journal and lever bore (c and d), distance between lever bore axes (e), and tolerance fit between lower lever bore and handle (f and g). As mentioned, the distance between the top surface of the base plate (part 1) and handle (4) is a functional requirement. Indices U and L were included to denote the upper and lower deviation limit, respectively.



Dimension	+	−	TOL.
a		15	0
b	317		0
c	22.5		$c_{ut} = -0.009/2$; $c_{lt} = -0.034/2$
d		22.5	$d_{ut} = 0.039/2$; $d_{lt} = 0$
e		150	0
f		22.5	$f_{ut} = 0.025/2$; $d_{lt} = 0.006/2$
g	22.5		$g_{ut} = 0/2$; $g_{lt} = -0.025/2$
Sum	362	210	

Nominal functional requirement dimension:

$$DIM_{TC} = -a + b + c - d - e - f + g = 152 \text{ mm}$$

Stack equation for the upper deviation limit:

$$UDM_{TC} = -a + b + c_{ut} - d_{lt} - e - f_{lt} + g_{ut} = -0.008 \text{ mm}$$

Stack equation for the lower deviation limit:

$$UDM_{TC} = -a + b + c_{lt} - d_{ut} - e - f_{ut} + g_{lt} = -0.062 \text{ mm}$$

Fig. 5 Application of tolerance chart method

The tolerance stack coordinate system is defined next; the starting point is set at the base plate surface (1). The upward dimension is shown in Fig. 5 is selected as positive and marked with the indicator "⊕", while the downward is negative and marked with "⊖". The direction of the tolerance chain is chosen arbitrarily, but it is important to respect the specified direction along the chain. Finally, the results are calculated by adding and subtracting values along the tolerance chain and shown in Fig. 5.

3.2 Monte Carlo simulation results

Monte Carlo simulation was applied following the procedure explained in Section 2.1. Determining the appropriate distribution to each of the tolerances was the crucial step, as it affects the results. The distribution of geometric tolerances along with the interval between the upper and lower deviation limit most frequently follows the normal distribution.

Tolerance fits are asymmetrical, requiring the use of the skewed distribution according to [19]. Distribution of input values is described using ± 3σ process range (6σ). Since data about the manufacturing process was not available, 3DCS CATS software was used to determine the distribution models of tolerance fits. According to 3DCS, tolerance fits have unimodal continuous probability distribution called Pearson 1. Since tolerance limits assigned to dimension *c* are negative, the distribution model is skewed left from the nominal dimension. The same can be concluded for the tolerance assigned to dimension *g*. On the other hand, tolerance limits assigned to dimensions *d* and *f* are positive, and distribution is right-skewed.

Runs	2000
Nominal	152.000 mm
Mean	151.999 mm
STD	0.018 mm
6STD	0.110 mm
LSL	151.000 mm
USL	153.000 mm
EST. TYPE	Pearson I
EST. LOW	151.958 mm
EST. HIGH	151.995 mm
EST. RANGE	0.085 mm

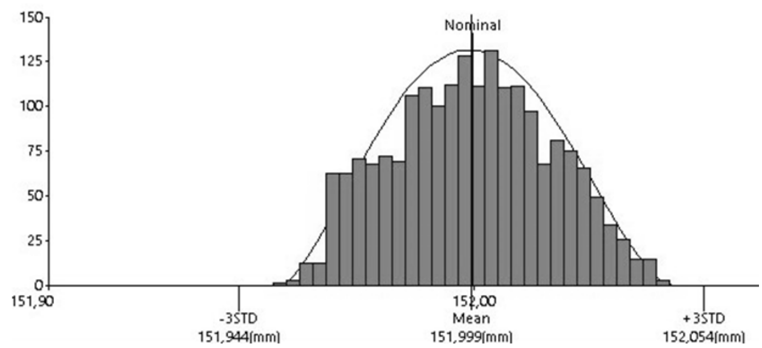


Fig. 6 Monte Carlo assembly results and histogram

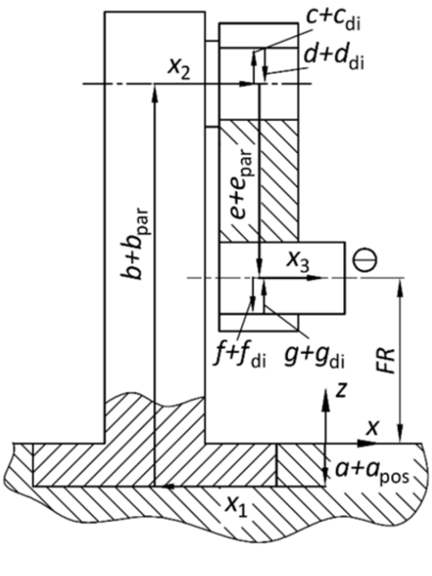
Next step is to define the variation model function. Since Monte Carlo is applied to tolerance chart method, tolerance stack equations are used to define it. After running the simulation for n = 2000 times with randomized input variables, an output model for FR was created. A variation analysis provides descriptive statistics, inferential statistics data, and a histogram (shown in Fig. 6). By adding and subtracting the input variables using the variation model functions, distribution of FR tolerances was found. The resulting functional requirement distribution is also Pearson 1. However, it is not as profoundly left- or right-skewed as are the input variables.

3.3 Vector-loop results

An assembly graph describing the open-loop of the assembly and its vector loop tolerance chain (or datum path) was created. It was used to identify of the number of vector chains and loops involved in the assembly (Fig. 4). Since each part is in contact with its two neighbouring parts only once, this assembly contains one open loop. Same can be seen on the assembly graph (Fig. 7) where each arrow is representing the contact between parts. Vector loop is open at the gap (noted g) between the Handle (Part 4) and Base (Part 1).

The datum path (Fig. 7, right) connects the point, surface, axis or DRF of a part with next part's point, surface axis or DRF. DRFs have been assigned to each part with respect to the origin coordinate system at the top of the Base (Part 1). All the DRFs have a horizontal x-axis and vertical z-axis. Origin coordinate system is set in such a way that positive direction of Z_0 axis corresponds with the positive direction of a tolerance chain in Tolerance chart method. This eases the tracking and method comparison.

The geometric tolerances were also accounted for. Each tolerance was represented as an additional vector of magnitude equal to $\pm\, t/2$, where t is the width of corresponding tolerance field (see Fig. 4; 0.2 for the positional, and 0.1 for parallelism and perpendicularity tolerances). The additional vectors represent gaps between parts contacting points and were denoted based on the corresponding nominal dimension. The position tolerance on the Base cut-out with respect to the datum A (a_{pos}) is represented as a translation vector of the surface in the z-direction (Fig. 7). The parallelisms applied to the Pole's pin (b_{par}), and Lever holes (e_{par}) with respect to the datum B were also represented as translation vector along the z-axis [1]. Perpendicularity applied to the horizontal axis of the Handle (g_{per}) with respect to the datum D can be described as a translation along x-axis [1]. According to the assembly graph there are $J = 3$ contacting points and $P = 4$ parts, resulting in 0 closed loops (Eq. 1 was used). There is also one open-loop functional requirement.



Var.	Tol. description	Gap vector length
a_{pos}	Position (Base top to cutout)	±0.1
b_{par}	Parallelism (Pole's to bottom)	±0.05
c_{d}	Dimensional tol. (Pole's pin)	c_{du} = –0.009; c_{dl} = –0.034
d_{d}	Dimensional tol. (Lever's upper hole)	d_{du} = 0.039; d_{dl} = 0
e_{par}	Parallelism (Lever hole axes)	±0.05
f_{d}	Dimensional tol. (Lever's lower hole)	f_{du} = 0.025; f_{dl} = 0.009
g_{d}	Dimensional tol. (Handle)	f_{du} = 0.0; f_{dl} = –0.025
h_{par}	Perpendicularity (Handle axis)	±0.05

Uppervalue of functional requirement:

$$FR_{\mathrm{u}} = -(a - a_{\mathrm{pos}}) + (b + b_{\mathrm{par}}) + \frac{c + c_{\mathrm{du}}}{2} - \frac{d + d_{\mathrm{dl}}}{2} - (e - e_{\mathrm{par}}) - \frac{f - f_{\mathrm{dl}}}{2} + \frac{g + g_{\mathrm{du}}}{2} + h_{\mathrm{par}} = 152.241 \text{ mm}$$

Lower value of functional requirement:

$$FR_{\mathrm{l}} = -(a + a_{\mathrm{pos}}) + (b - b_{\mathrm{par}}) + \frac{c + c_{\mathrm{dl}}}{2} - \frac{d + d_{\mathrm{du}}}{2} - (e + e_{\mathrm{par}}) - \frac{f + f_{\mathrm{du}}}{2} + \frac{g - g_{\mathrm{dl}}}{2} - h_{\mathrm{par}} = 151.680 \text{ mm}$$

Fig. 7 Vector loop assembly graph and results

3.4 Unified Jacobian-torsor results

Before creating the assembly graph (Fig. 8), it was necessary to identify the functional elements (*FE*) and functional requirements (*FR*). Also, it was required to differentiate between the internal and kinematic pairs. For the assembly at hand, there are four internal and one kinematic pair. First internal pair ($FE_{0\text{-}1}$) is located on the Base (Part 1), as the positional tolerance defined between its top and cut-out surface corresponds to functional surfaces 0 and 1 on the assembly. The parallelism tolerances define $FE_{2\text{-}3}$ and $FE_{4\text{-}5}$. Internal pair $FE_{6\text{-}7}$ is defined by the perpendicularity tolerance set on the Handle (Part 4).

Only kinematic pair ($\mathrm{FE}_{1\text{-}2}$) is set between the Base cut-out and Pole's bottom. However, the contact is assumed to be ideal so that it will not impact the analysis. Two more contacts defined by tolerance fits (between Pole and Lever, and between Lever and Handle) were not set as kinematic pairs even though they are in physical contact. This means they are defined as important conditions to be satisfied between two *FE*s. So, according to [13], they are then defined as functional requirements that will be taken into account in the analysis as kinematic pairs.

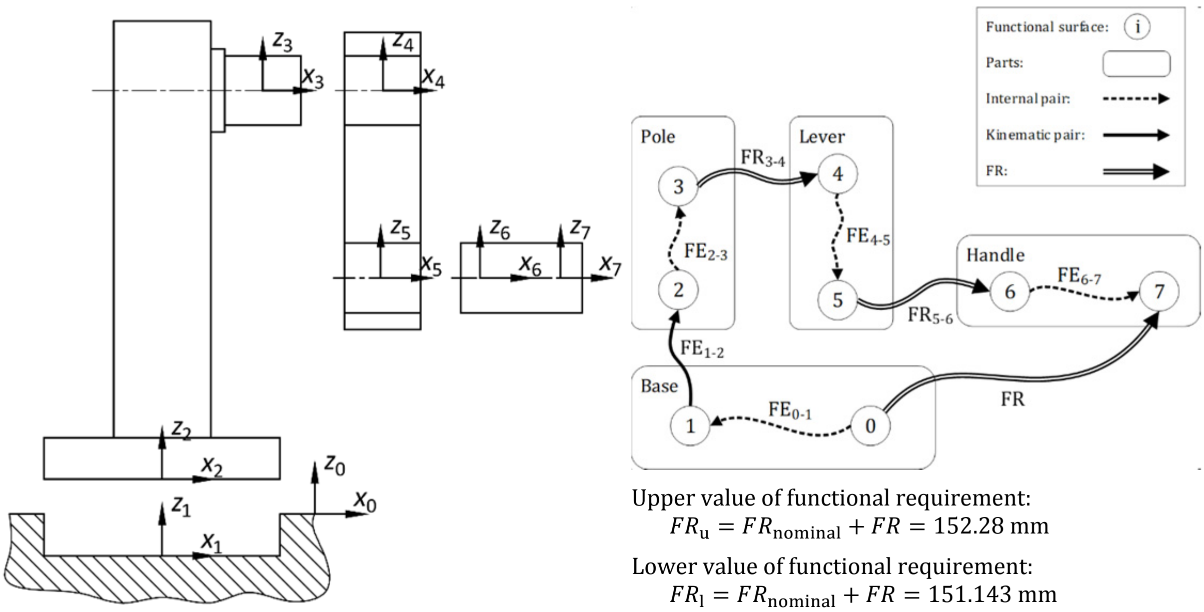


Fig. 8 Jacobian-torsor method and results

Jacobian matrix and small-displacement torsor vector were calculated for each internal and kinematic pair. A small-displacement torsor vector was also calculated for each *FE* (based on torsor representing the tolerance zone [21]):

$$[FR]^{\mathrm{T}} = \begin{bmatrix} \overline{u} & \overline{v} & \overline{w} & \overline{\alpha} & \overline{\beta} & \overline{\delta} \\ \underline{u} & \underline{v} & \underline{w} & \underline{\alpha} & \underline{\beta} & \underline{\delta} \end{bmatrix}_{\mathrm{FR}}, [FEi]^{\mathrm{T}} = \begin{bmatrix} \overline{u} & \overline{v} & \overline{w} & \overline{\alpha} & \overline{\beta} & \overline{\delta} \\ \underline{u} & \underline{v} & \underline{w} & \underline{\alpha} & \underline{\beta} & \underline{\delta} \end{bmatrix}_{\mathrm{FEi}} \tag{2}$$

For each tolerance, translational and rotational components inside the tolerance zone were determined [21]. Since the direction of a functional requirement is along the z-axis and rotations that would influence functional requirement are around x and y-axis, w, α and β component must be calculated.

Contact between functional surfaces 0 and 1 in the $FE_{0\text{-}1}$ is a planar contact with normal containing one translation component (w) and two rotational components (α, β) [12, 21]. Components are calculated using the equations for planar surface according to [21]. Internal pairs $FE_{2\text{-}3}$, $FE_{4\text{-}5}$, and $FE_{6\text{-}7}$, and functional requirements $FR_{3\text{-}4}$ and $FR_{5\text{-}6}$ are defined by the tolerance fits. They use translational components v and w and rotational components β and δ of a slipping pivot with the axis [21]. Below is a table containing displacements torsors for each internal and kinematic pair.

Table 1 Displacement torsors for each internal and kinematic pair

$$
\underset{FE_{0\text{-}1}}{\begin{bmatrix} \underline{0} & \overline{0} \\ \underline{0} & \overline{0} \\ \underline{0.1} & \overline{-0.1} \\ \underline{0.0013} & \overline{-0.0013} \\ \underline{0.0013} & \overline{-0.0013} \\ \underline{0} & \overline{0} \end{bmatrix}}
\underset{FE_{2\text{-}3}}{\begin{bmatrix} \underline{0} & \overline{0} \\ \underline{0.05} & \overline{-0.05} \\ \underline{0.05} & \overline{-0.05} \\ \underline{0} & \overline{0} \\ \underline{0.004} & \overline{-0.004} \\ \underline{0.004} & \overline{-0.004} \end{bmatrix}}
\underset{FR_{3\text{-}4}}{\begin{bmatrix} \underline{0} & \overline{0} \\ \underline{0.00365} & \overline{0.0045} \\ \underline{0.00365} & \overline{0.0045} \\ \underline{0} & \overline{0} \\ \underline{-0.0003} & \overline{0.0004} \\ \underline{-0.0003} & \overline{0.0004} \end{bmatrix}}
\underset{FE_{4\text{-}5}}{\begin{bmatrix} \underline{0} & \overline{0} \\ \underline{0.05} & \overline{-0.05} \\ \underline{0.05} & \overline{-0.05} \\ \underline{0} & \overline{0} \\ \underline{0.004} & \overline{-0.004} \\ \underline{0.004} & \overline{-0.004} \end{bmatrix}}
\underset{FR_{5\text{-}6}}{\begin{bmatrix} \underline{0} & \overline{0} \\ \underline{0.025} & \overline{0.045} \\ \underline{0.025} & \overline{0.045} \\ \underline{0} & \overline{0} \\ \underline{-0.002} & \overline{-0.0004} \\ \underline{-0.002} & \overline{-0.0004} \end{bmatrix}}
\underset{FE_{6\text{-}7}}{\begin{bmatrix} \underline{0} & \overline{0} \\ \underline{0.05} & \overline{-0.05} \\ \underline{0.05} & \overline{-0.05} \\ \underline{0} & \overline{0} \\ \underline{0.001} & \overline{-0.001} \\ \underline{0.001} & \overline{-0.001} \end{bmatrix}}
$$

Jacobian matrix is calculated according to the procedure presented in [21]. Its purpose is to calculate the effect of the traditional torsor set for each functional element (FE) on the functional requirement (FR) of the assembly [21]. Finally, after calculating small-displacement torsor vectors and Jacobian matrices for each FE, the same can be done for FR:

$$FR = J \cdot FE = \begin{bmatrix} -0.058 & 0.239 & \mathbf{0.665} & 0.001 & 0.005 & 0.004 \\ -0.434 & 0.184 & -\mathbf{0.947} & -0.001 & -0.011 & -0.010 \end{bmatrix}^{\mathrm{T}} \tag{3}$$

3.5 Comparison of the results obtained by different methods

After analysing the assembly presented in Section 3.1 using the four methods, results are presented in Table 2. Abbreviations are used to ease the result disambiguation; TC was used for tolerance chain method, MC for Monte Carlo simulation, VL for the vector loop method, and JT for the Unified Jacobian-torsor method. Since it is not possible to include geometric tolerances in TC and MC analysis, two results were provided for VL and JT methods. The first batch of results included dimensional tolerances, while the second includes both. Besides the quantitative analysis results, qualitative properties such as the scope and perceived complexity of each method were assessed.

Proprietary CAT tools that are used in day-to-day work are often perceived as black boxes. That means that the users are frequently not familiar with the underlying processes and mathematical models. Besides, the tolerance analysis methods used in CAT tools are often not complying to the technical standards. For this reason, we have analysed underlying tolerance analysis methods, aiming to determine their advantages and shortcomings.

When considering the dimensional tolerances (DT) exclusively, TC, MC, and VL provide similar results, with FR_{u} being practically equal. Contrary to the upper value of the functional requirement, the deviations in lower (FR_{l}) are greater – TC and VL provide more conservative results when compared to MC. A significant deviation in FR_{u} was found when calculating it using JT. Unlike other analysed methods, in Jacobian-torsor method tolerance analysis is carried out using a tolerance zone as a basis (instead of points), causing the afore-mentioned variations in results. By using zones and surfaces instead of points, it is possible to create a more credible representation of a realistic case.

Table 2 Method comparison

	Scope	FR_{u}	FR_{l}	Δ	Applicability	Complexity
Tolerance chain method	DT	151.992	151.938	0.054	For simple 1D tasks	Simple, carried out by hand
Monte Carlo simulation method	DT	151.995	151.958	0.037	Simple tasks, statistical analysis	Statistical tools required
Vector Loop method	DT	151.991	151.930	0.061	Multi-dimensional	Carried by hand/more complex
	D&GT	152.243	151.143	1.100		
Unified Jacobian-torsor method	DT	152.369	151.946	0.423	Multi-dimensional, automation	Requires mathematical tools, enables automation
	D&GT	152.665	151.053	1.612		

The MC method is the least conservative due to its statistical approach – when carrying out the tolerance analysis using the MC method, most extreme cases are excluded from the analysis and counted as write-offs. The advantage of such an approach is that it reduces the cost of manufacturing equipment; it is less expensive to write-off a portion of parts, then to purchase more accurate manufacturing tools. Thus, the analysis method should be selected in accordance with the manufacturing process. Statistical approaches are suitable when analysed products are manufactured in large series, while prototypes and one-of-a-kind products warrant the use of more complex and conservative methods, such as JT.

The applicability of methods regarding the tolerancing problem dimensionality should be addressed next. As applied in this study, by using TC and MC only 1D problem containing dimensional tolerances can be solved. This drawback can be partially mitigated by converting the geometric tolerances into their dimensional counterparts; however, methods remain limited to 1D problems. In comparison, VL and JT were developed with having the 2D and 3D tolerancing problems in mind. Besides the dimensional tolerances, both methods can be used to analyse the geometric tolerances as well. However, there is a significant difference between VL and JT in terms of tolerance representation. The former, vector loop, observes a set of tolerances simultaneously, forgoing the possible interactions among them. The latter, Unified Jacobian-torsor, includes both the translational and rotational components, thus including different tolerances as complementary.

The procedure complexity of each method should also be considered. TC is by far the most straightforward method and can be carried by hand. It is suitable for simple tolerancing problems that engineers solve daily. Second is the VL, which requires an additional schema of the vector loop. By procedure complexity, MC comes next. It is a statistical method, meaning that it requires a large sample in order to provide significant results – experience with similar parts and their tolerances is necessary. The last method is JT, which is found to be the most complex. To carry it out, it requires the detection of functional elements, functional requirements, and kinematic pairs.

When comparing the method performance on open and closed-loop tolerancing, changes were detected only in VL. The vector-loop method is affected by the procedure system of open and closed loops. In cases where only open-loop tolerances are used, the vector loop method is reduced to explicit equations. This allows for a direct calculation of the functional requirement values. In other words, the VL method loses its advantage to TC.

The limitations of the study should also be considered. Each of the methods is carried out strictly according to the literature, without additional data manipulation (for example, geometric tolerances were not converted to dimensional ones). Additionally, when carrying out MC, it should be stressed that previous knowledge about the manufacturing process and manufacturing tool properties is necessary to enable satisfying approximation of tolerance distribution.

Lastly, during the planning of the product design process, in addition to tolerance analysis methods, engineers should also consider applying the tolerance optimisation methods. Several studies have been carried out on the subject, such as [25, 26]. Using optimisation algorithms to tolerancing problems allows us to find the optimal trade-off between the tolerances, manufacturing costs, and quality loss [25]. Such an approach would surely increase the design effectiveness, increasing its market success.

4. Conclusion

Simple tolerancing problem was used to assess the similarities and differences between four tolerance analysis methods: Tolerance chart ("Worst-case analysis"), Monte Carlo Simulation method, Vector-loop method, and Unified Jacobian-torsor. Open-loop assembly was used to illustrate the problem-solving process using each of the methods. Based on the results, the authors have concluded the following:

- Tolerance chart and Monte Carlo Simulation methods do not account for the geometrical tolerances. This results in overly optimistic results; however, both methods are only suitable for solving simple, 1D tolerancing problems.
- The unified Jacobian-torsor method was found to be most conservative (i.e. provided the most substantial deviations in functional requirement), followed by Vector-loop, Tolerance chart, and Monte Carlo Simulation, respectively.
- Tolerance chart is the simplest and thus suitable for solving many day-to-day tolerancing problems. Monte Carlo Simulation and Unified Jacobian-torsor require more detailed analysis and know-how and are suitable for more pressing problems. Vector loop can be considered the middle ground – it offers good results at the moderate complexity.
- When comparing the method performance in open-loop assemblies to closed-loop ones, differences are detected only in Vector-loop method.

The field of tolerance analysis is fruitful, and there is more work to be done. Following this study, the authors aim to analyse the performance of tolerancing methods by carrying out an industrial case study. The part deviations measured during the quality assurance are to be compared to the values provided by analysis methods, providing additional insight.

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Awareness and readiness of Industry 4.0: The case of Turkish manufacturing industry

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A B S T R A C T

The concept Industry 4.0 (I4.0) represents intelligent production processes combining cyber and physical systems through a set of technologies such as internet of things, big data and cloud computing. Transition to Industry 4.0 is expected to cause formidable structural changes, productivity increments and competitiveness in manufacturing industry in all over the world. This study aimed to investigate the general approach to the concept of Industry 4.0 and levels of adoption of the basic Industry 4.0 technologies in manufacturing firms across Turkey. For this purpose, a survey was conducted with 427 firms with various sizes (micro, small, medium and large) operating in six sub-sectors (automotive; electronic; machinery; chemical; food; and textile) of Turkish manufacturing. The paper examined nine I4.0 technologies: autonomous robots, big data applications, cloud computing, cyber security, simulation approaches, additive manufacturing, system integration, internet of things, and augmented reality. The results revealed that, there is a significant correlation between the degrees of importance and implementation of the basic Industry 4.0 technologies. Moreover, I4.0 implementation degree increases as the firm size increases. The top three industries in Turkish manufacturing that use the most basic Industry 4.0 technologies are automotive industry, electrical and electronics, and machinery, respectively. The analyses are aimed to achieve a better understanding of the concept Industry 4.0 by comparing different groups of manufacturers.

A R T I C L E   I N F O

Keywords:
Industry 4.0;
Additive manufacturing;
Autonomous robots;
Cloud technologies;
Cyber security;
Internet of things (IoT);
Big data;
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1. Introduction

Industry 4.0 (I4.0) defines a new technological era (i.e. the intelligent factory system that combines embedded system manufacturing technologies and intelligent production processes) that will change the industrial and production processes [1], while providing production ecosystems produced by intelligent systems with autonomous features such as self-structuring, self-monitoring and self-healing [2]. Integration of these systems creates an intelligent manufacturing environment which yields higher productivity and faster production of customized and high-quality products. The main idea in here is to capture a competitive industrial advantage with the help of the state of art technologies. This concept not only changes the dynamics of competition between the nations and the companies in the business world, but also reshapes the way of doing business and setting strategies for the future. Just like other industrial revolutions, The 4th Industrial Revolution is a process that requires structural changes, new business models, destructive innovations and paradigm shifts from centrally controlled to decentralized production processes [3, 4]. Another aspect of Industry 4.0 is its potential to contribute to the sustainability of future supply chains with optimum use of resources [5].

The concept of Industry 4.0 was first used in 2011 at the Hannover Fair in Germany [6]. Then it was developed to create a national policy by The German Government and dispersed to other countries in the world under the label of The 4th Industrial Revolution. Strategic initiatives of many countries around the world aim to catch the benefits offered by this new digital era. However, the structure of the manufacturing industry of each country and their advancement in production technologies differ. For this reason, some indices are needed to measure the compliance of countries with industry 4.0. The Roland Berger Readiness Index, defines four Industry 4.0 readiness categories for European countries: (1) Frontrunners with high manufacturing share and high readiness: Germany, Sweden and Austria; (2) Potentialists with low manufacturing share and high readiness: Belgium, Finland, UK, France, Netherlands; (3) Traditionalists with high manufacturing share and low readiness: Slovenia, Slovakia, Czech Republic, Hungary and Lithuania; (4) Hesitators with low manufacturing share and low readiness: Portugal, Greece, Poland, Bulgaria, Italy, Spain and Turkey [7]. Although Turkey seems to be one of the hesitators with low digitalization level in between European Countries, TUSIAD (Turkish Industry and Business Association)'s industry report reveals the potential of Turkish manufacturing industry for Industry 4.0 transformation.

The purpose of this study is to investigate the approaches and readiness of Turkish manufacturing firms to Industry 4.0 by using self-assessment tools. For this purpose, a survey was conducted with firms operating in six different sub-sectors of Turkish manufacturing. The outline of the article is designed as follows: The next section gives theoretical background of the term Industry 4.0 and the key technologies it covers. The third section presents a comprehensive review of the existing literature on Industry 4.0 including articles and reports. Fourth section presents the methodology of data collection, and the descriptive statistics. Section five presents the basic findings of the survey and the results of the analysis while section six presents concluding remarks of this study and discusses future studies.

2. Theoretical background of Industry 4.0

The number of studies on industry 4.0 is increasing since it was first introduced in 2011, and yet there is no single common definition of industry 4.0. Based on the common points of the definitions, industry 4.0 can be defined as the production systems that production is made by smart and autonomous machines that can communicate and coordinate with each other [9].

In the new era of digitalization, companies are expected to face a new dynamic environment focused on machine learning and real time data processing. Firms will be able to accelerate their data collection and analysis methods through flexible production process. They would produce higher quality products with lower costs and hence increase their efficiency with the opportunities offered by Industry 4.0.

In literature, Industry 4.0 encompasses nine technologies which are big data and analytics, autonomous robots, simulation, horizontal and vertical system integration, the internet of things, cybersecurity, the cloud, additive manufacturing, and augmented reality [10]. The classifications of key technologies of Industry 4.0 and the brief descriptions of each technique are as follows:

Big data and analytics: Large-scale datasets are a combination of large, complex, diverse and heterogeneous data generated from a variety of sources, such as click flows, sensors, video sharing, business processes, and social networks [11]. Data and data analytics are critical in digital and smart factories emerging with Industry 4.0. Therefore, data from many different sources need to be collected, classified, evaluated and made available for decision-making in real time.

Autonomous robots: The organizational structure that promotes human-robot collaboration in the production process is emphasized. Robots will interact with each other in this structure via internet. These collaborative robots (Cobots) will not only work closely with other robots, but also humans and learn from them for better practices [12].

Simulation: The physical production processes in factories can be reflected by a virtual environment with the help of simulation technologies. For example, quality improvement in functions such as testing, setup and installation can be performed in virtual environments. In addition to quality enhancement, cost savings can be achieved by decreasing setup and maintenance times with simulation technologies.

Horizontal and vertical system integration: Companies, departments, functions and capabilities will become more consistent with Industry 4.0, and cross-company and universal data integration networks will evolve to autonomous value chains. Horizontal integration allows firms to create, an effective ecosystem to share information, financial resources and materials, while vertical integration enables them to obtain flexible and restructured production systems [12].

The internet of things (IoT): "The IoT refers to an inter-networking world in which various objects embedded to electronic sensors, actuators or other digital devices where they can connect to each other and exchange the data they collected" [14, 15]. IoT technologies can be used for automation of various operations such as remote controlling, machining, lighting and heating. Furthermore, decision making is decentralized by machine to machine (M2M) interactions via internet of things.

Cybersecurity: Perhaps one of the most discussed negative aspects of digitalization is the issue of cyber security. Users of Industry 4.0 technologies will not only face the traditional cyber security challenges, but also the unique security and privacy challenges inherent in the digital Industry [2]. The mechanization of production processes and internet-based interaction and communication between machines increase the need for security especially in the critical industrial systems. Therefore, secure and reliable systems are vital for sustainability in Industry 4.0.

The cloud: Due to data-based production systems, the amount of data produced increases and effective management and storage of this data becomes important. Unlike the traditional storage services, cloud technologies provide storage space in a smaller area for a large amount of data from various sources [16, 17]. "Machine data and functionality will be deployed to the cloud, enabling more data-driven services for production systems" [10].

Additive manufacturing: Additive manufacturing technologies are the technologies that enable a model to be produced by means of three-dimensional computer aided design systems without the need of any process planning [18]. The system receives the information needed from a computer-aided design (CAD) program [19]. This technology facilitates the production of products with complex production processes.

Augmented reality: "Augmented reality (AR) can be defined as a computer graphics technique where virtual symbols are superimposed to a real image of the external world" [20]. Augmented reality technologies ease daily lives of the users by providing information about objects [21].

3. Literature review

The literature on the readiness and preparedness to Industry 4.0 is increasing with different types of publications. Our review on the current literature includes both academic papers and industry reports is given in Table 1.

Table 1 Literature review on Industry 4.0

Author	Topic/Aim is	Method	Results
Ratnasingam *et al.* (2019) [22]	to measure Industry 4.0 readiness of the firms operating in the furniture sector in Malaysia.	Survey method	- Machining centres and finishing processes are the processes requiring the most technological infrastructure - Driving forces on the way to digitalization are higher production capacity, cost, product characteristics and government policy. - The sector is not yet ready for Industry 4.0
Machadoa *et al.* (2019) [23]	to appraise the readiness of seven companies on the digitalization	Survey and case study	- Firms are at the beginning of the Industry 4.0 process. - One of the biggest obstacles related to Industry 4.0 is stated as lack of knowledge
Schumacher *et al.* (2019) [24]	to present a model to manufacturing companies related to Industry 4.0	Model design	- Model consists of 65 critical success factors to assess maturity, and roadmaps with 10-step. - The model was applied on manufacturing companies in Hungary, Austria, Germany, China, Slovakia and India.

Table 1 (continuation)

Pacchini *et al.* (2019) [25]	to propose a model of readiness of a manufacturing companies for Industry 4	Model design	- The model covers Industry 4.0 principles and technologies. - This model was implemented in auto-parts manufacturing company in Brazil. - The model provides information about the challenges in the transition to I4.0 to managers, and contributes to both theory and practice.
Castro *et al.* (2019) [26]	to present a model for self-assessment on the i4.0 readiness	Model design	- This model covers six dimensions: smart factory, data-driven services, smart operations, strategy and organization, smart products and human resources. - The result of this study shows that how a company can make better Industry 4.0 readiness level by using SHIFTo4.0.
Stentoft *et al.* (2019) [27]	to measure digitalization readiness level of small and medium-sized manufacturers	Survey method	- Danish SMEs have a low to moderate Industry 4.0 preparation. - Incentive implementations cause an in-crease in Industry 4.0 readiness
Castelo-Branco *et al.* (2019) [3]	to measure factors and the degree of adoption of Industry 4.0	Factor and cluster analyses	- There is a large distribution between countries in required conditions for that readiness.
Nick *et al* (2019) [28]	to search Industry 4.0 approaches in some countries such as Germany, Austria and Hungary	Model design	- This results help to capture the different phases of digitization and Industry 4.0 in these countries - This study defined objectives, strategies and also solutions for Industry 4.0 related problems
Medic *et al.* (2019) [29]	to evaluate the usage of advanced manufacturing technologies in Serbia	FAHP and PROMETHEE model	- The results show that, digital data sharing among supply chain members, production planning and production control systems are important issues in the context of I4.0 implementation.
Resman *et al.* (2019) [30]	to propose a new model based on I4.0 technologies for smart factory planning	Model design	- The proposed model is easy to use and offers a more reliable and simple modelling of smart factory compared to reference architectural model of I4.0.
Mittal *et al.* (2018) [31]	to analyse available systems and Industry 4.0 maturity models	Model design	- This study provides information to help improvement of realistic smart manufacturing.
Vieira *et al.* (2018) [32]	to introduce a R&D agenda for discrete-even simulation (DES) in the context of I4.0	Literature review	- The significant DES characteristics are: automation of data exchange, automatically generated simulation models and visualization.
Kusiak (2018) [33]	to provide a theoretical framework of smart manufacturing	Theoretical study	- Manufacturing technology, sustainability, networking, data analysis, material science and predictive engineering are the essential issues of smart manufacturing.
Basl (2017) [34]	to analyse the level of knowledge of firms and employees about I4.0.	Survey method	- 40 % of companies deal with Industry 4.0 for more than one year. - 75 % of companies says that their main reason for not implementing Industry 4.0 is low awareness of the topic.
Deloitte report (2017) [35]	to evaluate Industry 4.0 readiness.	Survey method	- Public institutions will be more effective in shaping society, the greatest impact on companies is to deliver the best possible product / service to customers, two most talked topics in the past year is to develop / create new products and services and improve productivity, technological initiatives are mostly in operations / processes.
Berger report (2017) [7]	to determine the advantages and disadvantages of Turkish food and beverage Industry in terms of Industry 4.0.	Survey method	- Although Turkey has the positive position in rankings, it is in the low country group in the readiness of Industry 4.0. - There are advisory steps as to how Turkey can ensure and improve readiness of Industry 4.0.
Europarl report (2016) [36]	to introduce related issues with Industry 4.0 such as its challenges and technologies.	SWOT analysis	- The supporting policies of the European Union for Industry 4.0; cyber security risks; and technological, social and business changes were discussed. - New policy proposals were presented.
TUSIAD report (2016) [8]	to analyse the opportunities emerging from Industry 4.0 and to demonstrate the potential of Turkish manufacturing Industry.	Survey method	- It was observed that some concrete steps have already taken for Industry 4.0 in Turkey. - It is sated that there is high-level of awareness and interest in the Industry to benefit from Industry 4.0 technologies and create competitive advantage in Turkey.
Infosys report (2015) [37]	to find out what the companies' plans for the technology journey are.	Survey method	- Although the majority of the companies are aware of the potential power of the Industry 4.0 technologies, only a few of them use these concepts in practice. - China is in a leading position compared to other countries. - The process Industry is the leader to the other industries.

4. Research method and sample description

This study tries to find out the readiness of Turkish manufacturing companies to the new digital era by examining the implementation degrees of basic Industry 4.0 principles in their businesses. The sampling manufacturers were drawn from the database of "The Union of Chambers and Commodity Exchanges of Turkey". The data was collected through a survey conducted by phone interviews. The data includes 427 observations (respondent firms) from six different manufacturing sectors. Sampling universe is determined as 600 firms at the beginning of the study, and we were able to have response from about 70 % of these firms. The sample industries are chosen in accordance with the Industry 4.0 report of TUSIAD, (2016) [8]. The sub-industries included in the study are electrical and electronic products, machinery, food and beverage, chemical, automotive, and textile manufacturing industries. Table 2 summarizes the distribution of these firms by industries.

The distribution of respondent firms by size is given in the Table 3. The sample includes micro, small, medium and large firms. The basic distinction between various size segments is based on SMEs (small and medium-sized enterprises) definition of EU (European Union) and Turkey. According to its definition, SMEs are examined mainly in three categories which are micro, small and medium-sized enterprises with personnel numbers "1-9", "10-49", "50-249" respectively [38, 39]. Since this study is aimed to investigate companies in all sizes, the segment of large firms having employees more than 250 is also included. In order to be able to make accurate comparisons, the composition of the firms in the sample universe was chosen homogenously.

According to Table 4 which indicates the respondent's position in the company, the great majority of the firms (252 firms) are represented by a "production manager" with the ratio of 59.3 %. The titles following "production manager" are general manager (20 %), company owner (6.1 %) and R&D manager (4.2 %), respectively.

SPSS 22.0 software package is used to analyse the data collected via survey.

Table 2 Distribution of firms by sector

Industries	Number of firms	Ratio
Electrical and Electronic Products Manufacturing	71	16.7
General and Special Purpose Machinery	70	16.5
Food and Beverage Manufacturing	71	16.7
Chemical Manufacturing	75	17.6
Automotive Manufacturing	68	16.0
Textile / Clothing Manufacturing	70	16.5
Total	425	100.0

Table 3 Distribution of firms by size

Size	Number of employees	Number of firms	Ratio
Micro	1-9	106	24.9
Small	10-49	107	25.2
Medium	50-249	107	25.2
Large	250 and more	105	24.7
Total		425	100.0

Table 4 Respondent's title in the firm

Respondent's title	Number of firms	Ratio
Production Manager	252	59.3
General Manager / Business Manager / General Coordinator	85	20.0
Owner / Partner	26	6.1
R & D Manager	18	4.2
Production Planning Manager	17	4.0
Quality Manager	11	2.6
Technology Manager	7	1.6
Factory Manager	5	1.2
Assistant General Manager	3	0.7
Other	1	0.2
Total	425	100.0

5. Results and discussion

The questions covered in the survey are aimed to understand the readiness of respondent firms for Industry 4.0 and the degree of implementation of basic Industry 4.0 concepts into their businesses. The first question of the survey is aimed to find out approaches of the firms towards the Industry 4.0 and it is adapted from the study of Basl [34]. Table 5 gives the respondents' answers. According to Table 5, although the great majority of the firms heard about the term Industry 4.0 with the ratio of 80.7 %, only 15.3 % (corresponds to 65 firms) of them are dealing with it for more than 1 year. By combining the new implementers, we can conclude that the total of 26.8 % firms are implementing the concepts of Industry 4.0. While 21.2 % of the companies admitted that they have not enough knowledge related to the concept of Industry 4.0, 32.7 % of them haven't considered its implementation due to various reasons.

Considering the approaches of the firms to Industry 4.0 technologies by sub-sectors, it can be concluded that the automotive manufacturing industry is the leader in implementing Industry 4.0 principles as expected. Together with the new implementers and long term users, a total of 35.3 % of the firms operating in automotive manufacturing industry have adopted Industry 4.0 principles into their business operations. Indeed, the automotive industry is expected to yield better results compared to the other industries, because it experiences the best practices of Industry 4.0. Following automotive industry, electrical and electronic and machinery manufacturing industries are the second and third industries with the highest ratio of the firms implementing Industry 4.0 practices. While 20.8 % of chemical manufacturers have adopted Industry 4.0 technologies, the ratios tend to decrease in textile and clothing (14.2 %) and food and beverage (12.8 %) industries. Data reveals that the great majority of the firms in textile and clothing industry have not heard about the term Industry 4.0. The ratio in this industry is twice as much as the average of all covered industries. The food and beverage industry has the highest ratio (34.3 %) among the companies who have heard the term Industry 4.0, but have no idea what exactly it covers. It can be said that both of these sectors need to be well informed about this new industry revolution and its content.

The summary of the distribution of the approaches to Industry 4.0 technologies by the size of the firms are given in the Table 6. According to Table 6, there is a positive and strong relationship between the size of the firms and their implementation of Industry 4.0 principles into their businesses. While more than half of the large firms have been implementing Industry 4.0 concepts, this ratio decreases as the firm size decreases. On the other hand, the number of companies who have not heard the topic Industry 4.0 increases as the firm size decreases. These results are in the line with the results of European Parliament Industry 4.0 Report suggesting that a large amount of investment is required by firms to catch the benefits of Industry 4.0 [32]. It is predicted that the necessary investment is about €40 billion annually until 2020 for Germany alone. In addition to capital and managerial needs, lack of qualified employees, and knowledge are the basic limitations that prevent companies from implementing Industry 4.0 technologies.

Table 5 General approach to the topic Industry 4.0

Statements	Number of firms	Ratio
We have been dealing with Industry 4.0 for more than 1 year.	65	15.3
We are trying to implement the concepts of Industry 4.0 right now.	49	11.5
We know the term Industry 4.0 but we haven't considered its implementation so far.	139	32.7
We have heard the term Industry 4.0 but we have no idea what exactly it covers.	90	21.2
We have not yet heard about the topic Industry 4.0	82	19.3
Total	425	100.0

Table 6 Summary of firms' approach to Industry 4.0 technologies by firm size

Statements	Firm size			
	Micro	Small	Medium	Large
We have been dealing with Industry 4.0 for more than 1 year, or we are trying to implement the concepts of Industry 4.0 right now.	9.4 %	14.9 %	28 %	55.2 %
We have not yet heard about the topic Industry 4.0.	35.8 %	23.4 %	13.1 %	4.8 %

In the next question, the managers are asked in what extent they apply Industry 4.0 principles and in which organizational department (unit) in their firm. According to the answers of the respondents, it is concluded that, 7.5 % of all firms implement Industry 4.0 principles in "finance and accounting departments" in advanced level. "IT department" follows "finance and accounting" with the percentage of 6.8 %. Following finance and accounting and IT departments, "production" (6.3 %), "product design" (5.9 %), "research and development" (4.4 %), "repair and maintenance" (4.2 %), "marketing and sales" (4 %), "purchasing" (3 %) and logistics (3 %) departments are using I4.0 principles in advanced level.

Table 7 lists the implementation degrees of the 9 basic technologies that constitute Industry 4.0. There are 9 technologies constituting Industry 4.0, which are autonomous robots, big data applications, cloud computing, cyber-security, simulation, additive manufacturing, system integration, internet of things and augmented reality [10]. The respondents are asked about the degree of their usage of each technology. They are given 1-7 Likert scale with the ratings from "1-never" to "7-advanced level". The resulting average scores are between 1.59 and 2.96 which are quite low, since the great majority of the firms responded as "never (1)". According to Table 7, the most used technology is cyber security with the mean of 2.96. It is followed by cloud technologies (2.22) and system integration (2.19), respectively. Having the mean of 1.59 augmented reality is the least used technology among these nine technologies. Although the means of implementation degrees are quite low in general, there are a numerous firms that use these technologies in an advanced level. Fig. 1 indicates the total number of the advanced implementers of each Industry 4.0 technology and their distribution by sectors.

Fig. 1 shows that cyber security is the most popular technology among all industries. While autonomous robots are widely used by electrical and electronic products manufacturers, system integration is mostly implemented by automotive manufacturers. The usage of big data and cloud technologies are relatively rare between the advanced users in all industries. We also used the ANOVA statistical method to test the differences between all types of sectors in implementation degrees of Industry 4.0 technologies. The probability value is below 0.05 in nine Industry 4.0 technologies. This result shows that there is statistically significant differences in the means of implementation degrees of Industry 4.0 technologies among the different types of industries.

The respondent firms are also asked in what extend the key concepts of Industry 4.0 are important to them (on a scale of 1 to 7). The results point out that, all of the concepts are important for the managers. As one can see in Table 8, the means of importance degrees are between 6.25 and 5.23, which are very close to the highest rate 7. According to the respondent firms, cyber security is the most important technology followed by autonomous robots and big data, respectively.

Among these nine I4.0 technologies, augmented reality is found to be the least common technology, since it has the lowest implementation degree with the mean of 1.59 and the lowest importance degree with the mean of 5.23. Hence, we can conclude that, augmented reality will be the most difficult I4.0 technology to introduce in the Turkish manufacturing sector.

Table 9 summarizes the correlations between implementation and importance degrees of Industry 4.0 technologies. Having a correlation coefficient r = 0.822, proves a positive and significant relationship between the implementation degrees of Industry 4.0 technologies and their importance to the firms. This result indicates that the manufacturing companies try to use the Industry 4.0 concepts which they find the most important.

Table 7 Implementation degrees of Industry 4.0 technologies

I 4.0 technologies	Number of firms	Mean	Standard deviation	Number of advanced users
Cyber Security	427	2.96	2.01	60
Cloud Technologies	425	2.22	1.63	19
System Integration	425	2.19	1.69	30
Internet of Things	425	2.06	1.58	19
Simulation Technologies	425	2.02	1.66	25
Big Data	425	1.94	1.55	18
Autonomous Robots	427	1.92	1.64	25
Additive Manufacturing	425	1.72	1.44	22
Augmented Reality	425	1.59	1.40	21

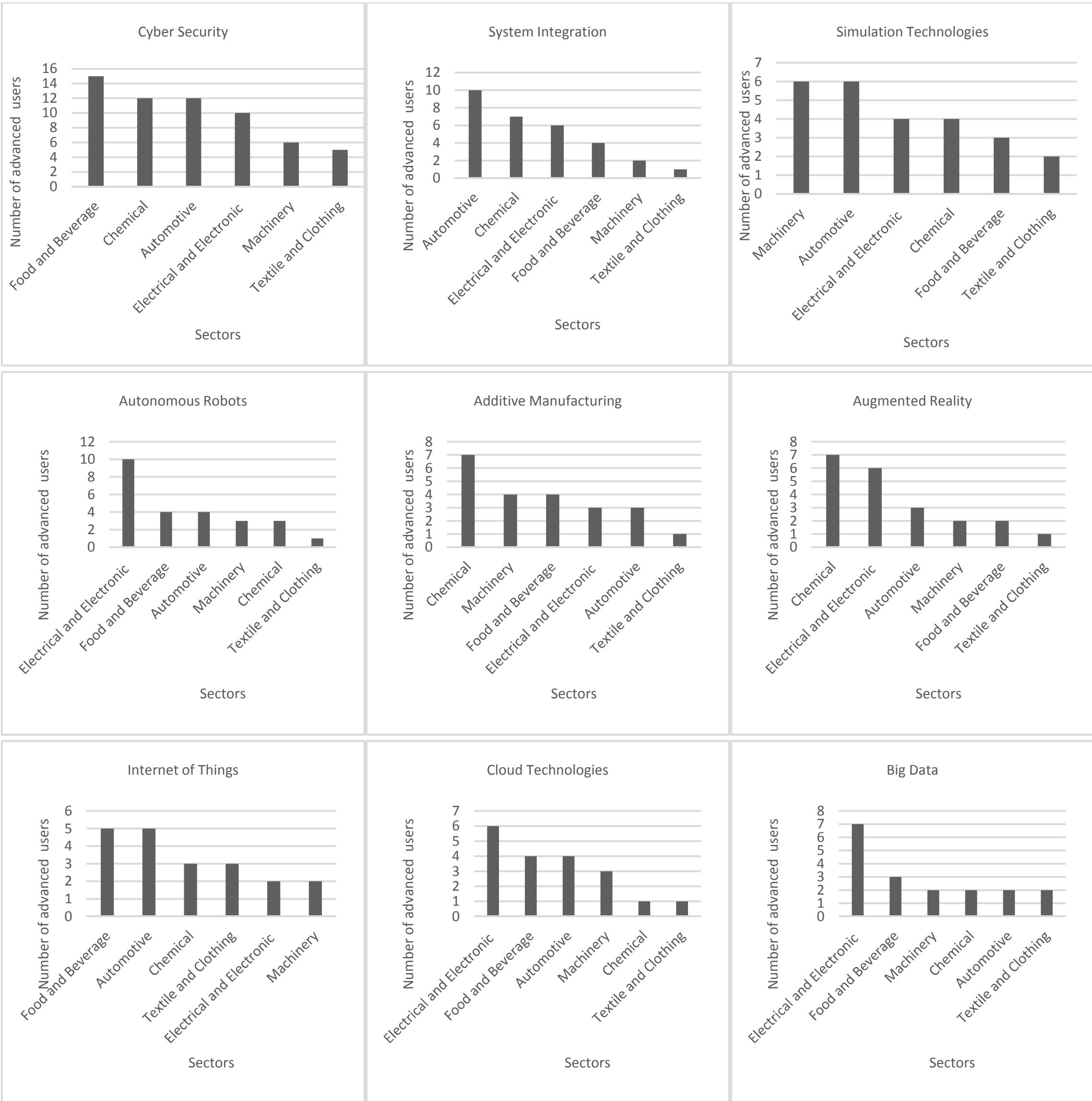

Fig. 1 Distribution of advanced implementers of Industry 4.0 technologies by sector

In this study, Cronbach Alpha (α) coefficient is calculated to test the reliability of the survey. There are 57 Likert-scaled questions in the survey. The overall Alpha (α) coefficient is calculated as 0.95 indicating a very high level of reliability.

In addition, the analyses indicate the existence of a positive and significant relationship between the implementation degrees of basic Industry 4.0 principles and the size of the firms. Fig. 2 shows the results of regression analysis between the number of manufacturing companies who are the advanced users of the basic Industry 4.0 technologies, and the size of these firms.

Table 8 Importance degrees of Industry 4.0 technologies

I4.0 Technologies	Observations	Mean	Std. Deviation
Cyber Security	426	6.25	1.30
Autonomous Robots	426	5.84	1.54
Big Data	426	5.59	1.57
System Integration	426	5.54	1.45
Internet of Things	426	5.52	1.53
Cloud Technologies	425	5.43	1.59
Simulation Technologies	426	5.39	1.59
Additive Manufacturing	426	5.32	1.62
Augmented Reality	425	5.23	1.63

Table 9 Correlations between the means of implementation and importance degrees

Correlations			
		Implementation degrees of Industry 4.0 technologies	Importance degrees of Industry 4.0 technologies
Implementation degrees of Industry 4.0 technologies	Pearson correlation	1	0.822**
	Sig. (2-tailed)		0.007
	N	9	9
Importance Degrees of Industry 4.0 technologies	Pearson correlation	0.822**	1
	Sig. (2-tailed)	0.007	
	N	9	9

** Correlation is significant at the 0.01 level (2-tailed).

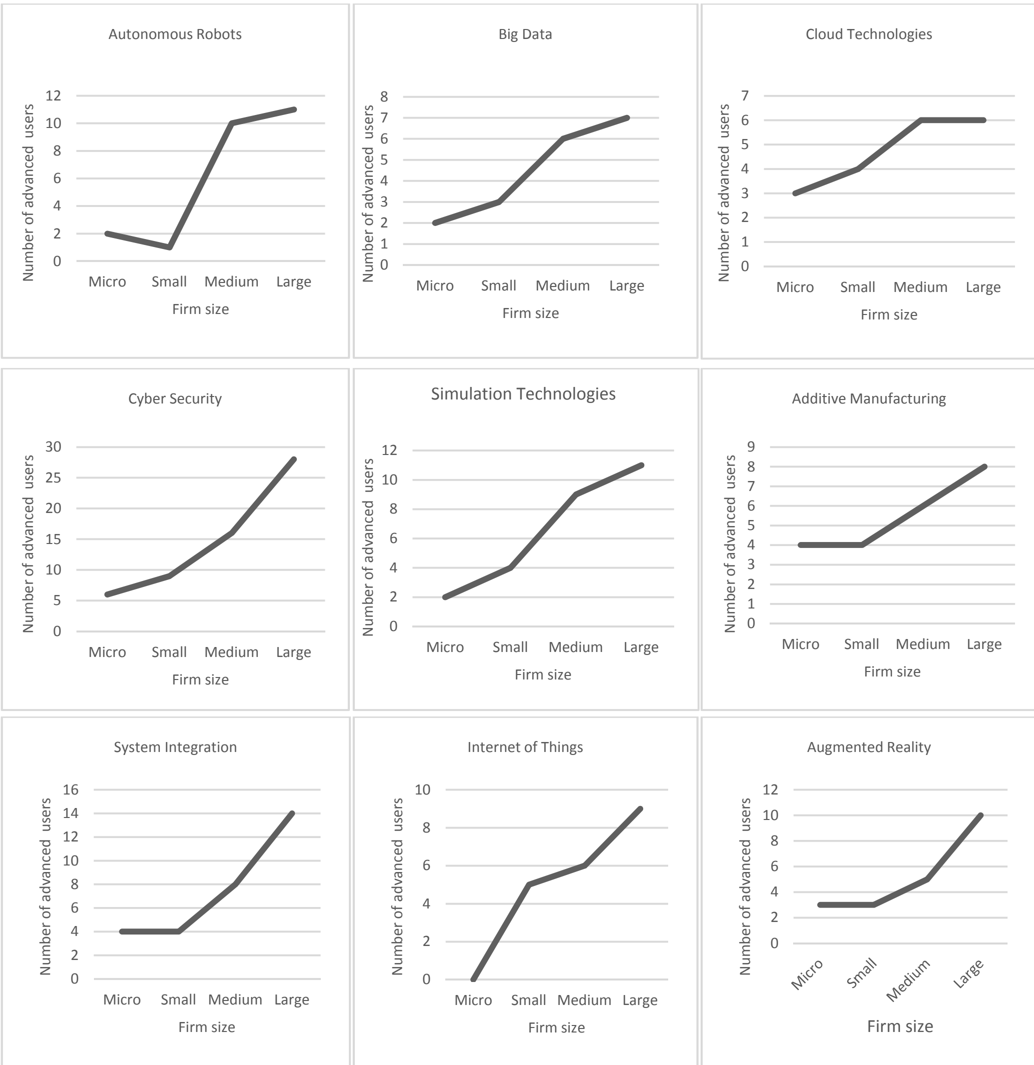

Fig. 2 The relationship between the number of advanced users and the firm size

According to Fig. 2 the number of advanced users increases as the firm size increases for the following technologies: big data, cloud technologies, internet of things, cyber security, and simulation. While there is no difference between micro and small firms for the technologies additive manufacturing and system integration, there is a slight decrease in autonomous robots for small-sized firms. However, the numbers of micro and small-sized firms are too few to make an accurate comparison. The increment is much more obvious in the middle-sized firms and large ones. ANOVA test are applied to test the differences between the firm sizes in implementation degrees of Industry 4.0 technologies. The probability value is below 0.05 in all Industry 4.0 technologies ($p \leq 0.05$). This result shows that there is a statistically significant differences in the mean implementation degrees of Industry 4.0 technologies among different sizes.

The survey results can be compared to the results obtained by the studies in other countries. The ratio of Turkish manufacturers who deal with I4.0 for more than one year is 15 % which is very low compared to the ratio in Czech Republic (40 %) [34]. Danish SMEs has an average readiness score of 2.9 (1 to 5-scale) [27]. Although the readiness score of Danish SMEs is interpreted as average, it is slightly higher than readiness scores of Turkish manufacturers. The firms are at the beginning of I4.0 process in Sweden and the main obstacle in transition to I4.0 is reported as lack of knowledge among Swedish firms [23] just like Turkish manufacturing firms.

6. Conclusion

This study presents the level of awareness and readiness of Turkish manufacturing firms for The Fourth Industrial Revolution. For this purpose, a survey was conducted with the managers of 427 firms of all sizes (micro, small, medium and large) operating in six sub-industries of Turkish manufacturing. The results indicate that the great majority of the firms are aware of the concept Industry 4.0 and its importance for their survival. Automotive, electrical and electronic, and machinery manufacturing are the first three industries in implementing Industry 4.0 principles while textile and clothing, and food and beverage manufacturing industries are the ones with the lowest ratios. The implementation level of Industry 4.0 technologies increases as the size of the manufacturing firms increase. It can be concluded that larger firms have relatively higher chance to reach the required financial or nonfinancial resources compared to small and medium-sized firms.

In this study, we examined nine basic Industry 4.0 technologies: autonomous robots, big data applications, cloud computing, cyber-security, simulation, additive manufacturing, system integration, internet of things, and augmented reality. Among these nine technologies, "cyber security" was found as the most popular Industry 4.0 technology in terms of both the importance and the implementation degrees. Although the implementation degrees of the related technologies are quite low on average, a number of firms, especially among large-sized firms, are advanced in implementing Industry 4.0 technologies. While the advanced users mostly implement the related digital technologies in their production, the priority of finance and accounting applications slightly surpasses the extensive usage in production.

Since there is a positive and significant correlation between the degrees of implementation and importance of basic Industry 4.0 technologies, we can conclude that the respondent firms try to use the technologies which are the most important (or familiar) to them. The priorities are defined by respondent managers according to their knowledge and understanding of the terms. When the survey results have been analysed, it is concluded that companies are confused about which digital application is considered within the scope of Industry 4.0. In order to help the manufacturing firms to catch the advantages of Industry 4.0 and ensure sustainable competitiveness, starting point might be to provide a comprehensive knowledge about Industry 4.0 technologies. By this way, firms would be able to decide the most adequate applications for their operations. Indeed, in order to catch the benefits of Industry 4.0, there is not only a need for significant amount of capital investment, but also for knowledge and training, strategic managerial approach, and qualified human resources.

We think that the biggest obstacle for fast implementation of Industry 4.0 into Turkish manufacturing industry is the lack of a collaborative strategy of digitalization. Such strategy needs acquiring and sharing a comprehensive up-to-date knowledge of technology. Furthermore, it should reflect the common goals and collaborative efforts of all members of supply chains in the manufacturing industry. The union of chambers, policy makers, researchers, and the sector leaders shall play a pioneering role in creation of such a technology sharing environment.

We hope, the results of this study help managers and decision makers in setting appropriate strategies and policies in adaptation to this new digital era. This is a preliminary study that reveals the awareness of the manufacturing firms about Industry 4.0 and their approach to Industry 4.0. Moreover, this research reveals the implementation and importance degrees of basic technologies related to Industry 4.0 for the Turkish manufacturing firms. In order to fully understand the current business environment and define a road map for manufacturers, future studies may focus on following issues: Corporate strategy for digitization, qualified workforce, organization and culture, infrastructure and other necessary resources.

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Assembly transport optimization for a reconfigurable flow shop based on a discrete event simulation

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A B S T R A C T

Reconfigurable Manufacturing Systems (RMSs) are widely used to produce small batches of customized products in the current manufacturing environment. We comprehensively optimized the assembly transport strategy, production process, and production configuration of a reconfigurable flow shop (RFS). Firstly, three assembly transfer strategies, one-to-one, one-to-many, and many-to-many, are proposed for an RFS, given the specific process limitations. In addition, a production simulation model of the RFS is established by the Plant Simulation software to verify and compare those three strategies with realistic production constraints considered. Moreover, the production processes are optimized, and the optimal buffer configuration and vehicle configuration are optimized by the design of experiment (DOE) method. After the optimization processes, the throughput and facility utilization under each strategy increases significantly. Additionally, the optimal buffer size and vehicle quantity under each strategy are determined and compared. The one-to-one strategy can maximize the production output, but it requires the most production resources. In addition, the many-to-many strategy is more efficient than the one-to-many strategy. Our study provides a variety of assembly transport strategies for an RFS and offers an efficient optimization method for production performance and production configuration.

A R T I C L E I N F O

Keywords:
Reconfigurable manufacturing systems (RMS);
Discrete event simulation;
Assembly transport strategy;
Optimization;
Plant Simulation;
Reconfigurable flow shop;
Production configuration;
Production performance;
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1. Introduction

The current manufacturing environment aims at getting an increasing variety of customized, high-quality products in flexible batches [1]. Reconfigurable Manufacturing Systems (RMSs) can rapidly change its structure, hardware, and software configuration to adapt to a dynamic market demand [2, 3]. With flexibility, the RMSs have been studied extensively [4-6].

For an RMSs, due to its frequent changes, the production performance and production configuration need to be optimized frequently and efficiently. Various methods have been proposed to optimize the RMSs. Amiri and Mohtashami optimized the buffer allocation using a genetic algorithm and line search method. They presented a multi-objective formulation and determined the optimal buffer size [7]. Many algorithms, such as the Simulated Annealing (SA) [8] and Genetic Algorithm (GA) [9, 10], are also used to optimize production performance. However, it is hard for algorithms to solve the problems that are closer to reality, and the convergence speed and efficiency of algorithms are usually slow for complex optimization problems [11].

Discrete event simulation (DES) is one of the most commonly used techniques for optimizing and analyzing manufacturing systems. It can be used to evaluate and optimize different alternatives of production configurations and operating strategies [12]. Because of its high flexibility, DES has been widely used in the design and operations of manufacturing systems [13-17]. Gyulai *et al*. evaluated different modular cell configurations using the DES [18]. Gironimo *et al*. optimized the scheduling problems of a high-speed train using the DES [19]. Leitão2012 *et al*. used the Delmia software and Petri net based service-oriented frameworks to design, analyze, simulate, and control manufacturing systems in a virtual environment [20]. Rifai *et al*. studied the scheduling problem of a flexible manufacturing system (FMS) and evaluated the part dispatching sequence and the routing options using the FlexSim [21]. Subulan and Cakmakci determined the major influential parameters that affect the performance criteria of a storage system, using the ARENA 3.0 program and MINITAB15 [22]. Renna and Ambrico developed three simulation models for the design, reconfiguration, and scheduling of a manufacturing system using the LINGO package [23].

In addition to those DES studies, the Plant Simulation software is widely used to optimize production performance and production configuration due to its powerful logistics simulation functionality. Andrade-Gutierrez *et al*. optimized a flexible die-casting plant using the Plant Simulation software. They evaluated several numerical models, identified the bottlenecks, and adjusted the production line components [24]. Ištoković *et al*. determined the size and entry order of the product batches, using the GA model implemented in the Plant Simulation software [25]. Yang *et al*. optimized the production process and main production configurations, including the equipment allocation, worker allocation, buffer allocation, and logistics vehicle allocation of an assembly shop [26]. Supsomboon and Varodhomwathana used the Plant Simulation software for production planning design for an automotive part production process to fulfill the desired capacity and customer needs with the minimum number of workers [27]. García-Montalvo *et al*. evaluated two different scenarios of the sand recovery in a pilot plant using the Plant Simulation software [28]. Malega *et al*. improved the production efficiency of a tapered roller bearing using the Plant Simulation [29]. Fedorko *et al*. identified critical points of failure within a specific delivery process for a Milk Run system with the help of Plant Simulation [30].

From the above literature review, we can know that production performance and production configuration have been studied extensively for the RMSs and other types of workshops using the DES. However, as one of the widely used RMSs, the reconfigurable flow shop (RFS) has not received much attention. Little literature has been published on it. Besides, for an RFS, due to its variability, an efficient and adaptable assembly transport strategy is also crucial. Nevertheless, to the best of our knowledge, no research efforts have been studied the assembly transport strategy for an RFS.

This study comprehensively optimized the assembly transport strategy, production performance, and production configuration of an RFS using the DES. Considering the specific characteristics of an RFS, we proposed three assembly transport strategies, which were one-to-one, one-to-many, and many-to-many. For each strategy, we illustrated the scheduling strategy, optimized the production performance, and determined the optimal vehicle configuration. The results show that the one-to-one strategy produced the most output, but its vehicle utilization was the lowest. In addition, the many-to-many strategy produces a relatively large output with a moderate number of vehicles. Our study provides and compares a variety of assembly transport strategies for the RFS and offers an efficient optimization method for production performance and production configuration.

The paper is organized as follows. Section 2 presents the workshop layout and process flow of an RFS. Section 3 illustrates the three proposed assembly transport strategies. Section 4 establishes the simulation model of the RFS, optimizes the production processes and vehicle configuration. Sections 5 compares the three assembly transport strategies. Finally, Section 6 summarizes conclusions and provides suggestions for future work.

2. Workshop layout and process flow

An RFS is used as an optimization case study. The workshop layout in Fig. 1 shows that this workshop consists of an automated storage and retrieval system (ASRS), denoted as AS00, and 13 assembly or detection workstations, denoted as AS01-AS13. All workstations are moveable so that the assembly line can be reconstructed in future production adjustments. Besides, the Automated Guided Vehicle (AGV) is used to transport products between workstations. Considering the workshop layout and process flow, we divide the workshop into two workshops, i.e., front workshop (from AS00 to AS10) and rear workshop (from AS11 to AS13). Two types of AGV vehicles, AGV1, and AGV2, are used for the two workshops, respectively. And the speed of the AGV vehicle is 0.34 m/s.

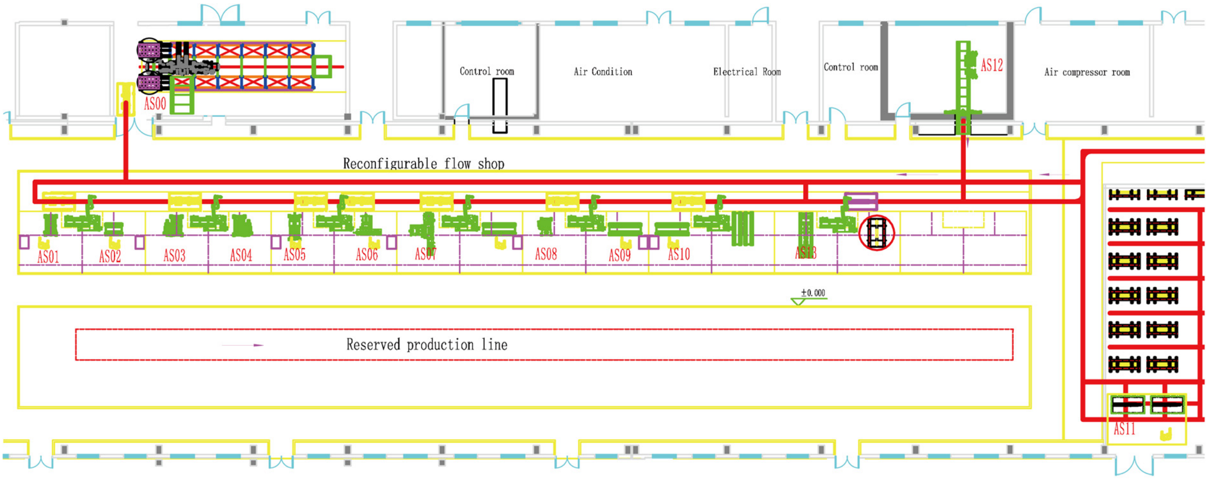

Fig. 1 Workshop layout of the reconfigurable flow shop

The workshop assembles a certain type of product. This product is mainly assembled by a main part and three sections (S1, S2, and S3). The main part and the three sections are first matched in the ASRS, i.e., AS00, and then transported by the same vehicle to workstations to ensure the corresponding relationship between the four parts. The three sections (S1, S2, and S3) are assembled to the main part in workstation AS01, AS02, and AS05, respectively. After AS05, all these three sections are assembled into the main part. Thus the product can be transported by other vehicles. Then some other assembly and detection operations are carried out in the following workstations (AS06-AS13). The operation time of each workstation is shown in Table 1. Moreover, some realistic constraints are considered. In the workstation AS00, the vehicle waits for 426 s to load all the three sections. In the workstation AS12, the vehicle maintains occupied before the operation finished.

Table 1 The operation time of each workstation

Workstation	AS00	AS01	AS02	AS03	AS04	AS05	AS06	AS07	AS08	AS09	AS10	AS11	AS12	AS13
Time/s	426	420	365	305	307	418	363	357	309	305	311	366	421	358

3. Proposed assembly transport strategies

As mentioned above, this workshop is divided into two workshops. In the front workshop, the three sections of the product are transported by the same AGV before those sections are assembled into the main part. According to the corresponding relationship between vehicles and workstations, three assembly transport strategies, one-to-one, one-to-many, and many-to-many, are proposed for the front workshop.

3.1 One-to-one

To ensure the corresponding relationship between the main part and three sections, we restrict it in the first assembly transport strategy that a vehicle can only transport the product away, which is processing on the current workstation. Therefore, one vehicle corresponds to one workstation, denoted as one-to-one. Every vehicle, AGV1, transports the main part and three sections of a product from the ASRS and transports them to the following workstations until AS10. After AS10, the product is transport by AGV2 to the rear workshop, and the AGV1 goes back to ASRS to transport parts of another product.

Two sensors for loading and unloading are set on the AGV route beside each workstation. When an AGV goes through the sensor, the operation for loading or unloading is triggered. Every running AGV has its destination information, which is Target Track and Target Workstation. If the current workstation is the target one, and the AGV is occupied, the product will be unloaded from the AGV to the Target Workstation. Then the AGV waits until a new transportation request is assigned to it and moves to the new destination. A new transportation request will be produced by a workstation when its operation is finished, and its next workstation is idle. For the one-to-one strategy, a vehicle can only fulfill the transportation request of the current workstation. The pseudocode of Unload is given in Fig. 2.

Procedure 1 Unload

```
if the current workstation is the Target Workstation and the vehicle is occupied then
    Stop the vehicle
    Unload the product from the vehicle to the Target Workstation
    Delete the destination of the vehicle
    Record the current time, t2
    Calculate the transportation time t, t = t2 − t1
    Waituntil a new request is assigned to the vehicle
    Get the Target Workstation and Target Track of the new request for the vehicle
    Move the vehicle to the destination using the shortest path principle
    Record the current time, t1
else
    Continue to move
end if
```

Fig. 2 The procedure of Unload

If the current workstation is the Target Workstation and the AGV is empty, an operation for loading is performed. The product is loaded from the Target Workstation to the AGV. Every product has its process information, including the Target Track and Target Workstation for all processes. The AGV will get the Target Track and Target Workstation for the next operation. Then, the AGV moves to the Target Track using the shortest path principle, which automatically plan the shortest route from the current location to the destination. The procedure is shown in Fig. 3.

Procedure 2 Load

```
if the current workstation is the Target Workstation and the vehicle is empty then
    Stop the vehicle
    Load the product from the Target Workstation to the vehicle
    Get the Target Workstation and Target Track from the product
    Move the vehicle to the Target Track by the shortest path principle
else
    Continue to move
end if
```

Fig. 3 The procedure for loading

3.2 One-to-many

The first transport strategy is simple, but it requires too many AGV vehicles. Hence we adopt the strategy to that one vehicle corresponds to many workstations, denoted as one-to-many. This means that a vehicle can fulfill the transport request of many workstations within a certain area. Under this strategy, six skip cars are introduced for AS00-AS05. A skip car carries the three sections (A1-A3) and the main part of a product at the same time, and the skip car is transported by an AGV to workstations. Therefore, the AGV can fulfill the transport request of other workstations without breaking the corresponding relationship between the four parts of a product. If one AGV is responsible for 5, 4, 3, and 2 workstations, the number of vehicles required for the 11 workstations in the front workshop is 2, 3, 4, and 5, respectively. The scope of workstations for each AGV under different number of AGVs is shown in Fig. 4. One vehicle is responsible for all the transportation tasks of all workstations within its scope. For example, if the number of vehicles is 3, the first AGV1 is responsible for workstations AS00-AS03. The second AGV1 is responsible for workstations AS04-AS06, and the last AGV1 is responsible for workstations AS07-AS10.

The procedure for loading and unloading is similar to those in the one-to-one strategy. However, for the one-to-many strategy, a vehicle can fulfill the transportation request of all the workstations within its scope.

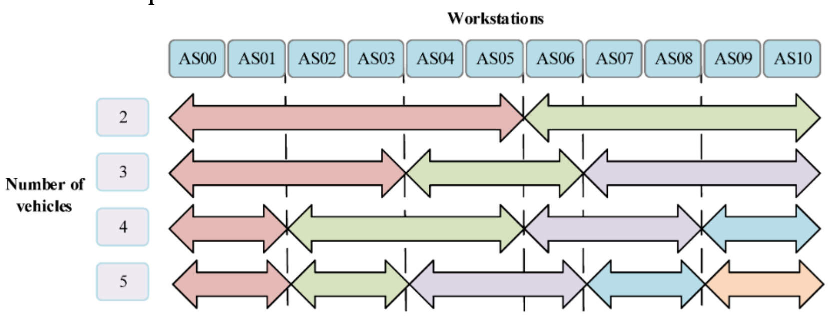

Fig. 4 Scopes of workstations for each AGV under different number of AGVs

3.3 Many-to-many

The last strategy is that many vehicles fulfill the transport request of many workstations within an area, and is denoted as many-to-many. Under this strategy, the front workshop is divided into two areas. The first area contains the workstations from AS00 to AS05, and the second one contains the workstations from AS06 to AS10. The first and second area is equipped with AGV1 and AGV3, respectively. And products in the rear workshop is still transported by the AGV2. For the first area, similar to the one-to-many strategy, six skip cars are used to carry the four parts of a product, and the skip cars are transported by an AGV. For the two areas of the front factory, the many-to-many strategy is used. Under this strategy, a certain area, which contains many workstations, is equipped with many AGV vehicles. When a vehicle finished its current transportation, it becomes available and can be used by all other workstations within this area.

When a workstation *a* finishes its operation, and its next workstation is idle, the workstation *a* generates a transport request and writes the request to the Distribution Table. Then, a method is accessed every 5 s to allocate the requests of the Distribution Table to a vehicle selected from the Available Vehicles. The Available Vehicles is the vehicle set of available vehicles within an area. If both the number of requests and the Available Vehicles are greater than 0, the first transport request is removed from the Distribution Table and assigned to an available vehicle. The vehicle is selected by the shortest distance principle, which first selects the vehicle closest to the workstation. Then the vehicle moves to its destination for loading or unloading. The pseudocode for allocating is shown in Fig. 5.

Procedure 3 Allocate requests to vehicles

m=sizeof(Distribution Table)
n=sizeof(Available Vehicles)
while $m>0$ and $n>0$ **do**
    Remove the first transport request from the Distribution Table
    Remove a vehicle from the Available Vehicles by the shortest distance principle
    Get the Target Workstation and Target Track of the request
    Move the vehicle to the Target Track by the shortest path principle
    Record the current time t_1
    Update the Distribution Table and Available Vehicles
    m=sizeof(Distribution Table)
    n=sizeof(Available Vehicles)
end while

Fig. 5 The procedure for allocating

A sensor for loading and unloading is set beside every workstation. When a vehicle passed by the sensor, the sensor is triggered. If the current workstation is the Target Workstation, the vehicle stops. Furthermore, if the vehicle is occupied, the vehicle unloads its product to the Target Workstation. Then, the vehicle becomes available and waits for a new transport request. If an empty vehicle reaches to its Target Workstation, the vehicle first loads the product from the Target Workstation and then moves to its destination by the shortest path principle. The pseudocode for loading and unloading is shown in Fig. 6.

In summary, three assembly transport strategies, which are one-to-one, one-to-many, and many-to-many, are proposed for the front workshop. Moreover, for the rear workshop, only the many-to-many strategy is used.

Procedure 4 Load or unload

if the current workstation is the Target Workstation **then**
    Stop the vehicle
    if the vehicle is occupied **then**
        Unload the product from the vehicle to the target workstation
        Delete the destination of the vehicle
        Record the current time, t_2
        Calculate the transportation time t, $t = t_2 - t_1$
        Append the vehicle to the Available Vehicles
        Waituntil a new request is assigned to the vehicle
    else
        Load the product from the Target Workstation to the vehicle
        Get the Target Workstation and Target Track of the product
        Move the vehicle to the Target Track by the shortest path principle
    end if
end if

Fig. 6 The procedure for loading and unloading

4. Modelling and optimization of the proposed transport strategies

This section establishes a production simulation model for the RFS. The three assembly transport strategies are implemented and verified in the model. Besides, production process and vehicle configuration of each strategy are optimized.

4.1 Establishment of the simulation model

The Plant Simulation software is used to establish the simulation model of the RFS. The simulation model mainly contains the ASRS, workstations, vehicles, scheduling strategies, experiment module, and statistical analysis. For more modelling information about the workshop logistics processes, please refer to [26]. Finally, the simulation model of the RFS is shown in Fig. 7.

The production is operated 7 hours a day and lasts for 10 days. The throughput, facility utilization, and vehicle quantity of those three transport strategies are evaluated and optimized.

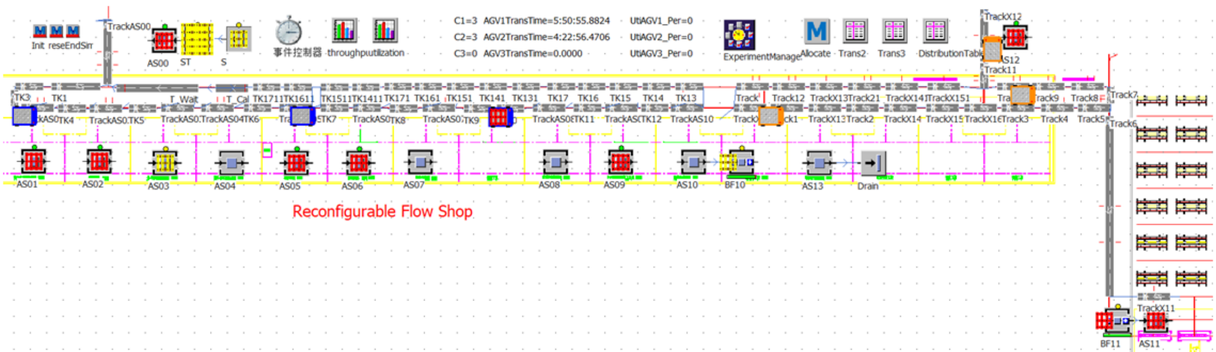

Fig. 7 Simulation model of the reconfigurable flow shop

4.2 Optimization of the one-to-one strategy

Recall that the front workshop contains 10 workshops and an ASRS, and the rear workshop contains four workstations. Firstly, sufficient vehicles (11 AGV1 and 5 AGV2) are provided for the two workshops to evaluate production performance. After 10 days of production, the throughput is 390, and the facility utilization is shown in Fig. 8A. Fig. 8A shows that the overall facility utilization is relatively low, and many workstations are blocked. The blockage appeared in AS10 and its front workstations. This is because the finished product in AS10 is to be transported away by the vehicles of the rear workshop. The rear workshop uses the many-to-many transport strategy, which may wait for a long time before a vehicle is available. Moreover, there is a long distance between the AS10 and the AS11. Thus, the finished product in the AS10 may wait for a long time before transported away, which results in a blockage in AS10. When AS10 is blocked, the workstations in front of it will also be blocked. To lessen the blockage, we set buffers after AS10 and before AS11, namely BF10 and BF11, respectively.

Buffer sizes are optimized by the design of experiment (DOE) method. The buffer size of BF10 and BF11 are increased from 0 to 3 and from 0 to 5, respectively. A total of 24 experiments are carried out, and the output is shown in Fig. 9A. Fig. 9A shows that when buffers are set, the throughput increases significantly. The maximum output is 566, which is 45.1 % higher than the output before the buffer optimization.

Among the experiments reaching the maximum output, the 10th experiment uses the least buffer size. In this experiment, the buffer size for BF10 and BF11 are 1 and 3, and this buffer configuration is chosen as the best one. The facility utilization under this buffer configuration is shown in Fig. 8B. It shows that after the buffer optimization, facility utilization of all workstations increases obviously, and blockages reduce significantly. However, workstations AS04 and AS11 still have some blockages. This is because the next workstation of AS04 and AS11 have more operation time, and no extra space exists besides the two workstations.

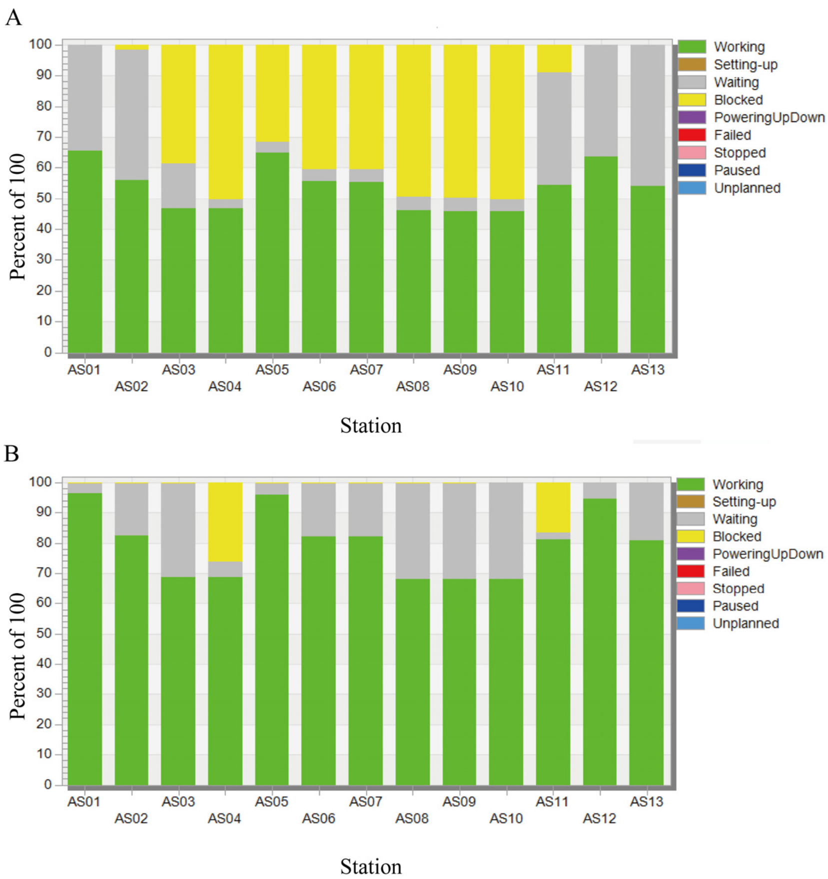

Fig. 8 Comparison of the facility utilization before and after the buffer optimization: (A) Before the buffer optimization, (B) After the buffer optimization

Under the optimal buffer configuration, vehicle quantity is optimized by the DOE method. The number of AGV1 and AGV2 are increased from 5 to 11 and from 1 to 5, respectively. Thus, a total of 35 experiments are carried out, and the output of those experiments are shown in Fig. 9B. Fig. 9B shows that when the vehicle configuration changes, the output varies greatly, from 304 to 566. In the 23rd experiment, the maximum output is reached for the first time. In this experiment, the number of AGV1 and AGV2 are 9 and 3, respectively.

Further analysis is carried out to find the relationship between the number of vehicles and the maximum output and vehicle utilization. The maximum output for a certain configuration of a type of AGV is the maximum output obtained when other types of AGV are equipped with the maximum number. Fig. 9C shows that with the increases in the number of AGV1, the maximum output increases. When the number of AGV1 increases to 9, the maximum output is reached for the first time. Before the maximum output, with the increase of AGV1, the output increases accordingly, and there are no significant changes for vehicle utilization. After the maximum output is reached, with the increase of AGV1, the output does not increase, but vehicle utilization decreases significantly. Fig. 9D also shows a similar trend for the AGV2. The maximum output is reached for the first time when the AGV2 increased to 3. Besides, the utilization of the AGV2 is obviously higher than that of AGV1. Finally, considering the output and vehicle utilization, we set the number of AGV1 and AGV2 to 9 and 3, respectively.

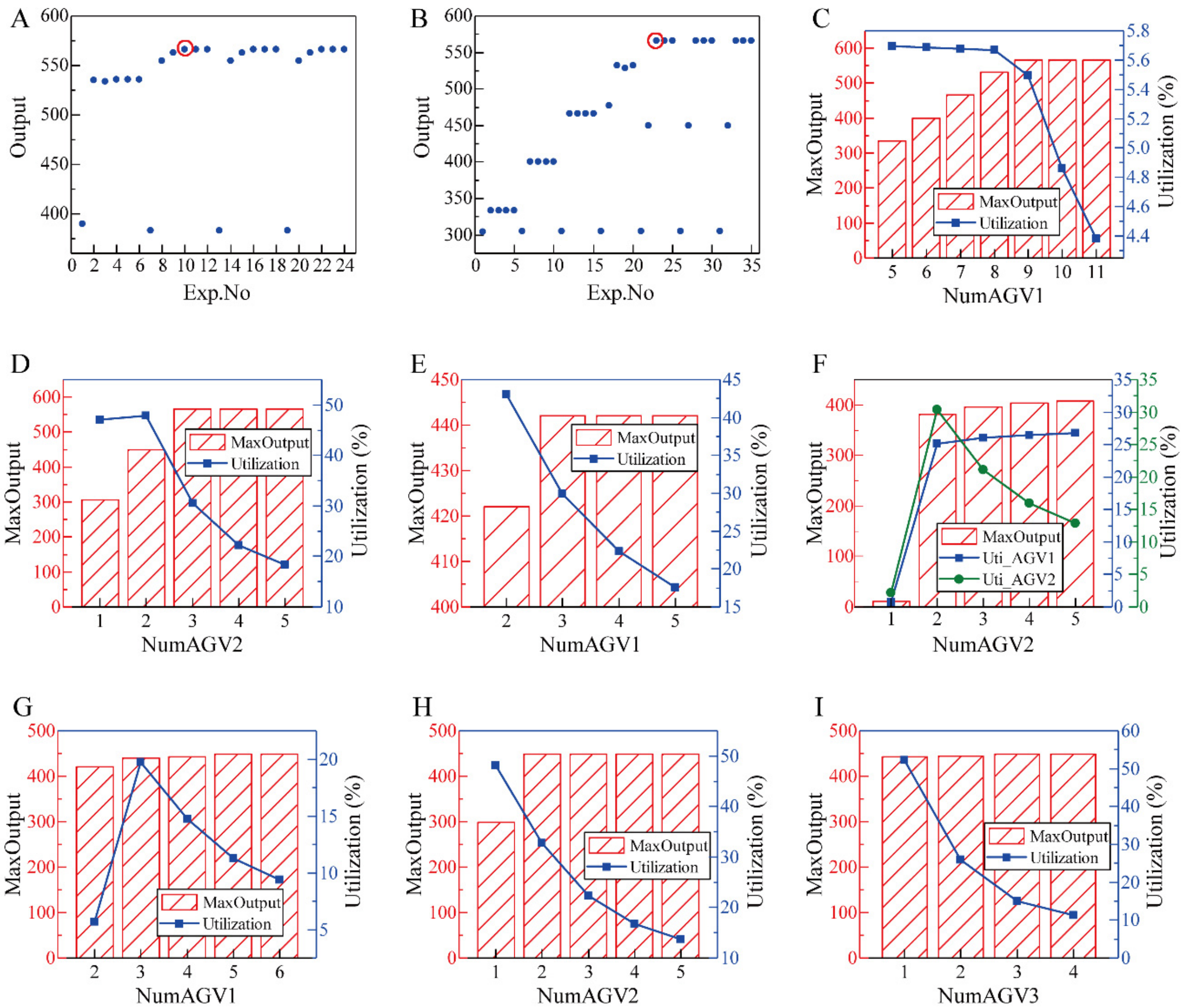

Fig. 9 The output and vehicle utilization of the optimization experiments for all three strategies: (A) The output of experiments in buffer optimization, (B) The output of experiments in vehicle configuration optimization for the one-to-one, (C-D) The output and vehicle utilization for the AGV1 and AGV2 under the one-to-one strategy, (E-F) The output and vehicle utilization for the AGV1 and AGV2 under the one-to-many strategy, (G-I) The output and vehicle utilization for the AGV1 and AGV2 under the many-to-many strategy

4.3 Optimization of the one-to-many strategy

As mentioned above, six skip cars are introduced in the front workshop. Firstly, to determine the best number of AGV1, the front workshop is considered separately, i.e., the production is finished after AS10. The number of AGV1 increased from 2 to 5. The maximum output and the vehicle utilization of all the four configurations are shown in Fig. 9E. Fig. 9E shows that when the number of AGV1 increased to 3, the maximum output (422) is reached for the first time. And vehicle utilization is relatively high. Therefore, the number of AGV1 is set to 3.

Under the optimal number of the AGV1 and sufficient number of AGV2 (AGV2=5), we optimized the buffer size of BF10 and BF11 using the same procedure for buffer optimization illustrated in the one-to-one strategy. After the optimization process, the optimal buffer size of BF10 and BF11 are set to 1 and 0, respectively.

Finally, the number of AGV2 is optimized under the optimal configuration of AGV1 and buffers. When the quantity of AGV2 increases from 1 to 5, the maximum output and the vehicle utilization of AGV1 and AGV2 are shown in Fig. 9F. As shown in Fig. 9F, the output is very low when there is only one AGV2. And when the number of AGV2 increases from 1 to 2, the output surges. However, when the quality increases from 2 to 5, the output increases slowly and reaches the maximum output (408) at 5.

The vehicle utilization for both AGV1 and AGV2 is very low when the number of AGV2 is set to 1 because of the low output. When the number of AGV2 increases from 2 to 5, the vehicle utilization of AGV1 increases slightly; however, the utilization of AGV2 decreased significantly. This is because the number of AGV1 is fixed at 3; its utilization increases slowly with a small increase in output. For AGV2, with the increase of vehicles, the output does not increase considerably; thus, the vehicle utilization decreases significantly. When the number of AGV2 is 3, the output is 396, which is close to the maximum output 408. Moreover, the utilization rate of AGV2 is relatively high, which is 21.1 %. Therefore, the number of AGV2 is set to 3.

4.4 Optimization of the many-to-many strategy

Six skip cars are used for the workstations from AS00 to AS05. Moreover, for the workstations from AS06 to AS10, AGV3 is introduced for transportation. We carry out a similar optimization procedure, as illustrated in the buffer size optimization for the one-to-one strategy. After the optimization, the optimal buffer size for BF10 and BF11 are 1 and 2, respectively.

The quantity of the three types of AGV is optimized by the DOE method. And the specific number of those AGVs is as follows: AGV1: 2-6, AGV2: 1-5, and AGV3: 1-4. Thus, a total of 100 experiments are performed. As shown in Fig. 9G, with the number of AGV1 increases, the output shows a slight increase. When the number of AGV1 is 3, the output is close to the maximum output, and vehicle utilization is the highest, which is 18.4 %. Fig. 9H shows that the maximum output can be achieved when the number of AGV2 is 2, and the vehicle utilization decreases markedly with the increase of vehicle quantity. Fig. 9I shows that for the AGV3, one vehicle can meet the production requirement. Finally, the number of three types AGV is set to 3, 2, and 1.

5. Comparison of the results and discussion

Three assembly transfer strategies are proposed for an RFS. For each strategy, the optimal vehicle configuration, buffer configuration, and vehicle utilization are shown in Table 2. As shown in Table 2, the output of the one-to-one strategy is significantly larger than the other two strategies. However, the vehicle utilization of AGV1 in the one-to-one is very low, which is 5.5 %, and the buffer size is large. This indicates that the one-to-one strategy can maximize the production output, but it requires more investment costs. Additionally, the one-to-many strategy generates the least output and requires the least buffer size. Moreover, the total number of AGVs used in the many-to-many strategy is equal to those of the one-to-many, but the many-to-many strategy produces 12.4 % more output than those of the one-to-many strategy. And the average vehicle utilization in the many-to-many strategy is also higher. It shows that the many-to-many strategy is more efficient than the one-to-many strategy.

Table 2 The optimal production configuration and its maximum output of the three strategies

	Max output	Number of vehicles			Vehicle utilization			Buffer size	
		AGV1	AGV2	AGV3	AGV1	AGV2	AGV3	BF10	BF11
one-to-one	566	9	3	-	5.50 %	30.50 %	-	1	3
one-to-many	396	3	3	-	26.30 %	21.10 %	-	1	0
many-to-many	445	3	2	1	18.40 %	32.20 %	53.30 %	1	2

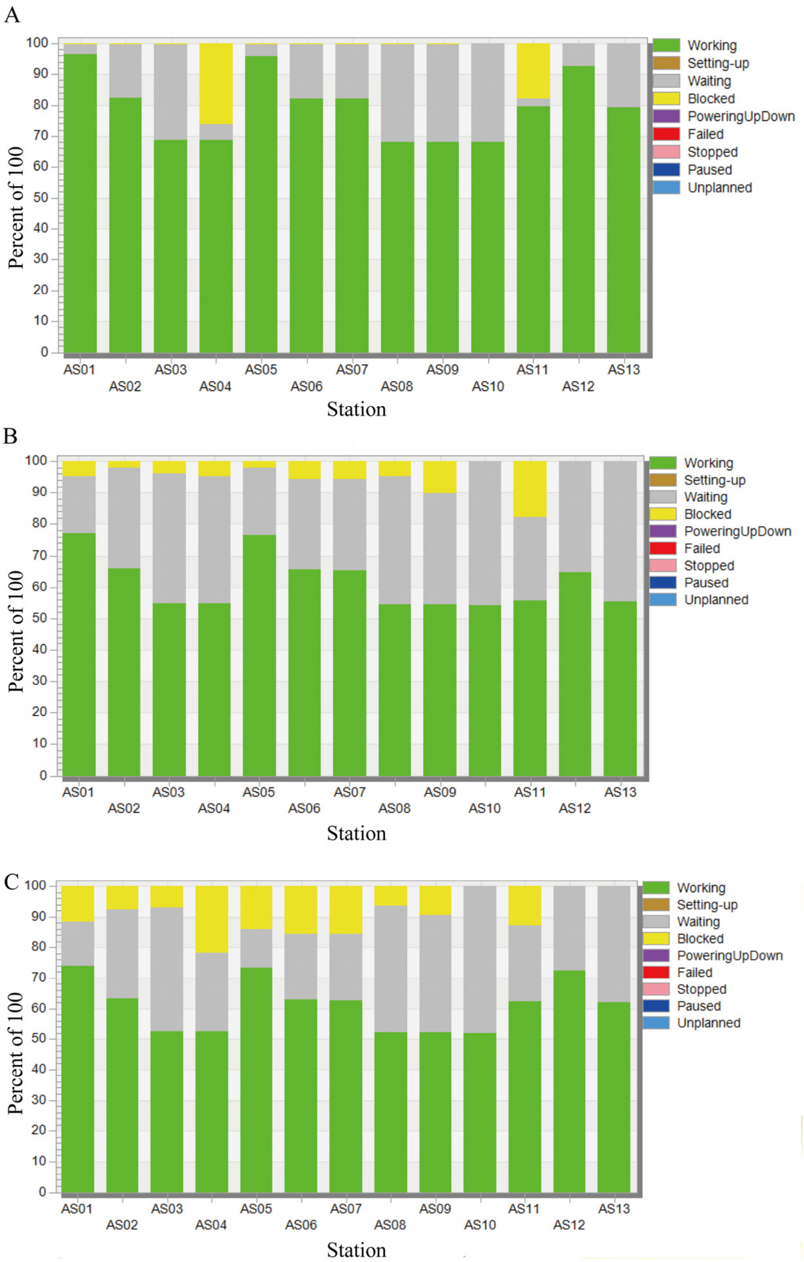

Fig. 10 The facility utilization of the three strategies under their optimal production configuration: (A) one-to-one, (B) one-to-many, (C) many-to-many

The facility utilization of those three strategies under their optimal vehicle configuration and buffer configuration is shown in Fig. 10. As shown in Fig. 10, the facility utilization in the one-to-one strategy is the highest, which is basically over 70 %, and the highest is 96.2 %. And there is no significant difference between the other two strategies. Considering the output, facility utilization, and production configuration provided, decision-makers can select a transfer strategy according to the market demand and investment cost.

6. Conclusion

We proposed three assembly transport strategies for a reconfigurable flow shop (RFS). We compared the three strategies using the DES, optimized the production performance, and determined the optimal buffer configuration and vehicle configuration of each strategy. Buffers are set at critical workstations to improve production performance. After the buffer optimization, the output and facility utilization increased significantly. The optimal vehicle quantity for each strategy is determined by the DOE method. Moreover, production performance and production configuration of those three strategies are compared. The results show that the one-to-one strategy obtains the maximum output and facility utilization, but it requires the largest number of vehicles. The many-to-many strategy generates relatively large output with a moderate number of vehicles. This study provides three assembly transport strategies for an RFS and shows that we can verify and optimize various scenarios using the DES. Our work has important implications for the reconfigurable workshop, which requires considerable simulation, verification, and optimization. However, the assembly transport strategy was designed for a flow shop. If the strategy was to be used for other types of workshops, vehicle scheduling must be adjusted accordingly.

Future research could be conducted to apply this assembly transport strategy to other types of reconfigurable workshops. Moreover, more production configurations, such as worker configuration and machine configuration, should be considered.

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The impact of using different lean manufacturing tools on waste reduction

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A B S T R A C T

Lean and green production was introduced to the western manufacturing industry nearly thirty years ago. The essence of the new business model was to eliminate waste through lean tools according to Taiichi Ohno's eight categories of waste. Many companies became more competitive with waste reduction techniques but some of them faced, and still are facing failures. Such failures are closely related with misapplication of lean and green tools, and its sequential order of implementation. In order to define most powerful lean tools for reduction of certain types of waste, a study was made among lean companies. The concept of a study was to define best lean toolbox for reduction of each category of waste and to determine right sequential order of lean tools implementation. Stepwise multiple regression model revealed that Total Productive Maintenance, Poka-Yoke, Kaizen, 5S, Kanban, Six Big Losses, Heijunka, Takt Time, Andon, OEE, SMED, and KPIs are best waste management techniques. Nevertheless, it has been demonstrated that 5S, Kaizen, Kanban, Poka-Yoke and TPM are highly recommended for start of every lean manufacturing initiative.

A R T I C L E I N F O

Keywords:
Green production;
Lean manufacturing;
Lean tools;
Waste reduction;
Waste management;
Waste reduction techniques

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1. Introduction

Many studies have proven that lean and green production can improve operational performance, regardless of the industry where it has been applied [1]. Despite this, many organisations face problems with lean implementation, less than 10 % of organisations which have implemented lean in the U.K. were successful [2]. Studies made in automotive plants in the U.K., U.S.A., and India also showed that the success rate of lean implementation is also low [3]. Each organisation has its individual view of lean methodology, but the success of lean implementation is closely related to the work culture and ongoing efforts to create a value-system approach [4]. Many organisations undergoing lean implementation are looking for a lean-tools implementation 'cookbook'; however, this can provide only short-term improvements [5]. During the process of 'going lean', lean tools are the key to the lean philosophy for organisations because they represent something practical. Philosophy is good for business, but tools work [6]. To achieve long-term benefits from lean production (LP), organisations should focus on building the proper culture, where the culture represents the values, traditions, and ways of thinking that shape the organisation's identity [7]. Recent studies of proper lean implementation have pinpointed that the transition should be made with a project-based approach, with focus on the specific lean tool [8]. If the selection model of lean tools is inaccurate during the lean implementation period, the lean success will be poor or even suspended [9]. All lean activities should have process approach, where problems have to be solved one after another. Study on Czech companies pointed that usage of standard parts together DFLs (Design for Logistics) can make great results [10].

2. Literature review on lean implementation

The lean concept can be implemented through various methods, but consistent vision is a 'must-have' when an enterprise is moving towards LP [11]. Another vital task for going lean is to create sense of urgency [12] and to create short-term goals to achieve a continuous pace of small improvements [13]. These elements are important for lean implementation, but the most significant element for adoption and sustainability of the lean concept is the organisational culture [14]. It is easier to implement lean in collectivistic cultures than in cultures that promote individualism [15]. The lean concept is a continuous process of seeking perfection that involves everyone in the organisation, including the owners, with a vision of creating a competitive business [16]. The next key element of a successful lean transition is creation of deep understanding among people that the activities they perform have impact on themselves [17]. If an organisation is trying to change its employees' mind-set, the leaders must expend much effort toward achieving the desired behaviour. Lean leadership is the interconnection between the lean toolbox and continuous improvement of the organisation. Leadership is an important element of continuous improvement but leading as an activity is not value-adding, whereas a shop-floor worker is the person who adds value to the product. Shop-floor workers must be encouraged to drive continuous lean improvement [18], so to describe importance of shop floor workers, an often quoted Toyota principle could be used: 'Before we build cars, we build people' [14].

Many authors are proposing a lean roadmap or framework for the transition process of lean implementation to provide an organisation with a general set of guidelines for lean applicability [19]. It has been proven several times that the best lean transitions are provided in the form of roadmaps, where the framework contains well-structured information on principles and practices [8]. In addition, many studies have proven that small and medium-sized enterprises (SMEs) and large companies face different challenges during the lean transition; thus, the lean framework must be adapted to the enterprise size [20]. The next necessity in a successful lean transition is management commitment and leadership [21]. Management must be charismatic, active, and visible on every level and share their enthusiasm for execution of the transition [22]. In lean management, it is preferable that the management know the company very well, and ideally, they should have worked their way up through all organisation levels. This ensures that management has deep knowledge on all business and production activities, while their deep sense for organisational processes gives them an advantage in coaching others [23]. Every company, but also every country can take benefit from this business model. Recent authors have revealed advantages of lean companies in comparison with others towards going Industry 4.0. Lean companies have better organizational integration, standadatization on all levels, complete and precise communication while all activities are essential. This way integration of machines and real time data is minimized to only value-added activities, and Industry 4.0 is meaningful [24].

Lean production can be described and measured as a toolbox full of methods and tools for waste reduction or elimination [25]. On a strategic level, LP can be described as a philosophy; on a tactical level, LP is a set of principles; and on an operational level, LP is a set of practices and tools [26]. Therefore, the biggest challenge for an organisation is to acquire the proper lean tool in time to effectively accomplish its desired goals [27]. People involved in the lean transition must have sound knowledge and an in-depth understanding of lean thinking to achieve effective lean tools and sustain the transformation process [28]. There are over one hundred lean tools that can be implemented, but the most important lean management tools are 5S, Bottleneck Analysis, Continuous Flow, Value Stream Mapping (VSM), Heijunka (Level scheduling), Hoshin Kanri (Policy deployment), Jidoka (Autonomination), Just-In-Time (JIT), Kaizen (Continuous improvement), Kanban (Pull System), Key Performance Indicators (KPIs), Muda (Waste), Overall Equipment Effectiveness (OEE), Plan-Do-Check-Act analysis (PDCA), Poka-Yoke (Error Proofing), Root cause analysis, Single-Minute-Exchange of Dies (SMED), Visual Factory, SMART goals, Standardised Work, Takt Time, Total Productive Maintenance (TPM), Gemba (The real place) and Six Big Losses, as of March 23, 2017, as Vorne Industries listed on its website. Some researchers suggest implementing all or most lean tools to achieve a successful lean transition [29], but the most frequently used lean principles among large multinational enterprises are Standardised work, Kaizen, Quality programs, Pull System, Flow Orientation, Value Stream, Employee Involvement, Visualisation, Customer Focus, Stability and Robustness, Workplace Management, and JIT. SMEs have a distinctive characteristic compared to large companies, and study made in Serbia has revealed that Standardized Work, 5S, VSM and Kaizen can have significant role in lean implementation [30]. All these principles and tools must be seen as a direction, and not as an end goal [31]. However, the implementation of a different set of lean tools, in conjunction with other relevant factors, will put the organisation in a different state at certain times. Lean was first adopted by automotive industry [32], so it is significant to mention major lean tools that have the most positive impact on automotive organisations. Research on 91 automotive organisations has resulted in awareness that 5S, OEE, the 8-step problem-solving method, Pareto Analysis, Elimination of Waste, Kaizen, Setup Time Reduction, Process Mapping, and VSM are the lean tools that are the most influential in automotive industry environment [33]. All these tools have significant meaning in their respective environments; however, tools must not be copied directly from the literature. Lean practices and tools must be adapted carefully for each organisational framework to achieve a continuous improvement with a strong local impact [34].

3. Materials and methods

3.1 Overview

The guiding concept of this research was to point out major operational features of the lean transition process, with the ultimate goal of addressing the best lean tools for reduction or even elimination of waste according to Taiichi Ohno's 8 types of waste. The research was carried out in Croatia during 2017 and 2018 in the form of a questionnaire, where lean companies were identified through the three criteria presented in subchapter 3.2.

Generally speaking, all interviewed persons were from upper or middle management and closely related to business development. The survey covered nearly 300 companies; however, it should be noted that approximately 230 companies stated that they do not use or have never used lean manufacturing in their management models.

The questionnaire form was divided into three segments, where each segment was designed to reveal a certain aspect of the lean transition:

1) The first segment of questionnaire was in the form of scoreboard, where respondents provided information about their waste according to Taiichi Ohno's 8 types of waste.
2) The second segment of the questionnaire was based on a lean-tools implementation framework, and respondents provided information about the lean tools they had implemented, the lean tools had some positive impact, and the sequential order of lean tools implementation.
3) The third segment of the questionnaire was in the same form as the first segment, as a scoreboard, where respondents provided information about their improvements according to Taiichi Ohno's 8 types of waste. This segment of the questionnaire was designed to provide feedback about the lean implementation success.

3.2 Criteria for selecting the lean companies

Three forms of acquiring data were used for identifying lean companies in Croatia:

- The first form was created at the Green and Lean Production conference 2017 (GALP 2017). This conference was chosen for data collection because this is the largest conference in Croatia that deals with lean manufacturing. This conference was attended by approximately 150 lean practitioners from 40 companies.
- The second method was by contacting the Croatian Chamber of Economy and obtaining a list of all the companies that had attended lean presentations and courses in the last five

years. In this method, approximately 70 companies were contacted, although only 13 companies stated that they use lean manufacturing. These 13 companies completed the questionnaire.
- The last method was based on simply interviewing the best companies in Croatia. The best way to find successful companies in Croatia was to procure a list of the best companies in 2017 from the most-read business journal. Nearly 200 companies were contacted, while 32 replied affirmatively, saying that they use lean manufacturing.

Altogether, approximately 300 companies were covered by this research, where 63 companies were pinpointed as companies that used or still use lean production tools in their everyday activities.

3.3 Used software tools

This study was made in Statistical Package for the Social Sciences (SPSS) on a sample of 63 lean organisations, wherein a stepwise multiple linear regression model (SMLR) was carried out to find the most significant lean tools for boosting the reduction of different types of waste. As Taiichi Ohno categorised waste into eight types, it was logical to focus the survey on the quest for the most significant lean toolbox for each waste type. The input variables were the lean tools usage and improvement in the reduction level of the observed waste type. Specifically, the dependent variable (improvement level of waste reduction for the observed waste type) was measured on a scale from 0 to 3, where 0 stood for 'no improvement', 1 stood for 'small improvement', 2 stood for 'medium improvement', and 3 stood for 'huge improvement'. On the other hand, the independent variable (lean tools usage) was qualitative, where 0 stood for 'we did not use this lean tool' and 1 stood for 'we used this lean tool'. This statistical approach has resulted in clear findings, and the most significant lean tools for waste reduction forecast were determined.

4. Results and discussion

Generally speaking, the concept of lean manufacturing appeared in Croatia several years ago, but many companies still have not had enough courage to implement this concept and culture in their core business activities. Almost 300 companies and 25 lean tools were included in this survey, and 12 lean tools were identified as the best for boosting waste reduction.

4.1 Waste (losses) before going Lean

Lean is the constant search for perfection, where people make incremental daily improvements by eliminating waste. Therefore, it is important to see where the organisation creates small, medium, and large losses before the lean concept is implemented. If the organisation does not know its type and scale of waste, it is possible that incorrect lean tools will be launched to reduce or solve waste. When we talk about the scale of waste in a Croatian organisation, it is clear from Table 1 that these organisations generally have medium or small losses.

Table 1 Survey responses regard waste (losses) before lean

Rank	Type of Waste (Losses)	Subtype of Waste	0	1	2	3
7	Surplus production	Producing products that can't be launched on the market	43%	37%	19%	2%
		Conducting unnecessary operations	2%	56%	33%	10%
		Excess administration	8%	35%	37%	21%
		Poor market demand forecasting	19%	46%	30%	5%
		Production 'just in case'	32%	30%	27%	11%
4	Excess transport	Unnecessary circulation of material between operations	16%	35%	40%	10%
		Ineffective data transfer	3%	30%	52%	14%
		Unsuccessful communication: unreliability and data loss	8%	41%	37%	14%

Table 1 (continuation)

5	Waiting	Latency between operations	5%	41%	37%	17%
		Poor production and processes planning	8%	32%	44%	16%
		Waiting for approval or signature	25%	44%	16%	14%
		Untimely supplier delivery	11%	33%	38%	17%
8	Excess processing	Unreliable or faulty technological equipment	37%	38%	21%	5%
		Bad product design requiring too many processing	35%	27%	32%	6%
3	Redundant stock	Huge inventory on hand 'frozen capital'	17%	27%	37%	19%
		Huge quantities of redundant data in the archives	8%	35%	38%	19%
6	Unnecessary movements	Bad machinery arrangement resulting in movement	22%	44%	21%	13%
		Workers wandering in order to obtain information	13%	49%	27%	11%
		Poor workplace ergonomics	14%	48%	24%	14%
2	Fallout (reject)	Interruption of production flow for poor information	14%	33%	41%	11%
		Time required for fault correction	10%	27%	37%	27%
1	Insufficient use of employee potential	Insufficient use of employee potential	5%	41%	32%	22%
		Poor detection of capable employees	5%	46%	33%	16%
		Insufficient inclusion of workers in the improvements	2%	38%	40%	21%
		Note: scale of waste defined as: 0 = no waste; 1 = small waste; 2 = medium waste; 3 = huge waste				

4.2 Most frequently used lean tools and sequential order of implementation

The lean concept is a philosophy, lifestyle, and culture, but the development of such a lifestyle and culture must be supported by tangible practices, which brings us back to the significance of lean tools. In recent years, there has been a lack of studies made on the sequential order of implementation of lean tools. Enterprises crave a lean implementation cookbook, but nearly all authors have given up on this topic. It is clear that each company has its individual starting point and financial strength before going lean, but some lean tools should have an advantage in implementation over others. Therefore, we can see from Table 2 and Fig. 1 that 5S and Kaizen are the lean tools most used at the beginning of the lean transition. These lean tools are not state-of-the-art tools from the lean concept view, but these tools effect fast and visible improvements in the shop-floor environment. Study made on 49 Polish enterprises revealed that most frequently used tools are 5S, 5xWhy, SMED, Team Work, Standardized Work, Root cause analysis and TPM [35]. All these tools are also in narrow focus of Croatian companies but they tend to use more Standardized Work, Kaizen, 5S, KPIs and VSM. However, Polish companies have ranked waiting, unnecessary movements, fallouts and redundant stock as major waste. On the other hand, Croatian companies have most challenges with reduction of insufficient use of employee potential, fallouts, redundant stock and excess transport. In other settings, such as Lithuania, study among 41 enterprises revealed that most used lean tools are employee training, quality control line in work process, standardized work, gemba, 5S, lean dashboards and PDCA.

Generally speaking, the tools like 5S, Kaizen, VSM, Kanban, Standardised Work, SMART Goals, Muda, and Gemba were the first choice for eliminating waste in Croatian companies. It should be pointed that 5S, Kaizen and Mieruka (Visual Management) are also backbone of most lean initiatives in Vietnam. But then also, Vietnam study revealed that these tools can be more powerful if people have deep understanding on performed tasks. More precisely, if people see benefit in activities, performance will be better, consequently resulting better effectiveness [17].

After the implementation of these tools, the Croatian companies have focused on the implementation of tools like Poka-Yoke, Andon, Continuous Flow, Jidoka JIT, KPIs, OEE, SMED, etc. These tools are more sophisticated than the first one, because they are more complex and require a deep understanding of lean. It is also notable that these tools require more financial resources in implementation than 5S, Kaizen, VSM, etc. In the last phase of lean transition at the Croatian companies, tools like Heijunka and TPM played a significant role.

Table 2 Lean tools implementation framework according to survey participants

Lean practice	1	2	3	4	5	6	7	8	9	10	11	12
5S	49%	22%	19%	8%	0%	3%	0%	0%	0%	0%	0%	0%
Andon	0%	13%	25%	25%	13%	13%	0%	0%	0%	0%	13%	0%
Bottleneck Analysis	7%	34%	14%	14%	24%	7%	0%	0%	0%	0%	0%	0%
Continuous Flow	5%	25%	0%	15%	15%	15%	5%	5%	5%	5%	5%	0%
VSM	23%	27%	27%	3%	7%	3%	7%	0%	3%	0%	0%	0%
Heijunka	0%	0%	17%	0%	33%	17%	0%	0%	33%	0%	0%	0%
Hoshin Kanri	15%	5%	15%	15%	25%	0%	10%	10%	0%	0%	0%	0%
Jidoka	11%	33%	11%	11%	17%	0%	6%	6%	0%	0%	0%	0%
JIT	9%	0%	17%	22%	4%	4%	17%	4%	9%	4%	4%	4%
Kaizen	41%	24%	11%	19%	0%	0%	3%	0%	0%	3%	0%	0%
Kanban	27%	7%	20%	0%	13%	13%	7%	7%	0%	0%	7%	0%
KPIs	14%	20%	26%	11%	6%	9%	3%	3%	3%	3%	0%	3%
Muda	24%	33%	14%	10%	0%	5%	0%	5%	0%	5%	0%	0%
OEE	8%	15%	31%	0%	8%	15%	8%	0%	8%	0%	0%	0%
PDCA	8%	25%	17%	25%	17%	0%	0%	8%	0%	0%	0%	0%
Poka-Yoke	0%	17%	25%	17%	8%	8%	0%	0%	8%	8%	0%	8%
Root Cause Analysis	16%	0%	11%	16%	16%	16%	11%	5%	0%	0%	11%	0%
SMED	0%	5%	19%	19%	19%	10%	5%	10%	0%	0%	0%	10%
Visual Factory	4%	16%	28%	4%	20%	20%	4%	0%	0%	0%	0%	4%
SMART Goals	25%	11%	18%	14%	18%	11%	4%	0%	0%	0%	0%	0%
Standardized Work	23%	21%	8%	15%	10%	5%	8%	5%	0%	0%	3%	0%
Takt Time	14%	7%	0%	29%	0%	7%	14%	7%	0%	7%	0%	0%
TPM	0%	0%	0%	24%	14%	14%	24%	14%	5%	0%	0%	0%
Gemba	19%	19%	25%	6%	13%	19%	0%	0%	0%	0%	0%	0%
Six Big Losses	0%	20%	0%	20%	0%	20%	20%	0%	20%	0%	0%	0%

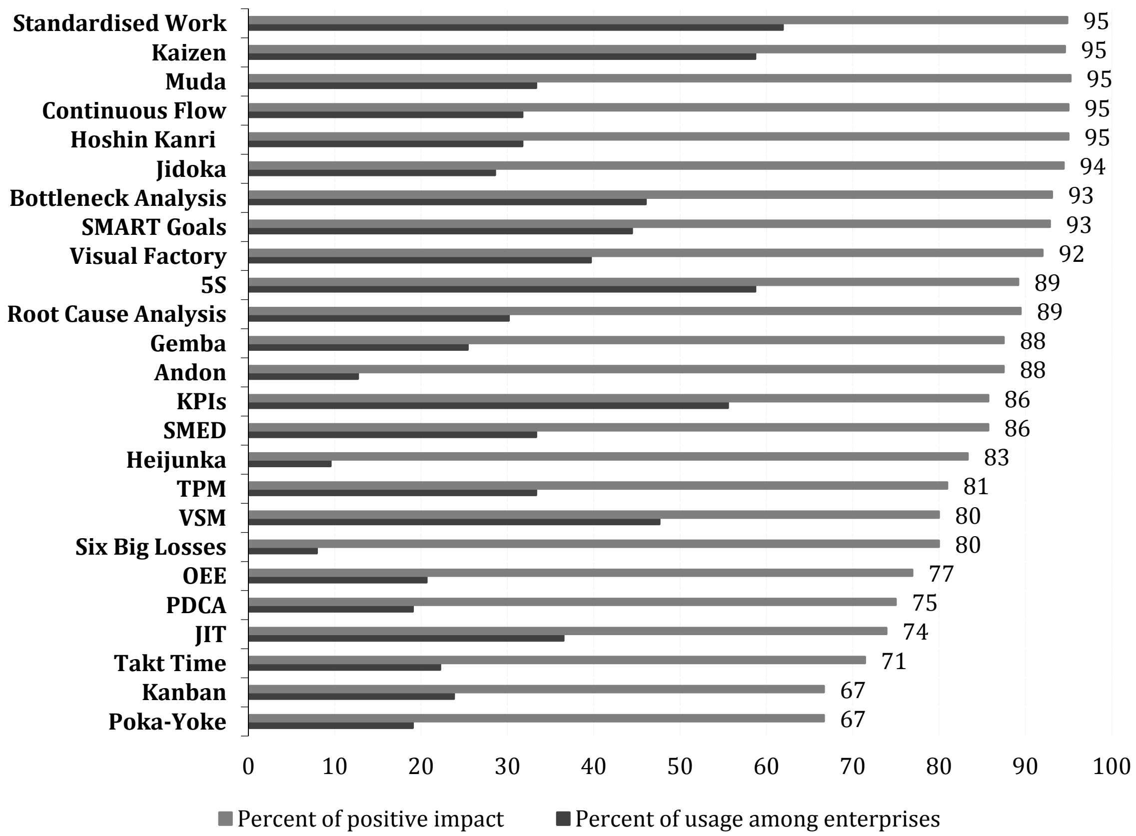

Fig. 1 Lean tools impact according to survey participants

Table 3 Survey responses regarding waste (losses) reduction after lean implementation

Rank	Type of Waste (Losses)	Subtype of waste-reduction improvement	0	1	2	3
6	Surplus production	Producing products that can be placed on the market	40%	48%	10%	3%
		Better operations performance	16%	57%	19%	8%
		Reducing administration	19%	52%	21%	8%
		Better market demand forecasting	29%	48%	17%	6%
		Production with smaller stock	22%	51%	21%	6%
3	Excess transport	Better circulation of material between operations	22%	29%	41%	8%
		Better data transfer	6%	46%	37%	11%
		Better communication: data reliability	6%	44%	38%	11%
4	Waiting	Reducing latency between operations	11%	48%	27%	14%
		Better production and processes planning	8%	43%	32%	17%
		Reducing waiting time for approval or signature	40%	35%	19%	6%
		Better and faster supplier delivery	44%	37%	13%	6%
8	Excess processing	Reliability or better choice of technological equipment	49%	38%	10%	3%
		Better product design not requiring a lot of processing	54%	29%	11%	6%
7	Redundant stock	Reducing inventory on hand 'frozen capital'	33%	46%	11%	10%
		Reducing quantity of redundant data in the archives	25%	54%	14%	6%
5	Unnecessary movements	Machinery arrangement resulting in less movement	38%	38%	19%	5%
		Shorter wandering to obtain information	17%	51%	25%	6%
		Better workplace ergonomics	30%	37%	30%	3%
2	Fallout (reject)	Improvement of the production flow	13%	40%	35%	13%
		Reducing time for fault correction	11%	38%	33%	17%
1	Insufficient use of employee potential	Better use of employee potential	10%	43%	37%	11%
		Better detection of capable employees	6%	48%	33%	13%
		Inclusion of workers in the improvement processes	6%	38%	33%	22%

Note: scale of improvement defined as: 0 = no improvement; 1 = small improvement; 2 = medium improvement; 3 = huge improvement

Many companies in Croatia mentioned waste elimination as a trigger for going lean, precisely 67 %. Other triggers mentioned by more than 50 % of participants were increase of efficiency (89 %), profitability (70 %), productivity (67 %) and reduction of manufacturing costs (65 %). Just as a comparison, Polish organizations seek to increase company's operation (81 %) and be more competitive (50 %) through lean management [35]. Again, Lithuanian companies are more oriented on increase of efficiency, problem solving, housekeeping level and overall improvement of organization [36]. The biggest improvements in waste elimination of Croatian companies were achieved in terms of the use of employee potential, fallouts, transportation, and waiting (see Table 3). When we examine Table 1 to determine the largest waste in Croatian companies according to the survey responses, we can see that the insufficient use of employee potential and fallouts are in first and second place. Therefore, many Croatian companies have detected their weakest spots and tried to solve them through the lean concept correctly. On the other hand, redundant stocks and excess transportation were detected by the Croatian companies as the third and fourth most significant waste through survey responses, but waste-reduction progress was not as high as it should be. Excess transportation is in fourth place, and redundant stock is in seventh place of waste-reduction progress. Therefore, we can conclude that only the appropriate lean toolbox can reduce the targeted waste type.

4.3 Most significant lean tools for waste reduction or elimination

The backbone of this research was to find statistically significant lean tools for the reduction of different types of waste. As was said earlier, SMLR was executed on a sample of 63 organisations to address among 25 basic lean tools only one with statistically significant positive impact on waste reduction. Eight SMLR analyses were carried out in SPSS to analyse the relationship between single dependent variable (waste-reduction improvement level on the observed waste type) with twenty-five independent variables (lean tools usage). The goal was to find a set of independent variables that significantly influence the dependent variable. More simply, the goal was to find, for each waste type, a set of statistically significant variables (lean tools) in the data set, resulting in the best models to increase the predicted waste-reduction improvement level. Such SMLR models could direct lean beginners in right direction during lean implementation and point statistically significant positive lean tools for certain waste types.

Dependent variable for each type of waste was precisely defined through two or more quantifiable measures (subtype of waste-reduction improvement), see Table 3. Survey respondents had to evaluate their subtype of waste-reduction improvement on a scale from 0 to 3 and those answers were summarised into one number from 0 to 3 that was presenting waste-reduction improvement level on the observed waste type. On the other hand, independent variables were defined through the survey respondent used or the implemented lean tools. Each organisation used different lean tools, therefore it was necessary to examine if there is any connection between used or implemented lean tools and waste-reduction improvement level of observed waste type.

The first step for building SMLR models was to check normality, linearity, homoscedasticity, and multicollinearity of data. All assumptions for building SMLR models were checked before running the models. Statistical analyses carried out in SPPS showed us that each type of waste has its best SMLR model for prediction of waste-reduction improvement level (see Table 4). These models are pinpointing statistically significant positive independent variables (lean tools) for prediction of waste-reduction improvement level. In layman's terms, the lean tools in Table 4 are good for implementation in terms of waste reduction, but each type of waste should be reduced with unique set of lean tools presented in the mentioned table.

Furthermore, we can divide the statistically significant lean tools into two groups. The first lean tools group comprises lean tools that statistically significantly reduce several waste types. These tools are TPM, Poka-Yoke, Kaizen, 5S, and Kanban (see Table 5). The second lean tools group comprises lean tools that are statistically significantly reducing only one type of waste. These tools are Six Big Losses, Poka-Yoke, Heijunka, Takt Time, Andon, OEE, SMED, and KPIs (see Table 5).

Summarizing findings presented in Tables 2, 4 and 5 we can say that each lean implementation should be launched and supported by 5S, Kaizen, Kanban, Poka-Yoke and TPM since these waste management techniques reduce several types of waste. In doing so, 5S and Kaizen should be implemented first, Kanban and Poka-Yoke immediately after, while TPM as most powerful waste management technique should be implemented last and with great care. This way, company will achieve quicker higher level of lean maturity whereas progress will be visible on every corner.

Table 4 Best SMLR lean toolbox models for prediction of dependent variable

	Surplus production	Excess transport	Waiting	Excess processing	Redundant stock	Unnecessary movements	Fallout (reject)	Insufficient use of employee potential
R	0.628	0.681	0.742	0.546	0.59	0.582	0.585	0.521
R^2	0.394	0.464	0.55	0.298	0.348	0.339	0.342	0.271
p	0	0	0	0	0	0	0	0
	TPM	**Poka-Yoke**	**Takt Time**	**Poka-Yoke**	**OEE**	**SMED**	**Poka-Yoke**	**TPM**
B (β)	0.697 (0.564)	0.740 (0.410)	0.712 (0.435)	0.653 (0.356)	0.572 (0.352)	0.521 (0.353)	0.932 (0.470)	0.711 (0.441)
	Six Big Losses	**5S**	**Andon**	**TPM**	**Kanban**	**Kaizen**	**Kaizen**	**Kaizen**
B (β)	0.546 (0.254)	0.557 (0.387)	0.638 (0.312)	0.410 (0.269)	0.545 (0.353)	0.392 (0.277)	0.516 (0.326)	0.359 (0.232)
		Heijunka	**5S**		**TPM**	**KPIs**		
B (β)		0.599 (0.248)	0.394 (0.285)		0.446 (0.320)	0.329 (0.235)		
		Kanban	**TPM**					
B (β)		0.350 (0.210)	0.368 (0.255)					

Table 5 Most significant lean tools for waste reduction

Lean tool	Sum of waste types this tool statistically significantly reduces	Usage of this tool will average make progress in waste reduction on scale from 0 to 3
TPM	5	0.526
Poka-Yoke	3	0.775
Kaizen	3	0.422
5S	2	0.475
Kanban	2	0.447
Six Big Losses	1	0.546
Heijunka	1	0.599
Takt Time	1	0.712
Andon	1	0.638
OEE	1	0.572
SMED	1	0.521
KPIs	1	0.329

On the other hand, if organization has goal to reduce one specific type of waste, then statistically significant waste management techniques presented in Table 4 should be applied. For example, if an organisation has problems with redundant stocks, it should use OEE, Kanban, and TPM to ensure that waste reduction will be done in a best possible way. The multiple-correlation coefficient (R) for the redundant-stocks lean toolbox is 0.590, which means that we have a good level of prediction of the dependent variable. The coefficient of determination (R^2) is 0.348, which means that our independent variables explain 34.8 % of the variability of our dependent variable. Table 4 also shows that all independent variables statistically significantly predict the dependent variable, $p < 0.05$ (i.e., the regression model is a good fit of the data). Finally, we can see from the unstandardized coefficients (B) for the redundant-stocks lean toolbox that the use of OEE will improve the reduction of redundant stocks by 0.572 points, the use of Kanban will provide another 0.545 points of improvement, and use of TPM will provide another 0.446 points of improvement. This result shows us that OEE is best predictor of the dependent variable (improvement level of waste reduction on the redundant stocks). Specifically, if we implement OEE in our organisation, we will improve the waste reduction of redundant stock of 0.572 point on a scale from 0 to 3.

A stepwise multiple regression model has shown us that organisations must use the proper lean toolbox for each type of waste. The desired outcome will be achieved with less effort and within a shorter period. This approach is an optimal path, and those who use this logic are saying, 'We prefer to use a scalpel rather than a sledgehammer'.

5. Discussion

There are many factors for lean implementation success. These factors are primarily related to active leading by management, employee education, communication, employee involvement in improvement processes, etc. No matter how well management leads the lean implementation, sooner or later, the lean toolbox will appear, and many questions will be raised. Among many authors, the lean framework is in the top ten critical success factors for lean success. There is no lean concept without lean practices. Lean without tools is just a philosophy. However, lean tools without a value-adding culture are unnecessary.

The Croatian industry missed its chance to be the pioneer of lean in Europe many years ago, but it has a chance now to become more competitive for the upcoming Industry 4.0. and to reduce negative environmental impacts by applying this concept. This survey documented that companies tend to make lean transitions in no more than nine steps, where each step produces a wish to implement one or more lean tools. Some lean tools or practices are used more frequently than others, but their significance cannot be determined only by their occurrence ratio. Lean-tools impact feedback, determined by an SMLR model, must be the measure of their greatness. The presented statistical model has shown us that TPM, Poka-Yoke, Kaizen, 5S, Kanban, Six Big Losses, Heijunka, Takt Time, Andon, OEE, SMED, and KPIs are statistically significant lean tools for waste reduction or even elimination.

Lean was created in a manufacturing environment, and its significance is commonly related to operative and strategic mind-set changes. This survey documented that lean is still the most frequently used method for the operative and strategic restructuring process. Lean tools are not a state-of-the-art product of the lean concept; they are simply visible practices that introduce a desired cultural and mind-set change among all people. A value-adding culture is a final product of lean, whereas a consistent search for perfection must be its basic principle.

Lean is one of many concepts for business improvement; however, successful lean implementation is characteristic of many market leaders. Organisational changes are a necessity on today's market. If market leaders are willing to make deep changes, then there is no excuse for others to not make the necessary changes. Many organisations wanted to adopt lean throughout the years, but lack of knowledge, loss of enthusiasm, and bad decisions led to poor change. Leaders and management are setting the direction of the change by their principles and practices. Lean tools are not just boring procedures, they are setting a framework for future changes. Lean can be simple, pragmatic, and comprehensive for all users only through lean tools. They represent organisational directions and aims.

6. Conclusion

This paper documented the most frequent and most significant basic lean tools for waste elimination among lean practitioners. The documented lean implementation framework enabled us to examine the occurrence of lean tools in all lean implementation stages, where the key lean tools were pinpointed. The results can help organisations see the lean experts' way of thinking. Every organisation should investigate the best practices in their industry for lean implementation. The lean practices identified in this survey are not unique lean implementation paths. Each company should redesign and adapt the lean framework for its needs.

In brief, the management must have a deep understanding of organisation waste and sound knowledge of the lean toolbox to make lean implementation more successful. It is wise to use lean tools that reduce several types of waste as the first steps of lean implementation because they have a statistically significant positive impact on waste reduction. Each lean tool has its own waste-reduction impact. Some tools are more reliable for waste reduction, and others for other tasks. Generally speaking, management should know its priorities before going lean. Going lean is a never-ending process, and tools and practices have a huge impact on lean transformation and creation of smart factories.

This study has some limitations. The lean practitioners interviewed through this survey were involved in lean implementation, but they had an individual view on waste before and after the lean concept. Second, the lean implementation is a long process in which many lean tools are implemented. The presented study investigated 25 basic lean tools; however, the interviewed lean practitioners might have implemented other lean tools during their implementation. Third, some interviewed organisations have a higher lean maturity level and have been using the lean concept much longer than others. Therefore, they have better progress in terms of waste elimination. In general, these results are based on the subjective vision of lean practitioners.

Lean implementation has many critical factors for success. This study has proven that lean tools are involved in every lean implementation. In addition to lean tools, there are many other factors that influence the success, duration, and sustainability of the lean concept. Further investigations should focus more on how managers conduct lean-tools implementation in various industries and other countries.

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Integrated management systems based on risk assessment: Methodology development and case studies

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A B S T R A C T

The implementation of management systems in organizations is often based on a "blind" meeting of requirements set by the selected standard, while these requirements are not in direct relation to the risks of the organizations. Therefore, it often happens that the established management system is not operational or is not aligned with the context and real needs of the organization. This paper presents general model for the design of an integrated management system based on risk assessment of organization's processes. The model was based on the primary hypothesis that a process that has a higher risk should be described in more detail in order to be adequately realized. The presented Model was tested on three diverse companies which had already implemented management systems according to international standards. Comparing the existing with the projected documentation in three companies, it was concluded that the number, scope and structure of documented information were optimized for successful risk management, which lowers the overall costs and enables efficient management of the company. The paper provides scientific approach and methodology for designing the integrated management system in any organization, using existing risks as universal integrating factor.

A R T I C L E I N F O

Keywords:
Integrated management system;
Risk management;
Process approach;
Failure mode effect analysis (FMEA)

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1. Introduction

The survival and prosperity of every company are closely related to the existence and control of various risks that arise in all aspects of business. Organizations are constantly forced to improve their risk management systems in order to be successful and achieve objectives in global conditions of rapid changes. Therefore, the top management of each organization must insist on adequacy and effectiveness of risk management system. As all the activities in the organization have certain risks that need to be managed, it is clear that the best way to handle those risks is to treat them within an integrated management system (IMS) [1]. This leads to a conclusion that the functional IMS must be aimed towards efficient and effective management of risks.

If the organization chooses to achieve conformance with specific standard requirements, it will reduce or eliminate some strategic and operational risks that could endanger business continuity. Those organizations that evolve faster will integrate their management systems, which should result with a competitive advantage in achieving higher added value rate and sustainability in competitive business world [2, 3]. A detailed review of management standards leads to the conclusion that every standard is bounded to the particular category of risks that can jeopardize functioning of the organization. This conclusion leads to the following:

- Implementation of standard ISO 9001 should reduce risks that can have a negative impact on customer satisfaction and quality of the processes.
- Implementation of standard ISO 14001 should reduce risks that can degrade the environment.
- Implementation of standard OHSAS 18001 should reduce risks of injuries and occupational ill health.
- Compliance with HACCP principles and standard ISO/EN 22000 provides a system that eliminates risks at all stages of the food chain.
- Standard ISO/IEC 27001 recommends the usage of appropriate mechanisms to treat information security risks, etc.

In addition to these standards that point out to specific risk categories, standard IEC/ISO 31000 defines the overall risk management principles and defines guidelines for risk management implementation. The accompanying standard IEC/ISO 31010 recommends the application of certain techniques for risk assessment that can be used in practice.

Although continual improvements are driven by internal initiative, implementation of IMS is mostly attained by external motivation [4]. The risk management process, according to [5] implies comprehensive identification of potential failures in processes, as well as risk assessment afterwards. The authors of this paper suggest that risk assessment can be used as a base for the development of appropriate IMS documentation which is aligned with the real needs of the organization. The implementation of risk based IMS is aimed to be a systematic and objective approach that involves all the basic principles used in management standards like the process approach and the PDCA cycle of improvement, as shown in section 3 of the paper.

2. Defining the problem

Generally speaking, implementation of international standards have a goal to define processes and reduce entropy level in companies, which is a prerequisite for effective risk control, but if IMS documentation is poorly designed, it can lead to duplication and vagueness [6]. Management standards are designed to be easily integrated, but in the implementation of integrated management systems, problems with compatibility are not rare. Some research results even suggest that compatibility and alignment are not crucial issues in implementing standards [7]. New versions of standards ISO 9001:2015 and ISO 14001:2015 do not have explicit requirements for the levels of documentation needed to support the management system (Manuals, Procedures, Instructions and Records). Nevertheless numerous "documented information" is inevitable for the system to function. This can be rather confusing for inexperienced users when the appropriate system documentation should be determined and there are no explicit rules defined.

Some problems that emerge in the implementation of integrated management system, as stated in [8], can be recognized in IMS complexity, reduction of the management effectiveness, increase of management costs, decrease of cultural compatibility and opposition of employees. To avoid these problems, Zeng *et al.* [8] propose a synergetic model for the integration of management standards at several levels. The first level refers to the strategic level and includes the activities of global routing (mission and vision), planning and setting goals. The second level is a synergy of resources, structures and cultural behaviours of employees, while the third level refers to the integration of IMS documentation.

Similar attitudes are shared by Zwetsloot who proposed three types of synergistic activities when establishing IMS [9]:

- synergy of common aspects,
- synergy of management systems, and
- organizational synergy.

On the other hand, an approach to integration that recognizes three levels of integration is proposed by Jørgensen *et al.* [10]:

- the increase of the compatibility of system elements,
- the coordination of generic processes,
- the awareness of the IMS of all participants through a culture of learning.

A specification PAS 99 [11] can be used as a guide for IMS integration. PAS 99 points out that, in addition to the specific requirements of each standard, there are common requirements which are divided into categories according to the following topics [11]:

- policy,
- planning,
- development and implementation,
- performance appraisal,
- improvement and
- management review.

In [12] integration can be seen as a merging of two systems into one, in a way that result in the loss of independence for at least one, if not both systems, but they agree that the integration usually leads to a stronger and more comprehensive management system.

In [13] authors suggest a two-step approach to integration:

- the creation of generic guidelines to support the integration of management systems, and
- establishment of generic guidelines for conducting audits.

According to [14] there are two ways of integration:

- implementation of individual systems, which follows their integration, and
- development and implementation of an integrated management system from the start.

Integration degree of IMS have been thoroughly analyzed by numerous researchers [15-18] however the authors' opinion is that full and effective integration is not possible without considering the risks of quality issues, environmental impacts and occupational health and safety (OH&S) risks, which can be highly related to the satisfaction of stakeholders [19] and to the development of sustainable and socially responsible organisation [20].

In [14] is also concluded that risk can be used as an integrating factor in establishing the IMS, which was a starting point for this paper.

3. Used methods

The main problem that occurs during the design of IMS documentation is the scope, which ultimately depends on the judgment of a project team. In order to determine the precise criteria that will define the required scope and type of IMS documents, a general model for the design of IMS documentation based on risk assessment of processes in organizations was developed.

The development of the presented Model was based on the hypothesis that the increased risks in processes increase the need for their more precise documenting. By increasing the extent of documentation that describes how to perform some activity of high risks, the entropy of the system should be reduced, as well as a chance for any deviation in the process.

The crucial steps needed for the development of a risk based model for IMS documentation design are presented in the further text.

3.1 Selection of a universal risk assessment method

The criteria for the selection of universal risk assessment method were as follows:

1. Convenience of application in all phases of risk assessment.
2. Convenience of application in all kinds of processes.
3. Possibility to obtain quantified results of the assessment.

IEC/ISO 31010 [21] shows the applicability of 31 techniques for risk assessment at each phase of the risk assessment process. After analyzing the presented recommendations, it has been noted that only four methods are "strongly applicable" in all phases of risk assessment.

These methods are as follows:

- environmental risk assessment,
- structure "what if" (SWIFT),
- failure mode effect analyses (FMEA),
- reliability centered maintenance.

To fulfil the second and third criteria that were set for the selection of a universal risk assessment method, the authors of this paper accepted recommendations given in [21], as shown in Table 1.

After insight into Table 1, it can be concluded that only the FMEA method meets all the criteria that were initially set for the adoption of a universal risk assessment method.

Relying on [22] the input data required for the implementation of the PROCESS FMEA method are:

- a flow chart of the observed process (see Subsection 3.2),
- parameters that can affect the outcome of the activity,
- the potential consequences of hazardous events,
- empirical data (if they exist).

Table 1 Additional criteria for the selection of a risk assessment method

Methods recommended in all phases of risk assessment	Additional criteria	
	Applicability in all kinds of processes	Quantified results
• Environmental risk assessment	-	√
• Structure "what if" (SWIFT)	√	-
• Failure mode and effect analyses (FMEA)	√	√
• Reliability centered maintenance	-	√

3.2 Modified flow chart application

The relationships of the company's processes to the environment are primarily determined by the flows of material, information and energy. If there are certain disorders in listed flows, they can cause consequences related to the operation of processes in the organization. Therefore, a flowchart used for the identification of risks in an integrated management system should display all three basic flows in the work processes.

The FMEA method emphasizes five elements of the process, which must be addressed throughout its application [22]:

- people,
- materials,
- equipment,
- work methods,
- environment.

It would be ideal to display all five listed elements in the process flow charts that will be used for risk assessment with the FMEA method. In the authors' opinion, the duration of the observed activities is also very important for risk assessment (particularly in probability assessment) so it is very useful to display that information in a modified flow chart.

The modified flowchart should present all the information necessary for an objective identification of hazards and accurate assessment of risks in analyzed activities [23]. A generic review of modified flowchart is shown in Fig. 1.

This unique way of graphic presentation is an original contribution of author's research. It displays all key elements of the process and it should be an ideal input for risk assessment using the FMEA method.

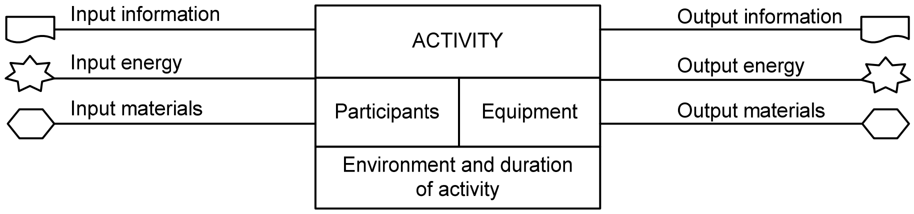

Fig. 1 Display of activity according to the modified flowchart

3.3 The application of the FMEA method

FMEA (Failure Mode and Effect Analysis) is a systematic method of identifying and preventing problems before they arise, both in products and in processes.

The main output after conducting the FMEA method is a quantified risk level that is expressed by an RPN value (Risk Priority Number). Originally, the RPN number was used for determining priorities when implementing adequate measures of risk control, while in this paper it is used as an indicator for determining the adequate type of IMS documentation.

The RPN number is determined by three factors [22]:

1. Severity – the potential consequences of failures,
2. Probability – likelihood of failure occurrence, or the frequency of its repetition,
3. Detection – the probability that the failure will be detected before the manifestation of its consequences.

Originally, each parameter should be valued on a scale that ranges from 1 to 10 for every potential type of deviation. Multiplication of the estimated values for all three factors (severity × probability × detection) determines the risk priority number (RPN).

3.4 The modification of the FMEA method

Due to specific shortcomings in FMEA method conduction, some authors suggest it can be effectively improved according to its purpose [24].

In order to facilitate risk management within an integrated management system, it is useful to classify groups of deviations (risks). The authors of this paper suggest that the number of risk groups depends on the number of management systems applied in an organization.

The modified FMEA matrix for IMS consisting of standards ISO 9001, ISO 14001 and OHSAS 18001 is shown in Table 2.

When conducting the FMEA method one must know that every activity usually has multiple risks and every consequence may have multiple causes. RPNs must be calculated for all of them.

As shown in Table 2, the authors of this paper did not consider the realization of preventive and corrective actions after the calculation of RPN number. Instead, a modified FMEA matrix results in risk ranks that define the level of IMS documentation. This modified FMEA method, together with the scale for the assessment of the severity of consequences shown in Table 3, and the scale for the detectability assessment shown in Table 5, represent an original contribution of author's research.

Table 2 Modified FMEA matrix

Process:										
FMEA process									Date:	
No.	Activity	Groups of risks: Quality degradation (ISO 9001) Environment degradation (ISO 14001) Health and safety degradation (OHSAS 18001)	Possible consequences	Severity	Possible causes of failures	Probability	Possibility of detection	Detection	RPN	Risk rank

Table 3 Scale for the assessment of the severity of consequences

Rank	Effect	Severity of consequences		
		Consequences of quality degradation (ISO 9001)	Consequences of environment degradation (ISO 14001)	Consequences of OH&S degradation (ISO 18001)
10	Extremely high	Failures may lead to the loss of important operational functions for a long period of time. Lawsuits by customers and serious sanctions from the government are inevitable. Possible cessation of the company.	Permanent degradation of the environment on a large area with contamination that can be expanded by emissions into the air, water or land. The level of contamination directly threatens human health. Lawsuits and sanctions from the government are inevitable. Possible cessation of the company.	Failures may lead to emergency situations with multiple fatalities among employees and other stakeholders. Lawsuits from stakeholders and serious sanctions from the government are inevitable. Possible cessation of the company.
9	Critically high	Failures may lead to the loss of operational functions for a short period of time. Lawsuits by customers and bad publicity are inevitable. Financial losses are sometimes irrecoverable.	Permanent degradation of the environment on a small area with contamination that can be expanded by emissions into the air, water or land. Human health is indirectly affected. Sanctions from the government and bad publicity. Financial losses can be irrecoverable.	Failures may lead to fatalities among employees. Lawsuits from employees, sanctions from the government and bad publicity are inevitable. Financial losses are sometimes irrecoverable.
8	Very high	Failure leads to the suspension of supply / provision of contracted services. In addition to direct financial losses, permanent loss of customers and the market position is expected.	Local degradation of the environment with no possibility of expanding pollution. Sanctions from the government and bad publicity of the company are expected.	Significant violation of employees' health, which cannot be compensated (permanent inability to perform work-related activities). A lawsuit by employees and bad publicity are expected.
7	High	Failure leads to a brief interruption of operational functions and delays in agreed deadlines. Expected financial losses to legitimate customer complaints.	Constant degradation of the environment over a long period of time (over one year). The consequences are not fully recoverable.	Permanent violation of health and work ability of employees due to serious injuries or chronic illnesses (30% disability)
6	Moderately high	Failure leads to a number of inconsistencies in the process of work. Non-conforming products / services are delivered to end-users, which leads to their dissatisfaction.	The consequences for the environment are evident, but not fatal for wildlife. There is no possibility of spreading negative impact, but the consequences may not be fully recoverable.	Injuries / ill-health that temporarily violate work ability, but full recovery is possible (sick leave up to 3 months)
5	Medium	Systematic deviations lead to hidden defects in the product / services, leading to claims under warranty and dissatisfaction of customers.	It is necessary to make an effort to overhaul consequences for the environment after the completion of work activities.	Injuries / ill-health that temporarily violate work ability, but full recovery is possible (sick leave up to 1 month)
4	Moderate	Deviations can lead to small inconsistencies in the process. The occurrence leads to dissatisfaction of customers and financial losses.	The effects of pollution are present over a longer period of time after the cessation of activities. The environment is able to regenerate inone year period	Injury / ill-health that requires a simple and short-term medical intervention (loss of up to 1 week).
3	Low	A decline in the performance of the process, which causes the appearance of a small number of nonconformities. End users are not affected.	The effects of local pollution are present in a short period after the cessation of activities. The environment is able to regenerate in a period of one month.	Injury / ill-health that requires first aid by internally trained persons (loss to one business day)
2	Very low	Decline in performance processes causing loss of time. Adverse effects are very limited.	Environmental impact exists only as long as the current work activities.	Slight degradation of health. After little intervention of the injured person, operation continues unimpeded.
1	Insignificant	Deviations have no effect.	Deviations have no effect.	Deviations have no effect.

The severity of consequences

Assigning the values for each assessed factor can be one of the greatest problems in implementation of any risk assessment method including FMEA. Converting qualitative into quantitative values is always fraught with the subjective attitude of risk assessors. Therefore, it is recommended to establish specific guidelines for the evaluation of factors as precisely as possible.

The scale for evaluation of the severity of consequences for three groups of risks linked to the ISO 9001, ISO 14001 and OHSAS 18001 is proposed in Table 3, but every organization can define its own scale tailored to its needs.

The probability of occurrence

It is much easier to quantify probability of occurrence, especially if empirical data are available. The scale for the probability assessment is given in Table 4.

Table 4 Scale for the probability assessment

Rank	Probability of occurrence	Likelihood of failure occurrence, or frequency of its repetition
10	Extremely high	More than 1 occurrence per day / more than 3 occurrences in 10 events.
9	Critically high	1 occurrence on every 3 to 4 days / 1 occurrence in 10 events.
8	Very high	1 occurrence per a week / 5 occurrences in 100 events.
7	High	1 occurrence per a month / 1 occurrence in 100 events.
6	Moderately high	1 occurrence per 3 months / 3 occurrences in 1.000 events.
5	Medium	1 occurrence per 6 to 12 months / 5 occurrences in 10.000 events.
4	Moderate	1 occurrence per year / 6 occurrences in 100.000 events.
3	Low	1 occurrence per 3 years / 6 occurrences in 1.000.000 events.
2	Very low	1 occurrence per 3 to 5 years / 2 occurrences in 10.000.000 events.
1	Insignificant	1 occurrence in more than 5 years / less than 2 occurrences in 100.000.000 events.

The probability of detection

Since the Model should be applicable in organizations of all types and sizes, it is almost impossible to define a scale from 1 to 10 that would be applicable for every possible process. The possibility of detection is often limited by the existence of measuring equipment in the company and by the nature of the process itself. Due to these limitations and the fact that the probability and consequence are prevalent in determining any risk in most risk assessment methods [21], the matrix for detectability assessment was simplified. According to Sankar & Prabhu [25], rankings of detectability can vary even for the same type of deviation (risks), so the authors of this paper created a scale in the range of 1 to 3, which is shown in Table 5.

After defining the scales for all criteria required for conducting the FMEA method, it is clear that potential results of assessed risks (risk priority numbers – RPNs) are in a range from 1 to 300.

Table 5 Scale for the detectability assessment

Rank	Probability of detection	Description of detectability
3	Low	The process is difficult to control, and the effect of the failure is very difficult to detect.
2	Medium	Process perpetrators perform a visual process control / periodic measurements of numerical values / counting attribute values.
1	High	The failure is detected and controlled automatically or semi-automatically in a way that prevents the occurrence of deviations.

3.5 Influence of risks on IMS documentation

A common hierarchical structure of IMS documents is shown in Fig. 2. The number and scope of IMS documents that should exist in an organization and describe identified processes (according to the process approach) have not been defined by any normative references. The authors of this paper consider that the ranks of risks in the existing processes are directly aligned with the type and number of needed documentation. The exact relations between assessed risks and IMS documents are described in the further text.

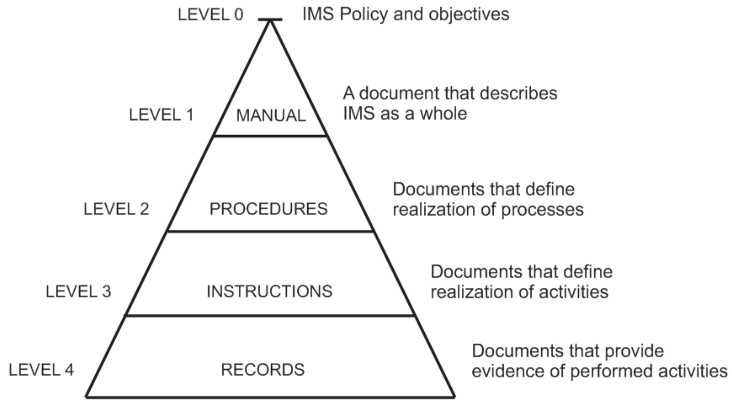

Fig. 2 Hierarchical structure of IMS documents

Level 0 – The Policy and objectives

The IMS Policy and objectives, along with the mission and vision, represent the highest level of documents in a company that are certainly affected by strategic risks.

Each management standard requires periodic management review of the system that should result in the adaptation of the policy and objectives of an organization in accordance with existing conditions. In this way, through the institution of management review, changes in operational risks indirectly reflect the changes in the policy and objectives of an organization, but the policy and objectives are not directly treated by the Model.

Level 1 – The Manual

Specification PAS 99 recommends the development of a single Manual that describes the overall management system [11]. This IMS Manual refers to the procedures and instructions of an integrated management system. Usually there is no need to describe all the processes by separate procedures because they can be very numerous and heavily burden the administration of a system. Therefore it is sufficient to describe some processes with minor risks (rank 1) just in the Manual.

Level 2 – Procedures

Some management systems insist on certain mandatory procedures but the system should be also documented with procedures that describe primary processes of the organization. The designed Model proposes that moderate risks (rank 2) must be described by procedures.

When documenting the observed process by a procedure, particular attention should be focused on those activities where the moderate risks were identified. In this way, documentation should be adapted to the risks of the organization which minimizes the possibility of deviations and errors in processes.

Level 3 – Instructions

The Model suggests that all activities with high risks (rank 3) should be described by separate instructions. The appearance of risks in rank 3 certainly implies the development of a procedure for the entire process in which risky activity occurs, but a separate instruction that will accurately describe the observed activity is also needed.

In that way, all high-risk activities would be separately described in detail, which would enable workers to adequately perform their tasks in safe manner.

Level 4 – Records

This level of documentation is actually dependent on the above-described documents of a system (especially procedures and instructions) which define the number and format of records that need to be kept. The designed Model does not foresee the changes that are directly related to the records, but their number indirectly depends on the level of estimated risks, since risks affect the quality and quantity of procedures and instructions in IMS.

Added Level 5 – Action sheets

Besides customary IMS documents, the Model introduces another level of documentation that is related to the most severe risks that can lead to disastrous consequences. Emergency situations are specially treated by ISO 14001, OHSAS 18001, ISO 22000, etc. (requiring preparedness for response in case of emergencies). The Model therefore requires the existence of special instructions called "Action sheets" which define preventive and recovery measures in case of emergency situations for all severe risks (rank 4). Action sheets should be posted in a visible location near a potential emergency spot which should enable everyone to react properly in case of emergency.

4. Results and discussion

4.1 Risk based model for the design of IMS documentation

Materials and methods used in previous chapter resulted with the universal risk based Model for IMS documentation design, which is a main result of this paper. To avoid arbitrariness in defining the scope and structure of IMS documents, the proposed Model introduces precise criteria that can be used to determine the number and types of documents required, depending on the rank of assessed risk.

The number of repetitions of all possible RPN results obtained by modified FMEA method is shown in the histogram in Fig. 3, which shows that the distribution of RPN values is far denser at the beginning of the scale where RPN values are lower.

The occurrences of high-risk deviations in practice are extremely rare, and low-risk deviations are far more common, which is in accordance with the distribution of RPN values shown in Fig. 4. The density of distribution of RPN values was taken into account when risk rankings were defined.

Since there are four levels of IMS documents that are treated by the proposed Model, the authors predicted four risk rankings within a range from 1 to 300 RPN values:

- Minor risks (Rank 1) – risks are in the interval 1 ≤ RPN ≤ 50.
- Moderate risks (Rank 2) – risks are in the interval 50 < RPN ≤ 100.
- High risks (Rank 3) – risks are in the interval 100 < RPN ≤ 150.
- Severe risks (Rank 4) – risks are in the interval 150 < RPN ≤ 300.

The description of IMS documents which directly depend on the rank of estimated risks is shown in Table 6.

Risk rankings in practice can be subject to change. Each organization could define its own scale for risks according to the objectives and available resources, so rankings should be periodically reviewed and adapted to the needs of the organization.

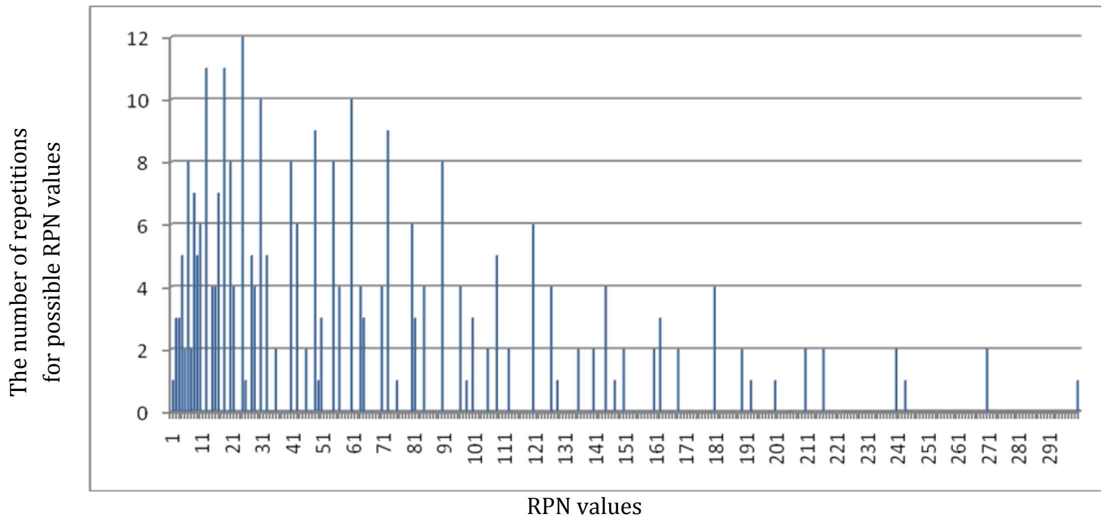

Fig. 3 The distribution of RPN values

Table 6 IMS documentation depending on the rank of the estimated risks

RPN of analyzed process/activity	RANK of risk	Description of required IMS documents
RPN ≤ 50	Minor risks (RANK 1)	Analyzed process should be described in the IMS Manual
50 < RPN ≤ 100	Moderate risks (RANK 2)	Analyzed process should be described by a Procedure and briefly described in the IMS Manual
100 < RPN ≤ 150	High risks (RANK 3)	Analyzed activity should be described by a separate instruction
150 < RPN ≤ 300	Severe risks (RANK 4)	Analyzed activity should be described by a separate instruction and by an action sheet for the prevention and treatment of possible emergency

It may be noted that, irrespective of the assessed risks, all processes should be described (at least roughly) in the Manual of the integrated management system, which is required by ISO/TR 10013:2001 [26]. The procedure is required only if the analyzed process has risks in rank 2. Risks in ranks 3 and 4 indicate that separate instructions for analyzed activities should be made. When it comes to risks in rank 4, at a first sight it could be stated that there is an overlap in the documentation for the same activities. However, the duplication of documentation does not actually exist because action sheets define just activities for the prevention and remediation of potential emergencies, but the way of carrying out the observed activities and corresponding responsibilities is defined by appropriate instructions. In addition, action sheets are designed for all present persons, regardless of their familiarity with the company processes. Unlike action sheets, the instructions are designed directly for the workers.

4.2 Case studies

The risk based Model for the design of IMS documentation has been applied in 3 various companies in Serbia:

- Company A is engaged in designing buildings and facilities and has implemented integrated management system which includes ISO 9001, ISO 14001 and OHSAS 18001.
- Company B is engaged in civil engineering, transport, asphalt production and exploitation of mineral materials. It has implemented integrated management system which includes ISO 9001, ISO 14001 and OHSAS 18001.
- Company C has implemented integrated management system which includes ISO 9001, ISO 14001, OHSAS 18001 and ISO 22000. It has three branches:
  - The first branch is engaged in the design, construction and maintenance of all types of gas, electrical and ventilation installations.
  - The second branch is engaged in the production and storage of fresh and frozen goods (food, fruit and vegetables).
  - The third branch is engaged in the production and packaging of brandies from fruits and grapes.

All three companies already had their integrated management system implemented and the comparison between the old and new IMS documentation was made. In order to facilitate the comparison and analysis of the results obtained, the following restrictions were made:

- Only the processes that have previously been identified and described in companies were analyzed and their risks were assessed (this was the only way for objective comparison between the old and new IMS documentation).
- System processes that are required to be documented in accordance with the implemented standards (such as: document control, record control, internal audit, corrective actions, etc.) were not considered by the Model.
- The categories of risk taken into account were in direct correlation to the standards applied in the organization.

Although the key performance indicators are often expressed through financial results of the company [27], the Model does not predict financial indicators for several reasons:

- The financial success of the company is not the subject of any management standard.
- Profit is just a consequence of consistent quality of the processes, products or services, which wins long-term customer satisfaction. Therefore, any deviations in the processes of the company influence its profit directly or indirectly.

After drawing flow charts for each analyzed process, the authors created corresponding FMEA tables, which resulted with a resume of IMS documents required by the proposed Model.

Comparative analysis between the documentation that existed in the companies A, B, and C in the past, and the documentation designed by new research model, showed following results:

- 9 specific processes were identified in the integrated management system of Company A. The primary system in the Company A consisted of 10 documents (6 Procedures + 4 Instructions) and the documentation designed by new model consisted of 8 documents (7 Procedures + 1 Instruction). It is obvious that number of IMS documents in Company A does not vary much depending on the approach used, but there are major differences regarding the type of designed documentation. This dispersion can be explained by the inconsistent application of the process approach when the documentation was primarily designed. Generally, Company A does not face great risks, especially when it comes to endangering health and safety at work or the environment, since the company is engaged only in the design and supervision, and not in the construction works. Therefore, the number of documents designed for this company in accordance with the proposed model is very small and covers mainly the quality aspect in accordance with ISO 9001.
- 12 specific processes were identified in the integrated management system of Company B. The primary system in the Company B consisted of 35 documents (10 Procedures + 13 Instructions + 12 action sheets) and the documentation designed by new model consisted of 48 documents (16 Procedures + 25 Instructions + 8 action sheets). There is a big difference in the size and type of business between Company A and Company B, so the IMS documentation in those two companies differs a lot, although it covers the same set of standards (ISO 9001, ISO 14001 and OHSAS 18001). It can be seen that total number of required documents designed by a risk-based model is higher by 13 than the documentation that was primarily designed. The analysis of the processes shows that unlike company A, Company B faces significant risks, especially when it comes to environment and occupational health and safety. That is why the designed documentation is "focused" on the most risky processes such as: construction, production of asphalt mass and machinery manipulation, to which most instructions and all action sheets are directed. Such a distribution of documentation was predictable, since the model was developed to be consistent with the risks of the company concerning the applied standards.
- 24 specific processes were identified in the integrated management system of Company C. The primary system in the Company C consisted of 34 documents (23 Procedures + 11 Instructions) and the documentation designed by new model consisted of 55 documents (25 Procedures + 26 Instructions + 4 action sheets). Company C has a much more complex structure and wider scope of activities than other companies analyzed in the case study. In addition, this company has the most complex management system, which comprises four standards (ISO 9001, ISO 14001, OHSAS 18001 and ISO 22000). The processes occurring in the branch which deals with the design, construction and maintenance of gas and thermo-technical installations can in some ways be compared with the processes already analyzed in companies A and B. However, other two branches have specific processes that are also subject to requirements ISO 22000, which generates a new group of risks and increases the number of required documentation. According to the set goal, the designed documentation is focused on the most risky processes such as: construction, machinery manipulation, production of frozen products, service storage of frozen products and production of brandy.
- Case studies generally showed that primary implementation of IMS was not carried out systematically and according to the process approach which is one of the core principles of quality management. This resulted with non-consistent number and types of IMS docu-

ments. For instance, that is why number of documents in the Company B was even slightly larger than in the Company C which is far more complex and even has additional standard implemented. Such omissions cannot happen when applying the proposed Model. Besides mentioned, previous documents were not aligned with existing risks in processes and by that they don't meet the needs of the organization. The practical application of the Model suggests that in some cases the same processes carry different risks in different companies. Risks vary according to an impact that the analyzed process has on the performance of the company and it should be treated and documented according to it. Therefore, there are no "a priori risky processes".

5. Conclusion

The paper presents all phases of the development and implementation of the Model for designing IMS documentation based on risk assessment in organizations.

In order to create this Model, the authors:

- Adapted flow chart, as a universal tool suitable for graphically displaying and analyzing essential process elements,
- Selected and adapted the FMEA method, as a universal tool suitable for risk assessment in the processes of the company, related to the applied management standards,
- Established a universal matrix for ranking different types of risk,
- Defined the relationship between the assessed risks and required IMS documentation.

For the purpose of practical verification of the designed Model, the following actions were performed:

- Implementation of the Model in three diverse companies that already had an integrated management system with at least three management standards implemented,
- Comparative analysis of the documentation obtained from a risk based Model and previous IMS documentation that existed in organizations.

Case studies showed that the Model can be applied in the organizations of all sizes and types in a way that the number and scope of IMS documents directly depend on the risks in the existing processes. That documentation should always be changed along with the changes of the company's risks. The risk based model for the design of IMS documentation has given precise guidelines that each company can use in creating the optimal level of IMS documentation. However, every organization can change the projected Model by adapting the scales for risk ranks in accordance with its goals and needs. Organizations that thrive in the field of risk management often desire to bring it to a higher level by reducing risk appetite.

The authors have also identified some weaknesses of the proposed approach, such as:

- Implementation of the Model depends on expertise and evaluation of FMEA team,
- Drawing the flow charts and FMEA matrix for every process can be time consuming,
- Current Model does not include financial, reputational, compliance, or similar risks,
- Current Model does not define operational actions for the reduction of assessed risks.

In order to correct recognized weaknesses, the authors anticipate following directions for further research:

- Developing adequate software would facilitate the implementation of the Model. Creating a database with all potential deviations, their consequences and associated risks, would help FMEA team to get the job done,
- Creating new types of risks related to the financial effects should broaden the use of proposed Model,
- Extending the Model with actions for the reduction of assessed risks should add operational value to the Model implementation.

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Appendix A

The list of the abbreviations in the paper:

FMEA	Failure mode effect analysis
IMS	Integrated management system
OH&S	Occupational health and safety
PDCA	Plan-Do-Check-Act
RPN	Risk priority number

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Communication and validation of metrological smart data in IoT-networks

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A B S T R A C T

An Internet of Things–network (IoT– network) allows for the communication of data both within the network and to data hubs. However, the usefulness of the data depends on its ability to be interpreted correctly. For metrology data, effective use of the data is only possible if the numerical value, associated unit and uncertainty, expressed in a standard format, are also available. In order to develop, provide and distribute a formal framework for the transmission of metrology data on the basis of the International System of Units, European project EMPIR 17IND02 SmartCom was agreed between the European Commission and the European Association of National Metrology Institutes (Euramet). The SmartCom project aims to provide the methodological and technical foundation for the unambiguous, universal, safe and uniform communication of metrological smart data in the IoT and Industry 4.0. The project will increase the industrial capabilities and the provision of regulations for data exchange in the IoT. It will also assist countries within the European Union (EU) and those with an association agreement with the EU in developing products that are able to communicate in IoT environments worldwide. In addition to describing the general ideas and aims of the project, this article presents the research results achieved in the first midterm period.

A R T I C L E   I N F O

Keywords:
Metrology;
Measurement metadata;
Information and communication technology (ICT);
Smart Data;
Data communication;
IoT-communication;
IoT-networking;
Digital calibration certificate

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1. Introduction

The current paradigm for industrial and engineering quality assurance is based on production processes that have short- to medium-term stability along with a significant investment in quality inspection. One of the goals of Industry 4.0 and data-centric engineering [1-4] is to use multiple sensors that measure all aspects of the production process. The resulting complete set of measured data can then be used to understand, in much greater detail, the performance of the system so that the process can be kept close to its ideal state, leading to reduced downtimes, fewer rejected parts, improvements in quality, better organised maintenance, better conservation of energy and resources, and increased business success. However, data-centric engineering depends on being able to assess the quality of the measurement information through the metrological concepts of traceability and uncertainty [5]. Rapid growth in digital communication such as cloud applications, distributed networks, smart devices and intelligent network architectures [3] demands new concepts for decision making based on reliable information.

Existing cloud storage and services provide state-of-the-art capabilities for storing data but, on their own, provide no information on the provenance of the data nor on how the data can be interpreted correctly. Smart data is used to overcome this situation. In the scope of this article, the term “metrological smart data” refers to digital information comprising metrology data formatted for further data consolidation and analysis of the data in Internet of Things-networks (IoT-networks). Such smart data provides metadata, such as measurement units and uncertainties, describing the meaning and purpose of the underlying data in a machine-understandable form. Thereby, benefit lies in using common standards for the provision of relevant metadata. More traditional data, such as raw data from measurement sensors or measurement data in calibration certificates, cannot be classified as smart. In many cases, such data has incomplete information (e.g. when a sensor outputs numerical values but with no associated unit) or the metadata can only be accessed by human-interpretation of a (paper) document.

Therefore, an essential component of a digitally-enabled metrology landscape for the IoT that can address the requirements of calibration, traceability and legal metrology [5, 6] is the automatic and secure communication of all relevant elements of the data and metadata formatted as smart data. This communication allows the unambiguous and correct interpretation of the data [7]. The interoperability of metrology data is severely degraded if essential information is lost or corrupted and current protocols do not address this issue.

In general, the confusion, ambiguity and incorrect interpretation caused by missing metadata, diversity of units, etc., represent significant risks for future investment in IoT–technologies. If the IoT is to bring its benefits to society, it must be founded on well-engineered principles, including those derived from the metrological concepts of traceability, uncertainty and interoperability. In addition, to avoid future loss of information and consequent impact on decision-making, and to make secure human lives and environment, the exchange of metrological information (measurement results and assigned information) must be defined for all measurement tasks.

Today, measurement results are communicated using base units of the International System of Units (SI) but also using domain-specific units such as foot, radian, inch, weber, gallon, etc. A BIPM brochure [8] provides guidance on using such derived units. However, this system is insufficient for the automated data processing required in the IoT, where information must be understood unambiguously and worldwide. One major goal of the research presented here is to define a data exchange format where the expression of measurement results in SI units [8-11] is mandatory. Optional information such as domain-specific or derived units will be covered, as well as additional information.

The presented research is focused on establishing the secure, unambiguous and unified exchange of data in all communication networks where metrological smart data is needed. It aims to develop, provide and distribute a formal framework for the transmission of metrological data based on the SI. The framework will be applicable to all metrology domains.

Furthermore, a worldwide-applicable concept for the use of digital calibration certificates (DCCs) will be made available for the first time. The development of demonstrators in two industrial domains will also prove the benefit and innovation potential for industry of the outputs of the project.

The most important scientific contributions of this research are:

- Establishing minimum required metadata models for the digital exchange of measurement data from a study of various international guides in the field of “traditional” measurement data and uncertainty representation,
- Establishing minimum required information to be contained in DCCs and requirements for the secure usage of DCCs from a study of standard documents and samples of “traditional” paper calibration certificates,
- Creating uniform metadata models that can help to facilitate interoperability of research data and increase reusability.

2. Research objectives, methods and the structure of research

The overall objective of the research is to provide the methodological and technical foundation for the unambiguous, universal, safe and uniform communication of metrological data in the IoT. Guidelines are being developed that can be used, for example, for the definition of pre-normative standards for the IoT and the supplementation of existing standards in order to define and harmonise the dissemination of measurement results and associated information. The specific objectives of the presented research are:

1. To define the requirements for a uniform, unambiguous and safe exchange format for measurement data and metrological information in an IoT network. The exchange format shall be based on the definition of SI units and meet central requirements from standards, guidelines and legal metrology.
2. To develop and establish secure DCCs. This objective requires consideration of exchange formats for administrative information, data transfer, cryptographic requirements, authentication and digital signatures.
3. To develop an online validation for services system for the types of data format as addressed under objectives 1 and 2.
4. To develop a reliable, easy-to-use, validated and secure online conformity assessment procedure designed for cloud system applications for legal metrology. The online conformity assessment procedure should also be applicable to calibration services and provide compliance with current international and European standards.
5. To build and validate demonstrators involving running applications from industrial stakeholders, to facilitate the uptake of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations and end users, and to work towards a European platform for metrological calibration services.

The idea of the research with the objectives is presented in Fig. 1. Technical realisation of the research is divided into 5 work packages:

- WP 1: Universal format for transfer of metrological data via digital communications,
- WP 2: Digital calibration certificate (DCC) considering technical and legal requirements,
- WP 3: Online validation of data formats and DCCs in digital communications,
- WP 4: Online conformity assessment in legal metrology,
- WP 5: SmartCom demonstrators.

Each work package is split into diverse activities, which are only briefly described in this section.

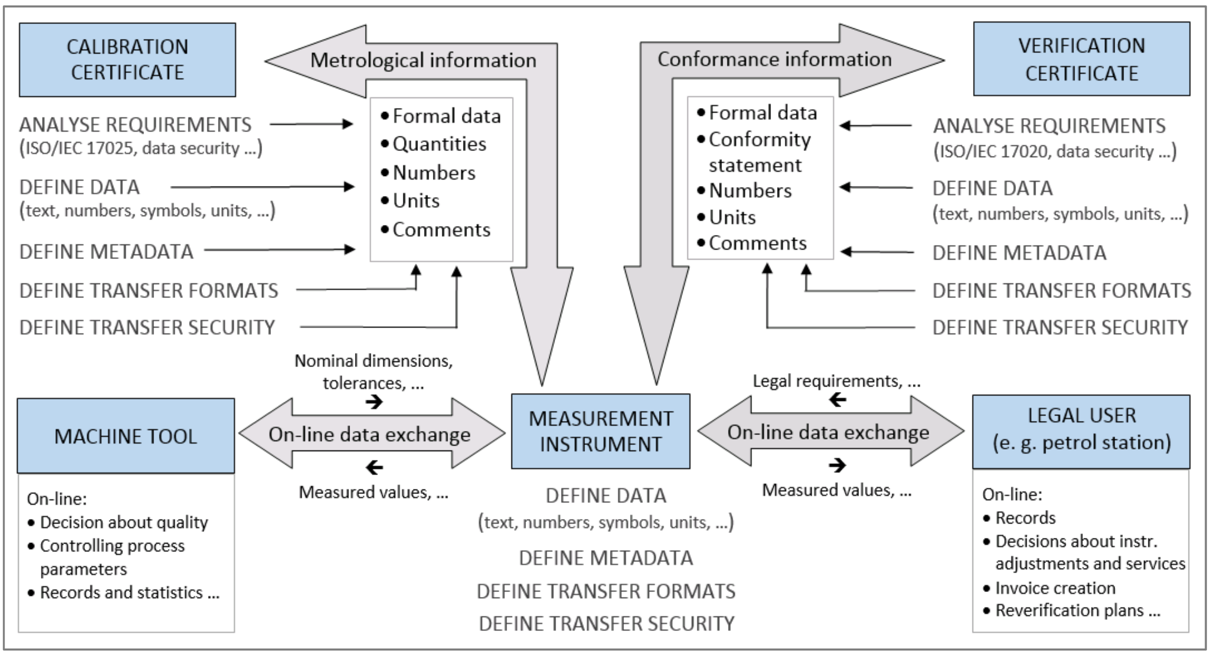

Fig. 1 Schematic presentation of the research goals and outcomes

2.1 Universal format for transfer of metrological data via digital communications

The aim of this work package is the elaboration and definition of a fundamental description applicable to all metrological data [5-7] used in digital communication. For the first time, and linked to the worldwide-established SI, project partners have defined the measures that are essential for the easy-to-use, safe, harmonised and unambiguous digital exchange of metrological data. The use of non-SI units has also been considered. The resulting universal format for the digital transfer of metrological data realises an implementation of the minimum requirements from guides in both metrology and Information and Communication Technology (ICT). This part of the research is complete and details are presented in Section 3.1.

2.2 Digital calibration certificate (DCC) considering technical and legal requirements

Within this work package, a universal structure of a DCC has been established. In order to obtain global acceptance of DCCs, the requirements for physical calibration certificates (paper form) of leading countries were first analysed. Using these requirements, a flexible and universal data structure was defined. The DCC was realised using extensible markup language (XML) [12, 13] with the metrological data represented according to the specifications developed in WP 1. In contrast to physical calibration certificates, new framework conditions required for digital communication [13, 14], such as the minimum requirements for transfer of encrypted data, authentication and digital signatures, will be developed and established (in a worldwide context and for the first time). Partial results are presented in Section 3.2.

2.3 Online validation of data formats and DCCs in digital communications

This work package aims to establish a worldwide accessible online service for all applications where metrological data is exchanged, and the validation of metrology information within a DCC. Best practice guides for this service will be produced in order to guide software engineers, purchasers of products used in "intelligent" communication networks, and managers of quality management systems. A classification of metrology data regarding its usability for machines has been developed. The highest classification, termed "Platinum" or "Next generation", refers to data provided using only SI base units. Other classifications include "Gold", "Silver" and "Bronze" while the lowest classification "Improvable" refers to data that does not include sufficient information, for example, omitting a measurement unit entirely. This part of the research is ongoing and is expected to be concluded in 2020.

2.4 Online conformity assessment in legal metrology

This work package will study requirements for a user-oriented and easy-to-establish online conformity assessment system that fulfils the general needs of legal preconditions. The research will focus on industrial users that develop sophisticated networks within digital networks and whose previous developments could not come to market due to restriction by national laws.

The online conformity assessment system will consist of three parts:

- XML-based communication interface [12],
- Unified user interface (UniTerm), and
- Security concept for the transmission of metrological information into a "world" outside the restricted and economic environment [13, 14].

This part of the research is ongoing and is expected to be concluded in 2021.

2.5 SmartCom demonstrators

Pilot applications (demonstrators) will be implemented in this work package to prove the metrological usability of the concepts developed during the research. The demonstrators will comprise the application of the validation system implemented in the TraCIM platform [15] on data from DCCs and an application of the UniTerm.

3. Midterm research results

3.1 Machine-readable SI format for the exchange of metrological data

This part of the research specifies the basic principles for the exchange of machine-readable data for all applications that transfer or require measurement data according to the specifications of the Système International d'Unités (SI) [8]. The research results thus provide the basis for the harmonised, clear, secure and economical exchange of digital measurement values for a universe in which digital data is being transferred in accordance with the specifications introduced below.

This new approach addresses the need for improvement in secure data communication in the sense of reducing the risk of incomplete and incompatible data exchange such as mixing up length measurement values with units inch and centimetre. Calculations combining such incompatible data can lead to catastrophic results. In safety-critical areas, a consequence could be loss of human life. Using the new approach will also improve the universality of communication, as the data and its metadata are based on common minimum required information from highly-authorative international guides such as VIM [5], GUM [7] and the BIPM SI brochure [8]. Other data models are in many cases very domain specific and hence only usable in their field of application.

For the digital exchange of metrological data, it is essential to associate at least one value to a corresponding unit [13, 14, 16]. These two pieces of information enable a statement to be made about the value of a quantity that can be interpreted according to the SI. Because of its indivisibility and fundamental importance, this form of representation is termed "atomic" (example: 1 kg).

The complete indication of a measured quantity may contain additional information such as a specification of measurement uncertainty [7] and a time stamp. For a single quantity, measurement uncertainty is usually expressed by a coverage interval corresponding to a specified coverage probability [7, 17, 18]. A time stamp [13] is required if probing is undertaken for time–variant materials (or substances) and if a measured quantity or a constant is interpreted over a longer period of time. Fundamental physical constants (e.g. the Planck constant) [19-21] have changed several times since the introduction of the SI [8].

In a digital network in which existing and new applications communicate with each other, even greater importance than before must be assigned to the SI. The ability to use the SI to describe all physical processes using only seven base units leads to an unprecedented clarity that is fundamental for the secure exchange of data.

It is important to distinguish between human-to-human and machine-to-machine interfaces. The specifications presented here primarily relate to an automated communication. It is essential for communication between machines and algorithms operating in an innovative digitised value chain.

The basic idea of the machine-readable format for SI units is presented in Fig. 2.

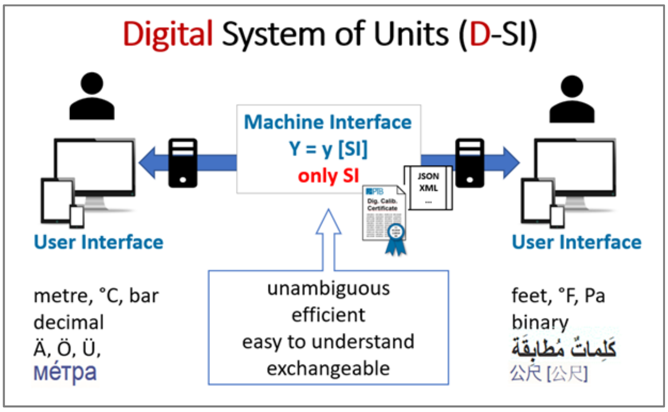

Fig. 2 Schematic presentation of the Digital System of Units (D-SI) as the universal format for the digital exchange of metrological data [22-23]

One of the research outcomes is also an adapter to allow the integration of non-SI units into the machine-readable D-SI data model [22-24]. This adapter is termed the "hybrid data model" or in short "hybrid".

The outcomes of this research segment include digital formats for:

- Machine–understandable unit format for SI–base units and units provided by the BIPM SI brochure [8],
- Real quantities,
- Complex quantities,
- Lists of real quantities (vector of real quantities),
- Lists of complex quantities (vector of complex quantities), and
- Coverage regions (related to multivariate measurement uncertainty).

For reasons of space, examples are presented only for the cases of a real quantity and a hybrid data model (for non-SI units). The complete D-SI data model and a reference implementation in XML (extensible markup language) have been published [22–24].

Real quantity

The uniform data format for real quantities is shown in Fig. 3. The model contains the measurement value with a corresponding unit, the measurement uncertainty in the same unit and a time stamp.

The components of the real quantity type in Fig. 3 were defined by considering the requirements of the most important metrological normative documents such as SI brochure [8], GUM [7], VIM [5], ISO 80000 [10, 11] and CODATA [19-21]. The data types of the components consider important standards from computer science such as IEEE 754, RFC 362 (UTF-8) [14] and ISO 8601 [13]. An example of an extended real quantity XML format [24, 25] is shown in Fig. 4.

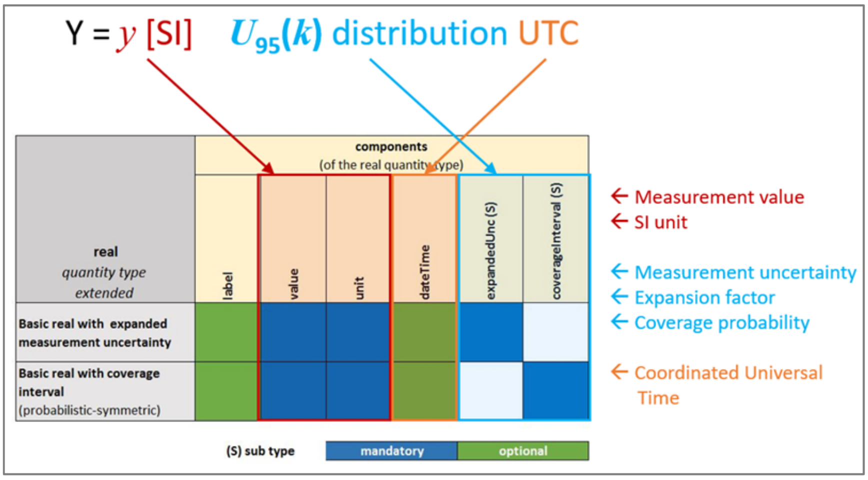

Fig. 3 Uniform data format for real quantity

```
<si:real>
    <si:label>temperature</si:label>
    <si:value>20.10</si:value>
    <si:unit>\degreecelsius</si:unit>
    <si:expandedUnc>
        <si:uncertainty>0.50</si:uncertainty>
        <si:coverageFactor>2</si:coverageFactor>
        <si:coverageProbability>0.95</si:coverageProbability>
        <si:distribution>normal</si:distribution>
    </si:expandedUnc>
</si:real>
```

Basic real

Expanded uncertainty

Fig. 4 Example of XML implementation of real with expanded uncertainty

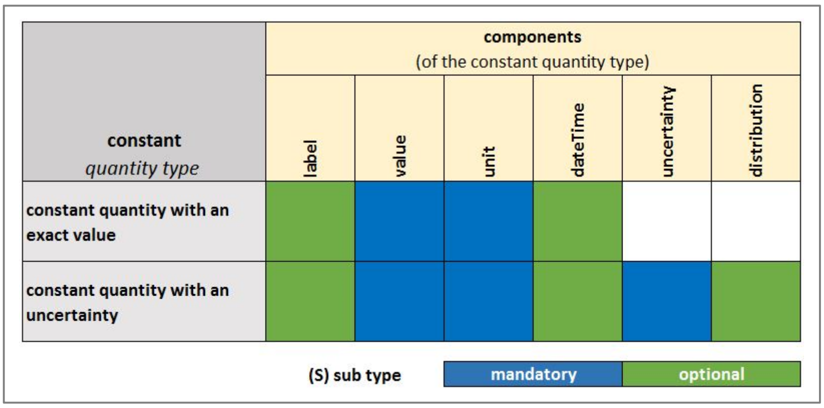

Fig. 5 Data model for machine-readable fundamental physical constants

Example a : XML representation of Planck constant before 2019-05-20:

CODATA 2014 value

```
<si:constant>
    <si:label>Planck constant</si:label>
    <si:value>6.626070040e-34</si:value>
    <si:unit>\joule\second</si:unit>
    <si:dateTime>2015-06-25T00:00:00Z</si:dateTime>
    <si:uncertainty>0.000000081e-34</si:uncertainty>
</si:constant>
```

Example b : XML representation of Planck constant since 2019-05-20:

new SI value

```
<si:constant>
    <si:label>Planck constant</si:label>
    <si:value>6.62607015e-34</si:value>
    <si:unit>\joule\hertz\tothe{-1}</si:unit>
    <si:dateTime>2019-05-20T00:00:00Z</si:dateTime>
    <si:uncertainty>0</si:uncertainty>
</si:constant>
```

Fig. 6 Examples of XML implementation of fundamental physical constants [20]

Within metrology, fundamental physical constants [19-21] and mathematical constants are also very important. The D-SI model [22, 23] for a machine-readable representation and transmission of these constants is shown in Fig. 5.

Component "uncertainty" of the fundamental physical constants is the standard deviation of an experimentally defined constant. For constants from CODATA [19], "uncertainty" is the uncertainty reported in the CODATA list.

For values of mathematical constants that must be rounded the component "uncertainty" provides the standard deviation of a rectangular distribution that contains the exact value of the constant with 100% probability.

An example of a fundamental physical constant in XML format is shown in Fig. 6.

Hybrid data model for real quantities

It is recommended to use only the following units in the D-SI data model:

- The seven SI base units,
- Units derived from SI base units, and
- Non-SI units that are allowed to be used together with the SI.

It is however not recommended to use units that are not listed in the SI brochure [8]. An exception to this recommendation is recognised for internationally accepted systems of units and scales in the area of reference materials and in the area of reference procedures.

While the recommended units can be directly used as references for real and complex quantities in the D-SI data model, this approach is not permitted for unrecommended units. The hybrid adapter allows the integration of those quantities with an unrecommended unit into the machine-readable D-SI data model. The application of the hybrid data model requires conversion of the quantity with the non-SI unit into a quantity with an adequate SI unit. Both quantities are then collected together into one data element – the hybrid element. The hybrid data element must contain at least one quantity with an SI unit. The number of additional quantities with other units can be one or more.

A real quantity in hybrid comprises one real component that must state the quantity value in a SI-base unit. Furthermore, it can provide additional real quantities with SI derived units or non-SI units that convert to the real quantity with the SI-base unit. An example of an XML implementation of a real quantity in hybrid is shown in Fig. 7.

```
<si:hybrid>
    <!-- A: length from B converted to SI -->
    <si:real>
        <si:value>0.3048006</si:value>
        <si:unit>\metre</si:unit>
    </si:real>
    <!-- B: length with imperial unit foot -->
    <si:real>
        <si:value>1</si:value>
        <si:unit>ft(U.S. survey)</si:unit>
    </si:real>
</si:hybrid>
```

Fig. 7 Example of XML implementation of a real quantity with a non-SI unit in the hybrid data model

3.2 Digital calibration certificate (DCC) considering technical and legal requirements

In the future, calibration services will require the exchange of comprehensive digital content of all kinds between customers, applicants and calibration service providers. Digital interfaces must therefore be developed and provided in such a way that the following aspects are guaranteed: authenticity; completeness of the transmitted data; data integrity and manipulation protection as well as protection of confidentiality. The first step for the exchange of calibration certificates in a digital environment is to have a uniform and internationally recognised structure of such digital documents. The following specification sets out the basic design for the structure of a DCC that was developed in WP 2 of the SmartCom project.

This basic structure is founded on agreed standards, including ISO/IEC 17025 for calibration certificates [26] and internationally-accepted guides like the SI brochure [8], CODATA [19-21], VIM [5] and GUM [7].

Fundamental DCC-Layout

The DCC designed within the project is structured in four layers and is presented in Fig. 8. These layers contain both regulated data, which are mandatory, and unregulated data, which are optional and contain additional information that does not necessarily have to be machine-readable.

- *Administrative shell*
  The administrative layer represents regulated (administrative) data. It contains required information of core interest (i.e. is not optional), for the unambiguous identification and collection of administrative information of the DCC. This information includes the unique DCC ID, identification of calibration laboratory, customer and items.
- *Calibration results*
  This layer contains a regulated area of measurement results according to the rules for the D-SI format [22, 23]. Moreover, individual additional information can be entered here in an unregulated area, e.g. individual calibration information, considering influence conditions, calibration methods and individual results.
- *Individual information*
  For general, optional, and additional comments, calculation tables and graphics of any individual data formats, typically requested by the recipient of the certificate.
- *Optional attachment*
  Here, a human viewable file can be stored (e.g. PDF format), which will typically be a conventional analogue calibration certificate. This layer will not be machine readable.

The structure described above provides for the integration of all aspects of ISO/IEC 17025 [26]. Firstly, industrial applications have been considered and have proven to be suitable for industrial requirements. The metrological data included in digital certificates must consist of a numerical value and a corresponding unit as a minimum. These specifications are described in section 3.1.

The structure described above is not dependent on any programming language and will work with many file formats including XML and JSON. Used identifiers and correct expression of measurement results have been taken from worldwide harmonised guides and standards to ensure international (machine) readability of the documents.

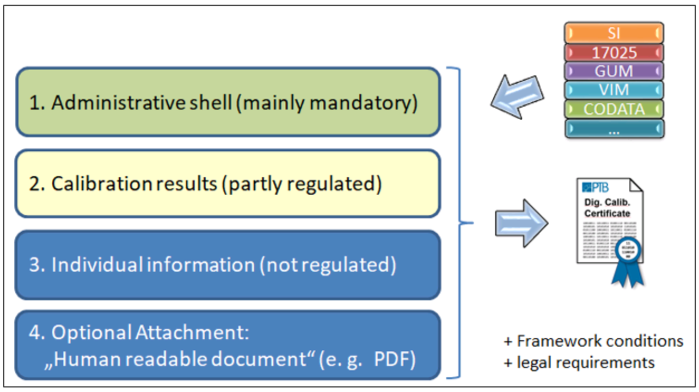

Fig. 8 General structure of digital calibration certificates

4. Conclusion

SmartCom is one of the first projects in metrology to define the universal minimum requirements for machine-readable data exchange in digital communication. The Digital System of Units (D-SI) metadata model presented in this paper can help developers of data formats to implement their data in an unambiguous, easy-to-use, safe and uniform way that is based on the International System of Units and other internationally accepted guides. It provides a data basis for representing data in future digital applications in metrology, such as: data for metrological services; data exchanged between virtual measuring instruments (DCC is virtual representation of properties of measuring artefacts and instruments). Analysis of big data is also facilitated if data is based on common terminology in metrology.

Digital calibration certificates (DCCs) are a very important application of the metrological data exchange. Using the principles from the D-SI, XML as machine-readable format and fundamental requirements from ISO/IEC 17025, a general structure for DCCs was specified.

In the future, DCCs will record all aspects of the calibrated items and make them available to a comprehensive quality management system. With these complete data sets, the performance of systems and processes can then be captured effectively and efficiently, allowing data analytic methods to provide information on optimised system performance. This activity leads to reduced downtime, less waste, significant improvement in quality, and ultimately greater economic success.

The work in the SmartCom project will be concluded in 2021. Until then, further tools will be developed to support the application of the DCC and D-SI [15]. The elaboration of aspects of cryptography will be of great importance for the transmission and use of DCCs. Suitable methods must be used to guarantee the integrity, completeness and authenticity of the calibration data. This area has proven to be particularly complex. No international standard in metrology is yet available for secure transmission, digital stamps and signatures or the withdrawal of digital data [27]. Preliminary approaches are using or envision the use of regulations such as the European eIDAS law [28] and blockchain technology in various areas such as Legal Metrology [29]. Finally, web-based services are being developed to help users of the D-SI and DCC to validate the correct usage of the data structure. PTB and NPL are planning to make available the validation services under the auspices of the TraCIM online test system.

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