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Original scientific paper

Predicting of Impact Strength and Elastic Modulus of Polypropylene/EPDM/Graphene/Glass Fiber Nanocomposites by Response Surface Methodology

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Abstract: In the present manuscript, Response Surface Method (RSM) of the experimental planning was applied to optimize the mechanical properties such as impact strength and elastic modulus of polypropylene (PP)/ethylene propylene dine monomer (EPDM) /grapheme Nano sheets (GnPs)/ glass fiber hybrid nanocomposites. According to a Box-Behnken method, three levels of parameters were used for EPDM (5, 10 and 15 wt.%), GnPs (0, 1 and 2 wt.%) and glass fiber (10, 20 and 30 wt.%). In addition, specimens were studied using differential scanning calorimeter (DSC) and scanning electron microscopy (SEM) to see their morphology and thermal properties. It was discovered that GnPs, glass fiber and EPDM played an important role in impact strength and elastic modulus of the nanocomposites. To reach the maximum value of the impact strength and elastic modulus simultaneously, the best amount of additives was about 0.82 wt.% of GnPs, 30 wt.% of glass fiber and 15 wt.% of EPDM. The gained R^2 values and the corresponding diagrams showed a desirable accordance (above 0.93 for all the responses) with the experiments and those guessed by the RSM.

Keywords: elastic modulus; graphene Nano sheets; impact strength; polypropylene; RSM (Response Surface Method)

1 INTRODUCTION

Polypropylene (PP) is a thermoplastic polymer that shows better thermal and mechanical properties compared to other industrial polymers. PP can be a good candidate for using in the packaging of food products, medicine, electrical tools, and automotive industries due to proper manufacturing cost, good recyclability and low weight [1, 2]. Nevertheless, some weaknesses such as its low stiffness and toughness has limited some of its applications [3]. However, the mechanical properties of PP could be improved by blending it with other polymers or nanoscale materials [4].

Blending of polymers together is an appreciate way to improve the toughness of them, which is not easily achieved by polymerization process [5]. Researchers have used many polymers including linear low density polyethylene (LLDPE) [6], low density polyethylene (LDPE) [7], high density polyethylene (HDPE) [8], ethylene propylene diene monomer (EPDM) [9] and other elastomeric polymers to modify the toughness of the PP. In some cases, EPDM is used for toughening of PP [10]. Blending PP by EPDM have reached great significant for commercial interest for structural adaptability. Recently, many researches have been published to investigating the mechanical properties the PP/EPDM blends [11, 12]. Khalili et al. [13] showed that the addition of EPDM led to a nominal increase in impact strength. For example, the impact strength of 50 wt.% flax fiber composites increased by 8% through the addition of 10 wt.% EPDM.

Newly, a large amount of researches have been concentrated on polymer composites having nano reinforced materials. The amount of carbon-based nano reinforcement materials is increased; from carbon nanotubes and nanofibers up to GnPs [14]. The addition of GnPs to a polymer matrix noticeably improves the material properties. In recent years, exfoliated GnPs have fascinated a large consideration because of their special characteristics [15]. Embedding low percentages of GnPs in PP matrix has been studied by many researches [16-18] and their results show improvement in the mechanical properties.

Recently, glass fibers are widely used as the reinforcement for composite materials because of their various advantages compared to natural fibers. The glass fibers have benefits such as their high temperature strength, corrosion stability, good dimensional durability, extremely light, solid material, support of the continuous production process of automotive industry and almost no moisture absorption [19, 21]. By the addition fibers to a matrix, the mechanical properties respect to base polymer increases properly. Güllü et al. found that polyamide reinforced with glass fiber exhibited an improving in their tensile and impact strength [22]. Response surface methodology (RSM) is an effective approach to develop, improve and optimize different procedures [23]. RSM supplies the interactions between variables better than any other procedures. Therefore, using RSM in optimization offers more appropriate data by a minimum of experiments. Up to now, experiments have been done in a way to study only one parameter at a time (neglecting the effects of the other parameters). It must be also noted that it is hard to find the best values of factors to guess the mechanical characteristics. To solve this, design of experiment (DOE) methodology was applied. This method permits of altering the value of factors altogether rather than one at a time and achieving the interaction between of the factors [24].

Considering the previous researches, one sees that the simultaneous presence of a rubber, a nanomaterial and glass fibers in a polymer matrix leads to an improve in its mechanical properties. The main goal of the present work was to use DOE methodology to study the modeling procedure and investigate the parameters effects of GnPs nanoparticles, glass fibers and EPDM on the impact resistance and modulus of elasticity of PP/ EPDM / GnPs / glass fiber nanocomposites at three levels. The design of experiments was done by the box-Behnken method and samples were prepared using a melt mixing method. Also, for each factor the optimal values were computed. Finally, the effect of GnPs on thermal properties of PP was investigated.

2 EXPERIMENTAL

2.1 Materials

The PP had a melt flow index (MFI) of 18 g/10 min and density of 0.918 g/cm^3. This material was provided from Arak Petrochemical Company (Iran). The graphene (C750-grade) provided from XG Science (USA). This type of GnPs were the sub-micron sheets that their diameters were below 2 mm, a few nanometer thickness and 750 m^2/g average surface area. In this study, the glass fibers type E by the average length of 6 mm, the average diameter of 14 µm and density of 2.25 g/cm^3 were purchased from Korean Chemical Contents Company. EPDM (KEP270 type) with the density of 0.9 g/cm^3 and including 57 wt.% ethylene / 4.5 wt.% dine monomer was provided by Kumho Company (South Korea).

2.2 Preparation of Samples

The samples were made with melt-process by an internal mixer (type Haake-HBI SYS 90) at 60 rpm and 180 °C for 10 min. After melting the PP in an internal mixer, EPDM in 5, 10 and 15 wt.% were added to it. Then, GnPs in 0, 1 and 2 wt.% and the glass fiber in 10, 20 and 30 wt.% were added to the melt. The mixing time was considered 10 min for all the cases. The test samples were made using hot-press molding having a square steel mold (250 × 250 mm^2) in 200 °C. Samples were preheated up to 200 °C at 2.5 MPa pressure and maintained at this pressure 5 minutes. To obtain more accurate results for impact strength and elastic modulus, each of the five specimens was prepared per combination.

2.3 Design of Experiments (DOE)

Box-Behnken system was applied in the present research to design of the experiments. Minitab@®17 was used for modeling of a design matrix and also to investigate on the experimental data. Input parameters including glass fiber, GnPs, and EPDM are shown in Tab. 1. In According to Box-Behnken method, 15 experiments having 3 center points were carried (Tab. 2).

Table 1 Variables and their levels in experimental design.

Variables (wt.%)	Low level (–1)	Middle level (0)	High level (1)
GnPs (X_1)	0	1	2
Glass fiber (X_2)	10	20	30
EPDM (X_3)	5	10	15

The important field of RSM is optimization methods to find an amount of variables that give a desirable response. The second-order model applied in RSM shown is:

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_{11} X_1^2 + \alpha_{22} X_2^2 + \\ + \alpha_{33} X_3^2 + \alpha_{12} X_1 X_2 + \alpha_{13} X_1 X_3 + \alpha_{23} X_2 X_3 \quad (1)$$

here Y is the response; X_1 , X_2 and X_3 are the variables; α_0 is the constant term; α_1, α_2 and α_3 are the coefficients of the polynomial linear effects; α_{11}, α_{22} and α_{33} are the coefficients of quadratic effect; and α_{12}, α_{13} and α_{23} are the coefficients of the polynomial interaction effect. In current work, the relation between X_1 (GnPs), X_2 (glass fiber) and X_3 (EPDM) as independent variables and the response Y as a model for the characteristics is found according to Eq. (1).

Table 2 Box-Behnken experimental design

Experiment run	GnPs (wt.%)	Glass fiber (wt.%)	EPDM (wt.%)
1	0	10	10
2	2	10	10
3	0	30	10
4	2	30	10
5	0	20	5
6	2	20	5
7	0	20	15
8	2	20	15
9	1	10	5
10	1	30	5
11	1	10	15
12	1	30	15
13	1	20	10
14	1	20	10
15	1	20	10

Tensile and impact test results in fifteen different modes based on Box-Behnken deign method with three repetitions for each compound is shown in Tab. 3.

Table 3 Impact strength and elongation at break experimental results

Experiment run	Elastic Modulus		Impact Strength	
	Values (MPa)	Standard Deviation	Values (J/m)	Standard Deviation
1	540	–115.13	103	-47
2	660	4.87	138	-12
3	695	39.87	163	13
4	720	64.87	148	-2
5	612	–43.13	122	-28
6	703	47.87	136	-14
7	598	–57.13	162	12
8	642	–13.13	172	22
9	648	–7.13	116	-34
10	737	81.87	158	8
11	610	–45.13	156	6
12	712	56.87	196	46
13	650	–5.13	158	8
14	645	–10.13	160	10
15	655	–0.13	163	13

2.4 Characterization

The elastic modulus characteristics were found by a Zwick/Roell z100 tensile test machine in accordance to ISO 527-1, with the stretching rate of 50 mm/min at room temperature. Notched Izod tests were done using a Santam SIT-20D pendulum impact tester. The tests were done following the ISO 179 at room temperature. To see the samples morphology, scanning electron microscopy (SEM) (WEGA-II TESCAN) was used to see the fracture surfaces of the impact samples. First, the samples covered by gold thin film at 20 kV accelerating voltage. Differential scanning calorimetric (DSC) was used with a Netzsch DSC 200 F3 Maia device number. DSC process was done in these three phases: At the first step, the samples were heated from 25 to 200 °C at the rate of 10 °C/minutes. At the second step, they were maintained in this temperature for 5 minutes and cooled up to 25 °C at the cooling rate of 10 °C/minutes. At the third step, they were reheated up to 200 °C at the rate of 10 °C/minutes.

3 RESULTS AND DISCUSSION

3.1 Effects of GnPs, Glass Fiber and EPDM Compounds on Impact Strength

To see the effect of factors on PP/ EPDM/ GnPs / glass fiber nanocomposites, analysis of variance (ANOVA) was accomplished. In an ANOVA table, the total degrees of freedom (*DF*) are the amount of information in the data. The analysis uses that information to estimate the values of unknown population parameters. The total DF is determined by the number of observations in your sample. Also in this table the sum of squares (*SS*) is used to predict the Fisher's variance ratio (*F*-value). Adjusted mean squares (*Adj MS*) calculate how much variation a term explains. F-value is the amount of variation in the information about the average. P-value is the minimum of significant that its can refute the hypothesis (it must be less than 0.05) [24]. Tab. 4 shows the effect of the ANOVA for the impact strength. From Tab. 4, the linear (GnPs, glass fiber and EPDM), square (GnPs × GnPs, glass fiber × glass fiber and EPDM × EPDM) and the interaction (GnPs × glass fiber, GnPs × EPDM and glass fiber × EPDM) coefficients of the three procedure parameters according to the *p*-value were important for the impact strength. When R^2 is near to 100% means that the design is very reliable. The value of R^2 in this research showed a well-fitting of the data. R^2_{Adj} is a handy tool to evaluate the explanatory power of the various models. Moreover, R^2_{Pred} is computed by a systematic removing of any observation datasets to estimate regression equation and show that how the model forecasts the removed data. Higher amounts of R^2_{Adj} (99.26%) and R^2_{Pred} (95.80%) shows that the model forecasting ability is excellent.

Table 4 The impact strength ANOVA results.

Source	*DF*	*Adj SS*	*Adj MS*	*F*	*p*
Regression	9	7785	865	210.9	0.000
Linear	3	6094	2031	459.4	0.000
GnPs	1	242	242	59.0	0.001
Glass Fib	1	2888	2888	704.3	0.000
EPDM	1	2964	2964	723.0	0.000
Square	3	1061	353	86.2	0.000
GnPs × GnPs	1	858	858	209.4	0.000
Glass Fib × Glass Fib	1	168	168	41.0	0.001
EPDM × EPDM	1	39	39	9.5	0.027
Interaction	3	630	210	51.2	0.000
GnPs × Glass Fib	1	625	625	152.4	0.000
GnPs × EPDM	1	4	4	0.98	0.369
Glass Fib × EPDM	1	1	1	0.24	0.642
R^2 = 99.74%	R^2_{Adj} = 99.26%			R^2_{Pred} = 95.80%	

The coefficients of second order polynomial equation were found using of ANOVA outcomes and regression analysis. After omitting negligible variables, the quadratic polynomial model of is presented below:

$$\begin{aligned} \mathit{Impact\ strength} &= 160 + 5.5X_1 + 19X_2 + 19.25X_3 - \\ &- 12.25X_1^2 - 6.75X_2^2 + 3.25X_3^2 - 12.25X_1X_2 \end{aligned} \quad (2)$$

In the above equation, terms without importance were omitted based on the ANOVA table. One sees that EPDM (X_3) has the maximum effect on the impact strength respect to GnPs and glass fiber. The plots of main effects were produced to demonstrate the effect of the model outcomes.

Fig. 1 presents the main effects of the whole parameters on the impact strength. The main effects demonstrate the deviations of the mean between the high and low amounts to every parameter. According to the Fig. 1, by increasing the GnPs, the impact strength increases 14% and, then, it decreases up to 8%. This increase belongs to GnPs condensations that prevents the crack propagation. It must be noted that some of the crack propagation energy is used to pull out the GnPs from the PP matrix. This loss of energy increases the impact strength [25, 26]. As previously mentioned, the small amount of the GnPs have a positive reinforcing effect. But, in high GnPs amounts, the agglomerations do as the points of cracks initiations which reduce the impact strength [25]. In addition, due to the Fig. 1, increasing of glass fiber increases the impact strength up to 26%, i.e. for the effect of fiber in wasting the energy of crack propagation in the specimens, increases the impact strength [27]. Also, according to Fig. 1, an increase in EPDM increased the impact strength by 29% because of flexibility of EPDM at low temperatures.

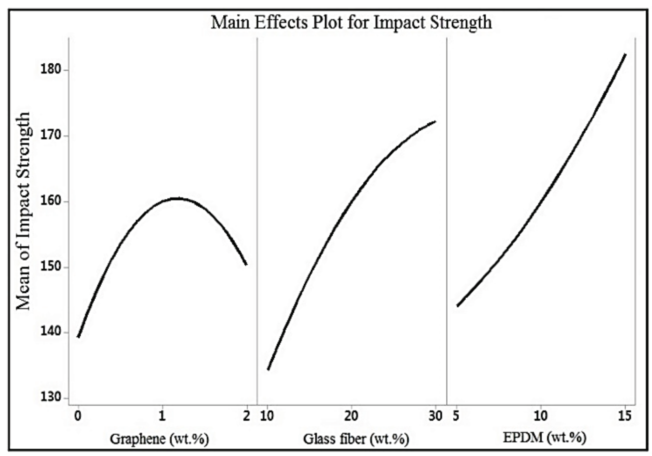

Figure 1 Main effects plot for impact strength

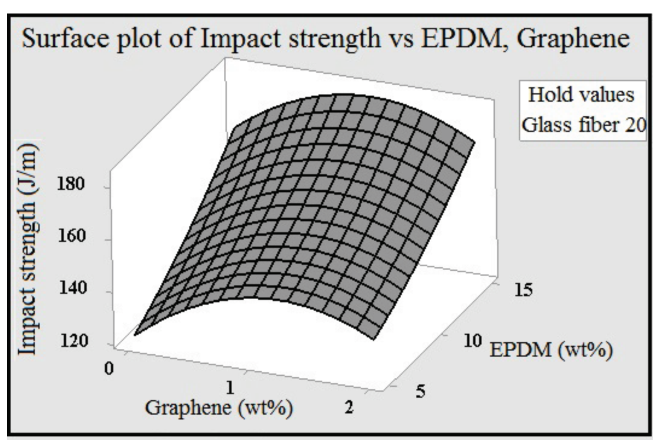

Figure 2 Impact strength versus EPDM and GnPs surface plot

Eq. (2) was applied to create the response surface plot for the impact strength versus GnPs, glass fiber and EPDM (on wt.%). Vertical axes of the response plots demonstrate the responses; as well as, each of the horizontal axis shows the design of variables by keeping the other one constant. For this model, if the reaction is significant, so it twisted the plane, and when the reaction is not important, the answer becomes as a flat plane. The 3D plots of response surface for impact strength versus EPDM × GnPs and GnPs × glass fiber are presented in Figs. 2 and 3, respectively.

Fig. 2 shows that the more EPDM is used, the less impact strength becomes. Furthermore, adding GnPs up to 1 wt.%, results in an increase and adding it higher than 1 wt.%, results in a decrease in impact strength. According to Fig. 3, one sees that the impact strength significantly improved by adding glass fiber from 10 to 30 wt.%; the highest increase in impact strength was at the middle level of GnPs (1 wt.%).

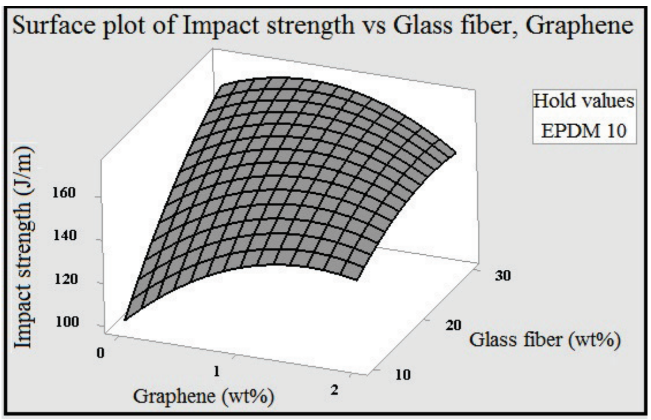

Figure 3 Impact strength versus GnPs and glass fiber surface plot

3.2 Effects of GnPs, Glass Fiber and EPDM Content on Elastic Modulus

Tab. 5 indicates the outcomes of ANOVA analysis to the elastic modulus. It is seen that the linear (GnPs, glass fiber and EPDM), square (GnPs × GnPs and glass fiber × glass fiber) and interaction (GnPs × glass fiber and GnPs × EPDM) the three procedure parameters factors are considerable on the elastic modulus. The R^2 for elastic modulus shows that just 0.39% of the variation was not described by this model (99.61% of variations are predictive). Also, the large values of R^2_{Adj} (98.90%) and R^2_{Pred} (95.49%) demonstrate that the model is very predictive.

Coefficients of a second order polynomial equation, using ANOVA and multiple regression analysis, were estimated in term of real parameters as:

$$\begin{aligned} &Elastic\ modulus = 650 + 35X_1 + 50.75X_2 - 17.25X_3 - \\ &-17.12X_1^2 + 20.88X_2^2 r - 23.75X_1X_2 - 11.75X_1X_3 \end{aligned} \tag{3}$$

It can be seen in Eq. (3) that among all the important variables, the glass fiber (X_2) has the biggest influence in the elastic modulus because of its higher coefficient.

Table 5 ANOVA results for elastic modulus

Source	*DF*	*Adj SS*	*Adj MS*	*F*	*p*
Regression	9	38665	4296	140.8	0.000
Linear	3	32785	10928	358.3	0.000
GnPs	1	9800	9800	321.3	0.000
Glass Fiber	1	20604	20604	675.5	0.000
EPDM	1	2380	2380	78.0	0.000
Square	3	3029	1009	33.1	0.001
GnPs × GnPs	1	1082	1082	35.5	0.002
Glass Fib × Glass Fib	1	1609	1606	52.7	0.001
EPDM × EPDM	1	127	127	4.1	0.096
Interaction	3	2850	950	31.1	0.001
GnPs × Glass Fib	1	2256	2256	73.9	0.000
GnPs × EPDM	1	552	552	18.1	0.008
Glass Fib × EPDM	1	42	42	1.3	0.292
R^2 = 99.61%	R^2_{Adj} = 98.90%			R^2_{Pred} = 95.49%	

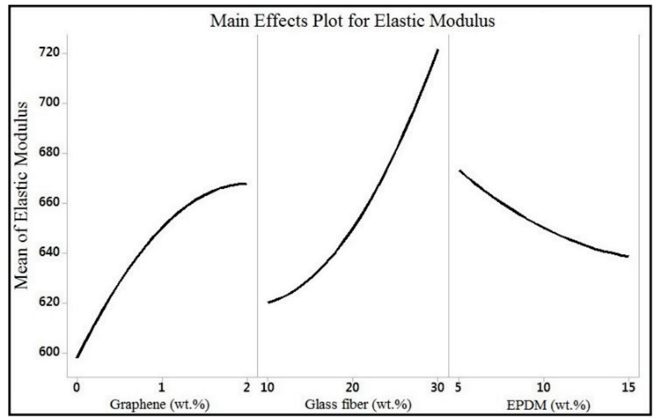

Figure 4 Elastic modulus main effects plot

The main effects plot in elastic modulus is indicated in Fig. 4. Accordingly, the addition of GnPs into PP matrix from 0 to 1 wt.% increased the elastic modulus of composites by 7% and, at high levels, increased it by 2%. The improvement in elastic modulus by increasing of GnPs into matrix related to good adhesion between the nano sheets and matrix. The addition of GnPs in binary matrix caused the proper adhesion of nano fillers in the matrix and created stronger bonds, which increased the elastic modulus [17, 18, 25]. In addition, from Fig. 4, with increase the glass fibers increased elastic modulus by 11%, the most important reason for which can be very high modulus of glass fibers and effect of transferring the load from a flexible polymer to rigid fibers [28]. Also, according to Fig. 4, the increase in EPDM reduced elastic modulus because EPDM elastomer to the PP was softer and had a lower elastic modulus.

The three dimensional plots of elastic modulus response surface versus EPDM × glass fiber, by keeping GnPs at 1 wt.%, and EPDM × GnPs, by keeping the glass fiber at 20 wt.%, are offered in Figs. 5 and 6, respectively. From Fig. 5, it is seen that the elastic modulus increased by increasing glass fiber from 10 to 30 wt. %; however, it decreased by increasing of EPDM from 5 to 15 wt.%. In addition, from Fig. 5, the highest amounts of the elastic modulus were reached at the maximum level of glass fiber (30 wt.%) and minimum level of EPDM (5 wt.%). Fig. 6 shows that the elastic modulus increased by increasing of GnPs from 0 to 2 wt.%; but, it decreased by increasing of EPDM from 5 to 15 wt.%; the highest increase in the elastic modulus was at the high level of GnPs (2 wt.%) and low level of EPDM (5 wt.%).

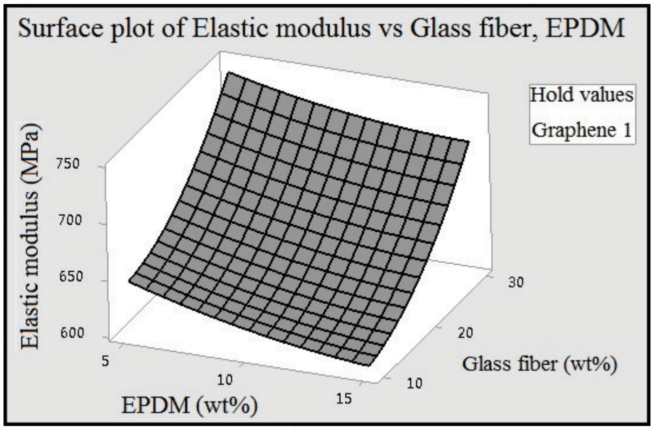

Figure 5 Elastic modulus surface plot versus EPDM and glass fiber

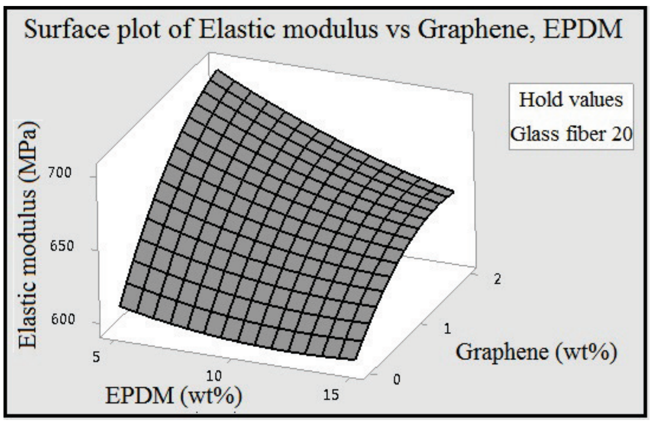

Figure 6 Elastic modulus surface plot versus EPDM and GnPs

3.3 Maximizing of Mechanical Properties

To optimize the mechanical properties, the impact strength and elastic modulus must be maximized together. A helpful method for solving a multiple response optimization subject is the use of the desirability function. In the method, every response equation is converted into an individual desirability function (d) that its value changes within $0 \le d \le 1$. Relevant to the response characteristics, there are three forms of the desirability function as follows:

(1) The higher is better – to maximize an objective function;
(2) The lower is better – to minimize an objective function;
(3) The nominal is better - to achieve a particular target, an objective function required [24].

Here, the elastic impact strength and modulus must be maximized. For this purpose, the associating desirability functions were the-higher-the-better. It can be written in a general form as presented in Eq. (4):

$$d_1 = \begin{cases} 0 & y < L \\ \left(\dfrac{y-L}{T-L}\right)^r & L \le y \le T \\ 1 & y > T \end{cases} \tag{4}$$

Where y is the response, T is the objective or target of the response, L shows the lower limit of the response and the super index r is the weight factor [29]. When the weight factor is 1, the desirability function will be linear. Selecting $r > 1$ means that it is more important to be close to the target value and choosing $0 \le r \le 1$ reduces its importance. Here, as two responses were studied, $r = 0.5$ was selected.

Depending on the desirability of each response, the component or overall desirability value was then calculated. This component desirability function ($0 \le D \le 1$) is optimized (maximized) to locate the optimal factor settings (factor combination) [24]. Overall desirability function is given by:

$$D = (d_1 d_2 \dots d_n)^{\frac{1}{n}} \tag{5}$$

Where n defines the responses number. The desirability function method was used in this work to join two responses (impact strength and elastic modulus) on a nanocomposite desirability function that may be written as:

$$D = \left(d_1(\mathit{impact\ strength}(x) \times d_2(\mathit{elastic\ modulus}(x)\right)^{\frac{1}{2}} \tag{6}$$

Where D defines the nanocomposite desirability function, d_1 and d_2 are individual desirability functions related to the first and second responses (*impact strength* and *elastic modulus*), x shows the vector of the designed variables (coded values), *impact strength*(x) and *elastic modulus*(x) are the predictor of the impact strength and elastic modulus given by the regression Eq. (2) and the Eq. (3) respectively.

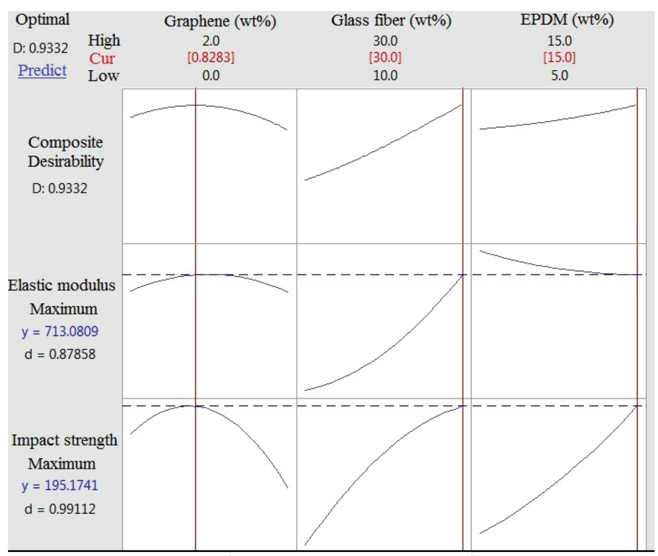

Figure 7 Desirability plot for simultaneous optimization of process parameters

The responses of desirability function analysis are presented in Fig. 7. To maximize impact strength and elastic modulus (in Fig. 7) under the best situation of nanocomposite desirability (D = 0.93), the amounts of GnPs must be at 0.83 wt.%, glass fiber at 30 wt.% and EPDM at 15 wt.%. Moreover, the RSM design of experiments predicted that the favorable mechanical characteristics can be achieved from the elastic modulus equals to 713.08 MPa and the impact strength equals to 195.17 J/m. Moreover, desirability function results indicated that the nanocomposite desirability (0.93) was exactly near to 1 that indicated the settings were appropriate to reach a good answer for each responses. Anyway, one sees that the settings were more effective for maximizing the impact strength (d = 0.991) than elastic modulus (d = 0.878).

Table 6 Validation of results for optimal conditions

Mechanical properties	Prediction	Confirmation experiment	Error Percent
Elastic modulus (MPa)	713.08	711.20	0.26
Impact strength (J/m)	195.17	194.10	0.55

After optimizing process, a verification test was done at optimal conditions. The impact strength and elastic modulus contents gained from the confirmation test were nearly similar to the data that is received from optimal value, as shown in Tab. 6 (less than 1 percent error).

3.4 Surface Microstructure

To study the effect of GnPs, glass fiber and EPDM content to increase the mechanical characteristics of the nanocomposites, the impact fractured surfaces of the compounds were investigated by the SEM, as indicated in Fig. 8. SEM pictures show the dispensation and adaptability among the fillers and the matrix clearly. From Fig. 8a, it is clear that the glass fibers did not have good adhesion with the field and, when applying the bending loads to fracture the samples, had an attitude to pull from the polymer matrix out. This behavior is not surprising in the composite [30].

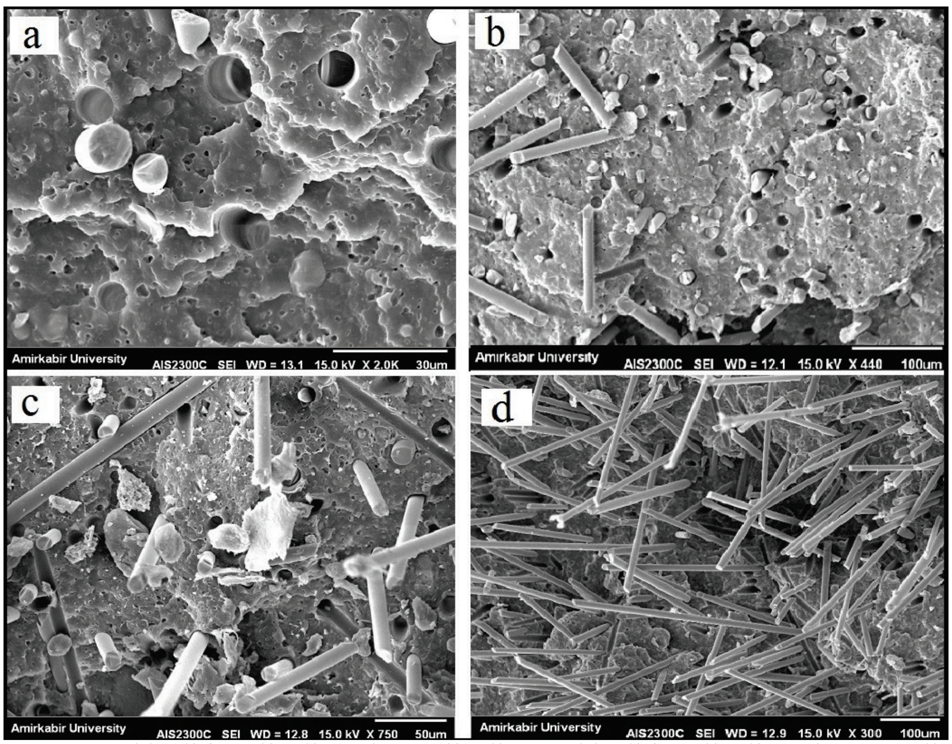

Figure 8 SEM images of the sample with: a) 0 wt.% GnPs, 10 wt.% glass fiber and 10 wt.% EPDM, b) 1 wt.% GnPs, 10 wt.% glass fiber and 5 wt.% EPDM, c) 2 wt.% GnPs, 10 wt.% glass fiber and 10 wt.% EPDM, d) 1 wt.% GnPs, 30 wt.% glass fiber and 15 wt.% EPDM.

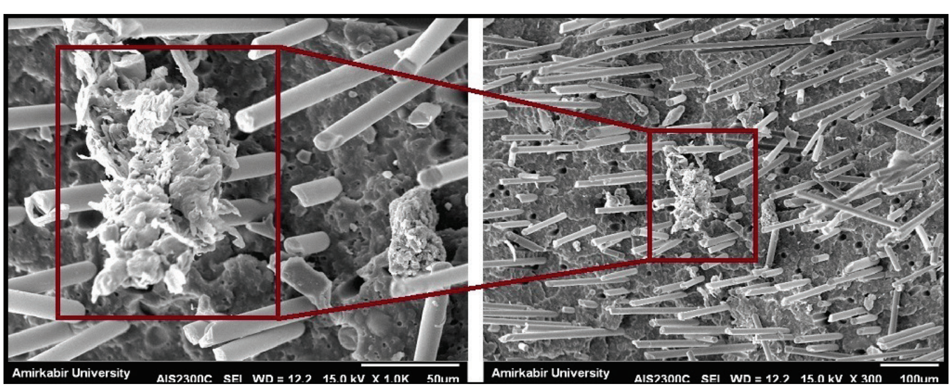

Figure 9 SEM images of the sample with 2wt.% GnPs, 20wt.% glass fiber and 15wt.% EPDM.

From Fig. 8b, the convenient distribution of 1 wt.% GnPs in the matrix could be seen. Also, the presence of 2 wt.% of nanoparticles in polymer matrix led to agglomeration, as is visible in Fig. 8c. Also, as can be seen in Fig. 8d, adding 1 wt.% of GnPs in the nanocomposites caused filling the cavities in the polymer matrix and improved adhesion between the fiber and matrix. The effects of the filler on mechanical properties in the nanocomposites have also been reported in the results of other researchers [26]. In Fig. 9, one sees that, if the values of GnPs become 2 wt.%, the nano sheets easily agglomerates. Actually, according to the van der Waals force, GnPs have high trend to agglomerate. This results in a decrease of mechanical characteristics of the nanocomposites, respect to nanocomposites filled with a less value of GnPs.

3.5 Thermal Properties

Figs. 10a and 10b indicates the melting and crystallization curves related to cooling and heating cycles of two samples. The cooling curve peak illustrates the crystallization temperature (T_c) and the heating curve peak demonstrates the melting temperature (T_m) of the nanocomposites. It is visible that the both of thermal parameters related to the T_c and T_m were obtained and presented in Tab. 7. As can be seen, an increase of 1 to 2 wt.% of GnPs can increase T_c less than 2%, but it did not significantly affect the T_m. Increasing of the T_c of the PP matrix with the addition of GnPs up to 2 wt.% indicates that GnPs helped crystallize the PP. Increasing the crystallinity of polymers increases the elastic modulus. Therefore, the presence of 2 wt.% of nanoparticles increases the elastic modulus of the compounds (Fig. 4).

Table 7 Results of DSC analysis.

Sample no	T_c (°C)	T_m (°C)
Pure PP	124.24	164.95
13	124.49	165.33
6	127.79	165.36

In fact, when the samples were cooled from high temperature, the GnPs acted as nucleating and crystallization starts were accelerated [31].

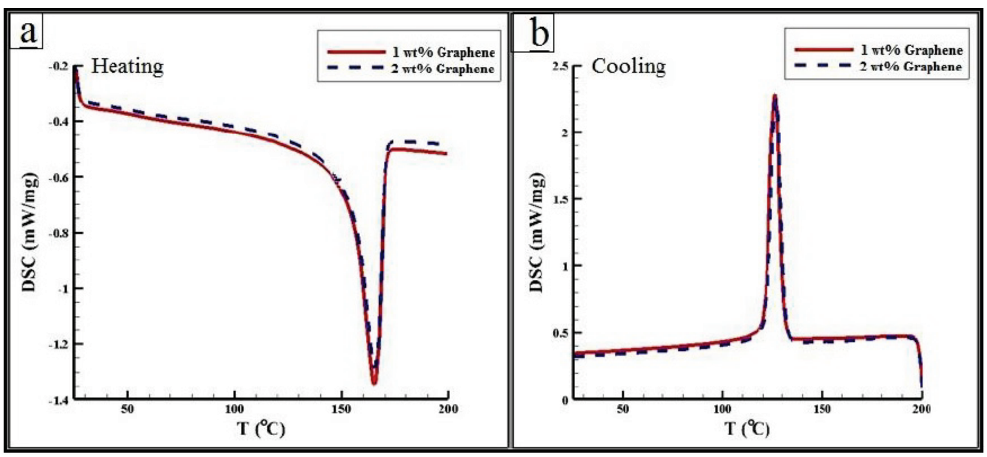

Figure 10 DSC curves: (a) heating run, (b) second cooling run.

4 CONCLUSION

Here, an optimization method, incorporated with a response surface methodology, a mathematical model and the desirability function approach, was used to predict and optimize the elastic modulus and impact strength of PP/EPDM/glass fiber/ GnPs polymer nanocomposites. It was found that:

1) The EPDM had the maximum influence in the impact strength and glass fiber had the most effect on the elastic modulus.
2) Embedding GnPs in the PP matrix increased the impact strength and elastic modulus by 14% and 12%, respectively, but this increase was depended to the appropriate amount of used nano filler (up to 1 wt.%).
3) Based on the main effects and interaction plots, increasing in EPDM contents resulted 28% increase of the impact strength, whereas an increase in glass fiber contents results in an increase of impact strength by 25% and elastic modulus by 16%.
4) According to the desirability function, ultimate impact strength and elastic modulus were forecasted as below: GnPs 0.83 wt.%, glass fiber 30 wt.% and EPDM 15 wt.%.

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Original scientific paper

Application of Numerical Methods for Research of Construction Design of Fastener Fractures

Leonid Kolomiets*, Aleksej Aniskin, Victor Orobey, Alexander Daschenko, Alexander Lymarenko, Kostiantyn Boriak

Abstract: The work uses modern numerical methods of mechanics of a deformable solid to analyze the stress-strain state of orthopedic structures in order to improve them and improve the quality of treatment of patients. Among the many numerical methods, the attention of the authors was drawn to the finite element method and to the numerical and analytical method of boundary elements in the author's edition. Settlement models of both metal apparatuses and parts of a person's arm with a fracture are constructed. The stress – strain state in various zones of the biomechanical system was calculated. It is shown that the numerical-analytical method of boundary elements allows obtaining more accurate results with fewer equations in the resolution system. It is noted that in the case of the considered biomechanical systems, its elements undergo tension – compression, shear, torsion, and bending. To consider them, solutions are presented for Cauchy problems, which are included in the general system of resolving equations of the MGE. It is shown that, unlike the FEM, the MGE simplifies the algorithm for calculating biomechanical systems. Comparison with the FEM results shows their good agreement, which proves the reliability of the calculation results of both methods.

Keywords: boundary element method; finite element method; orthopedic constructions; stress-strain state

1 INTRODUCTION

One of the ways to investigate various designs in medicine is a computer simulation or computer experiment based on numerical methods (finite difference method, boundary element method, finite element method, and others) [1, 2].

The capabilities of the numerical method depend on task and applied software package.

Numerical analysis allows you to calculate various design options of the studied object and take into account various combinations of loads.

The relevance of the research topic, the problems with the treatment of patients and of the forearm bones diaphysis fractures (compact bone substance), is determined by the insufficient perfection of the devices and the appropriate treatment methods [3, 4].

2 ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

From literary sources it is known that forearm bones fractures account for 5 – 15% of cases from all fractures of limb segments.

Ilizarov apparatus was the most widely used for the treatment of patients with injuries of limb segments [2]. The use of this apparatus gives a significant percentage of complications due to a decrease in the stability of the spoke fixation and the bulkiness of the external structure. This was the reason for the search by many scientists and researchers in the field of traumatology for alternative configurations of compression-distraction apparatuses (various designs of external supports, node connections, types of fixation).

Research overview [5, 6] shows that rod apparatus from the alternative devices for transosseous fixation have obvious advantages. Some restrictions of their use are associated with existing problems in osteosynthesis techniques depending on the type and pattern of the diaphyseal fracture of the bones (in our case the forearm).

During the work with literary sources [1-8] data gaps in comparative calculations of external structures for the treatment of forearm fractures by numerical methods became apparent.

3 THE PURPOSE OF WORK

The purpose of the work is the justification for the external fracture fixation design and methods for determining the deformation of geometric dimensions.

Calculation of the stress-strain state of cylindrical shells of BEM and FEM (ANSYS) [9-12] and comparison of their results (MATLAB).

4 MAIN PURPOSE OF THE ARTICLE

The basis of the research of this design is the purpose to design a fracture treatment device of the middle part of the forearm with damage to the diaphysis of the tubular bones by developing an alternative design in which the reposition of fragments that have come out of the correct state is achieved by increasing the degrees of mobility of the repair nodes. Thanks to this design it becomes possible to ensure the correct position of displaced bone fragments without gypsum immobilization and most importantly full mobility of the forearm is maintained without creating inconvenience in the patient due to compactness.

The problem is solved thanks to the external support in the construction in the form of a beam on which rod receivers with screw studs are located fixing screw rods that are successively passed through parts of intact bones to ensure their rigid connection [2].

The data for building models were obtained based on the transverse scans of the bones of the human forearm carried out on a TOSHIBA Asteion Super 4 multislice helical computer scanner. Further 3D model was created that adequately reflects the geometry of the bones of the forearm.

We conducted a computer simulation of fixation methods in order to determine the stiffness of fixation of fractures of the forearm bones with an apparatus for transosseous osteosynthesis with their specific layout and in the range of possible functional loads, identifying the optimal arrangement of the apparatus, determination of treatment tactics depending on the type of fracture.

From the point of view of mechanics, such systems are spatial structures from a set of thick-walled annular and rectangular plates with holes, classic rods, flexible rods (spokes) in combination with various types of joints.

The simplified analytical methods of calculation are often used among the methods of mechanics in engineering practice and scientific research. The design scheme of the investigated object is simplified both by the design of the elements of the spatial system, the nature of the relationship between each other and from the point of view of representing external loads. The widespread use of modern computer technology in research projects required a revision of existing methods. If so far, the main attention has been paid to the creation of calculation methods based on a number of simplifying assumptions and methods of artificially facilitating the calculation, then at present we can only talk about the development of mathematical models that are subject to the most efficient implementation on a computer. We mean here by effective such models that most fully reflect the real geometry and behavior of the structure require simple software and the least amount of machine time.

The most convenient for solving problems of mechanics both in medical research and in other fields of science and technology turned out to be the methods of the discrete theory of linear spaces: matrix calculus, the potential method, the boundary element method and of course the finite element method (FEM).

To solve the FEM problem it is necessary to present the entire construction in the form of a set of finite elements: rods, triangular and quadrangular plates, tetrahedrons and parallelepipeds connected to each other in nodes.

The initial stage in the finite element analysis of any constructions including orthopedic devices is the construction of a geometric and finite element model.

The geometric model represents the shape and dimensions of the construction and the finite element model contains complete information about the location of nodes and finite elements as well as the relationship between individual nodes and elements.

Theoretically, it is possible to carry out finite element analysis without using a geometric model but in this case, it is necessary to manually set the coordinates of all nodes and build the finite elements of the model, which is almost impossible for complex constructions.

Using a geometric model this drawback is absent as it is possible to automatically obtain a finite element mesh of a structure based on its geometric model in modern programs of finite element analysis [9, 12]. Therefore, such an approach to modeling orthopedic systems is preferable.

Elements of the core system of fracture treatment devices can be modeled using the following types of finite elements:

- beam and core elements
- plate elements
- volumetric elements.

The geometric model must comply with the type of element that will be used in the finite element breakdown. If the discretization of the structure will be carried out by beam and rod elements, then the geometric model should consist of lines, for plate elements – from surfaces, for volume elements – from volume bodies.

The paper considers models with rod and volume finite elements, because they ensure compliance with the geometry of the model of a real construction (Fig. 1).

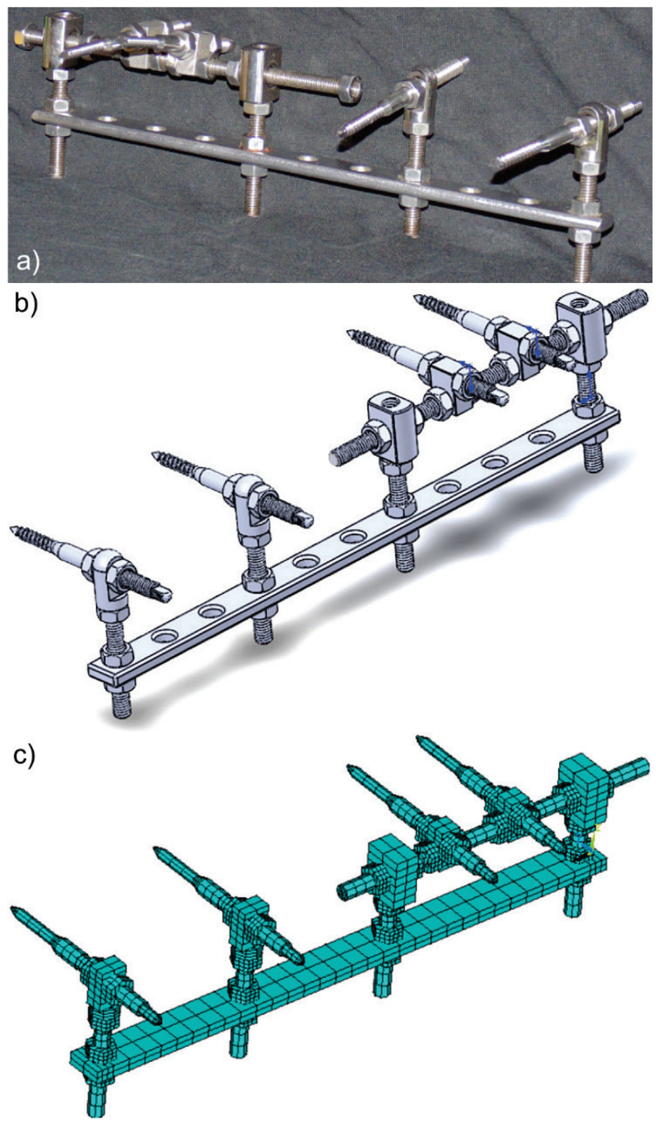

Figure 1 Real (a) and computer models of volumetric finite elements (b) and rod finite elements (c)

An approximation of model from a rod finite elements was done the BEAM188 element from the library of elements of the ANSYS program. The element is intended to solve spatial problems. Element properties are defined by describing the cross-sectional characteristics, material properties (modulus of elasticity and Poisson's ratio) and elastic base.

This finite element has two nodes with six degrees of freedom and each of them: displacements in the directions of the *x*, *y*, *z* axes of the nodal coordinate system and rotation angles around these axes.

To display geometric features original cross sections of the structural elements of the clamps were formed and a special function of the ANSYS – Taper Section program was used (we have created and recorded in the database the 37 cross-section programs).

The finite element partition of the model with volume elements is performed by the Solid45 element. The element is classified as follows: a volumetric (3D) element is used in solving problems of the mechanics of a deformable solid and is determined by eight nodes, each of which has three degrees of freedom – linear displacements in the directions of the *x*, *y*, *z* axes of the nodal coordinate system.

In both cases the fixing conditions should be chosen so that they prevent the movement of the structure but do not affect the deformation.

The geometric and mechanical characteristics of the studied devices were determined by the known mechanics dependencies of a deformable solid, experimental data and reference books.

The elastic modulus of the human bone was accepted equal $E_\kappa = 2\times10^4$ MPa, modulus of elasticity of steel $E_{cm} = 2.1\times10^5$ MPa, modulus of elasticity of titanium $E_m = 1.2\times10^5$ MPa (Fig. 1).

As a result of calculations for each of the options the parameters of the stress-strain state that were of interest to us for the analysis were determined:

σ_{equiv} – equivalent stresses according to the Huber-Mises hypothesis (IV theory of strength)

USUM – equivalent displacement values.

4.1 Application of the Numerical-Analytical Version of the Boundary Element Method

According to the accepted design scheme (Fig. 2) it may be considered that the orthopedic structure and the forearm bones form as a first approximation a spatial rod system. This system uses both hingedly connection of the rods and hard jamming of structural elements. These boundary conditions can be accurately taken into account if we apply a numerical-analytical version of the boundary element method (BEM). In general, the elements of a given biomechanical system will experience 4 types of resistance: tension-compression, shear, torsion, and bending. In this case, at the boundary points (x = 0 and x = l), kinematic and static boundary parameters arise:

a) Tensile compression:

$U(0)$, $U(l)$ – movement along the axis of the rods,
$N(0)$, $N(l)$ – normal forces;

b) Shift:

$V_c(0)$, $V_c(l)$ – cross movements
$Q(0)$, $Q(l)$ – cross forces.

c) Torsion of solid section rods:

$\theta(0)$, $\theta(l)$ – twisting angles of boundary points
$M_{kp}(0)$, $M_{kp}(l)$ – torques.

d) Bend:

$V(0)$, $V(l)$ – cross movements;
$\varphi(0)$, $\varphi(l)$ – turning angles of the sections at the boundary points
$Q(0)$, $Q(l)$ – cross forces
$M(0)$, $M(l)$ – bending moments.

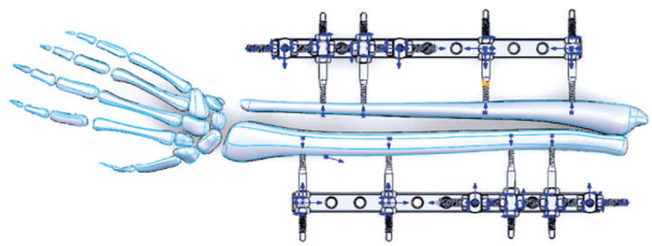

Figure 2 The design scheme of the object of study

In the formation of the permissible equations of the BEM, we will use the left-handed coordinate system and the following sign rules:

− Linear movements of boundary points are considered positive if they coincide with the positive directions of the axes 0*x*, 0*y*, 0*z*.

− Turning angles of rotation of the sections at the boundary points are considered positive if they are clockwise when viewed from the direction of the positive axes 0*x*, 0*y*, 0*z*. As an example Fig. 3 shows the positive directions of the boundary parameters during bending.

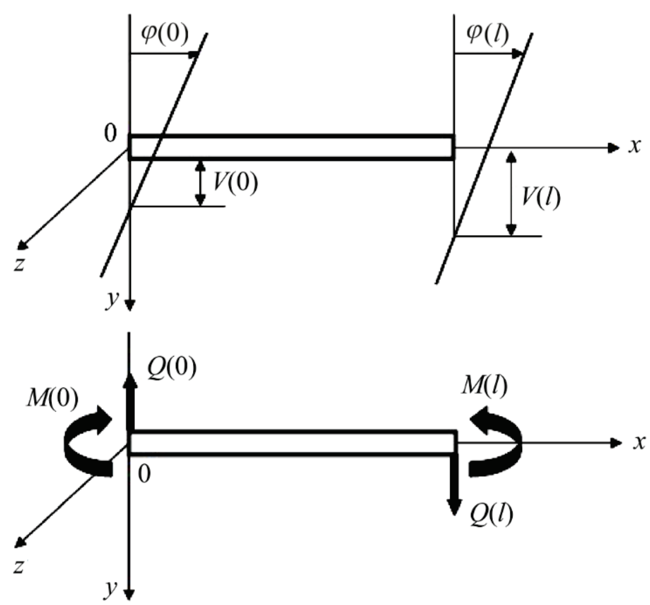

Figure 3 Positive directions of the boundary parameters during bending

In the case of deformation of the core system, the nodes receive certain linear and angular displacements, and the kinematic parameters in the nodes will be related by the equations of compatibility of displacements. Accordingly, the static parameters in the nodes will be related by equilibrium equations. These considerations allow us to form the resolving equations of the BEM of any core system. The solution of this system determines the stress-strain state of all structural elements.

Let us imagine solutions to Cauchy problems for the indicated types of resistances:

a) Tensile compression

$$\begin{bmatrix} EAU(x) \\ N(x) \end{bmatrix} = \begin{bmatrix} 1 & xEAU(0) \\ & 1\,N(0) \end{bmatrix} - \int_o^x \begin{bmatrix} (x-\xi)qx(\xi) \\ qx(\xi) \end{bmatrix} \mathrm{d}\xi \qquad (1)$$

b) Shift

$$\begin{bmatrix} \dfrac{GA}{k}V_c(x) \\ Q(x) \end{bmatrix} = \begin{bmatrix} 1 & x\dfrac{GA}{k}V_c(0) \\ & 1\,Q(0) \end{bmatrix} - \int_o^x \begin{bmatrix} (x-\xi)qy(\xi) \\ qy(\xi) \end{bmatrix} \mathrm{d}\xi \qquad (2)$$

c) Torsion of solid section rods

$$\begin{bmatrix} GI_k\theta(x) \end{bmatrix} = \begin{bmatrix} 1 & xGI_k\theta(0) \end{bmatrix} - \int_o^x \begin{bmatrix} (x-\xi)m(\xi) \end{bmatrix} \mathrm{d}\xi \qquad (3)$$

d) Bend

$$\begin{bmatrix} EIV(x) \\ EI\varphi(x) \\ M(x) \\ Q(x) \end{bmatrix} = \begin{bmatrix} 1 & x & \dfrac{-x^2}{2} & \dfrac{-x^3}{6} \\ & 1 & -x & \dfrac{-x^2}{2} \\ & & 1 & x \\ & & & 1 \end{bmatrix} \begin{bmatrix} EIV(0) \\ EI\varphi(0) \\ M(0) \\ Q(0) \end{bmatrix} + \int_o^x \begin{bmatrix} (x-\xi)^3\dfrac{q(\xi)}{6} \\ (x-\xi)^2\dfrac{q(\xi)}{2} \\ -(x-\xi)q(\xi) \\ -(x-\xi) \end{bmatrix} d\xi \qquad (4)$$

Using these solutions and the BEM algorithm it is possible to formulate the resolving BEM equation, find the unknown initial and final parameters of all elements of the biomechanical system and determine its stress-strain state.

4.2 Solving Boundary Value Problems of Biomechanical Systems BEM

If the rods of the biomechanical system are connected into a single structure then for such system it is possible to apply matrix forms of solutions to Cauchy problems (1)-(4). In this case, the matrix equation of the whole structure will take the form

$$\boldsymbol{Y}(x) = \boldsymbol{A}(x)\,\boldsymbol{X}(0) + \boldsymbol{B}(0) + \boldsymbol{B}(x) \qquad (5)$$

where: $\boldsymbol{Y}(x)$ – vector of deformation parameters in the current section; $\boldsymbol{A}(x)$ – quasi-diagonal matrix of fundamental functions of all kinds of resistances; $\boldsymbol{X}(0)$ − vector of initial parameters; $\boldsymbol{B}(x)$ – load matrix.

At the boundary value of the parameters $x = l_i$ (for all rods) there arises the possibility of an elementary transformation of Eq. (5) into the resolving equation of the BEM boundary value problem according to the scheme

$$\boldsymbol{Y}(l) = \boldsymbol{A}(l)\boldsymbol{X}(0) + \boldsymbol{B}(l) \rightarrow \boldsymbol{A}(l)\boldsymbol{X}(0) - \boldsymbol{Y}(l) = -\boldsymbol{B}(l) \qquad (6)$$

As stated above, coupling equation between the boundary parameters arise in the nodes of the rod system. This fact allows us to transfer all the finite vector options $\boldsymbol{Y}(l)$ on vector $\boldsymbol{X}(0)$. In this case, the quasi-diagonal matrix $\boldsymbol{A}(l)$ will be reset to separate columns and compensating nonzero elements are introduced into them as initial data; as a rule, this is (−1). Thus, a system of resolving equations is formed with respect to the initial and final parameters of the entire structure of the form

$$\boldsymbol{A}_*(l)\cdot\boldsymbol{X}_*(0,\,l) = -\boldsymbol{B}(l). \qquad (7)$$

Note that the load $\boldsymbol{B}(l)$ matrix is not involved in these transformations, which favorably distinguishes the BEM algorithm from the finite element method, where it is necessary to reduce the given load to the equivalent nodal load. The most complex equation formation operation (7) is the matrix transformation $\boldsymbol{A}_*(l)$. The following stages are stand out here:

- a quasi-diagonal matrix is formed $\boldsymbol{A}(l)$; its filling with blocks of boundary values of orthonormalized fundamental functions is performed according to the program using cycle operators;
- matrix columns are reset to zero $\boldsymbol{A}(l)$, whose numbers are equal to the vector zero line numbers $\boldsymbol{X}(0)$. Zero initial parameters of the rods are the source data and the numbers of zero lines of the vector $\boldsymbol{X}(0)$ are determined in the process of its formation. We denote the matrix nullable in separate columns $\boldsymbol{A}_0(l)$.
- compensating elements are determined that allow to transfer all the finite parameters of the vector $\boldsymbol{Y}(l)$ to the vector $\boldsymbol{X}_*(0,\,l)$. The compensating elements can be reduced to an auxiliary matrix $\boldsymbol{C}$ for clarity of the algorithm. This matrix characterizes the design topology and is invariant with respect to the type of calculation, i.e. can be used without any changes in tasks of statics, dynamics and stability. The coefficient matrix of the system of Eq. (7) is obtained by simple summation

$$\boldsymbol{A}_*(l) = \boldsymbol{A}_0(l) + \boldsymbol{C}. \qquad (8)$$

A system of resolving Eq. (7) is compiled for the design scheme according to Fig. 2. The results of determination of the stress-strain state of the construction according to the BEM algorithm are presented in Tab. 1. From the data Tab. 1 it follows that the results of the BEM and FEM methods are good accord with each other, which proves the reliability of these calculations.

Table 1 The maximum values of the stress-strain state parameters

SSS parameters	Fixator (FEM)	Fixator (BEM)
USUM (mm) Elbow joint area	0,00197	0,00186
USUM (mm) Fracture area	0,0089	0,0075
USUM (mm) Wrist area	0,0273	0,0218
$_{max}\sigma_{equiv}$ (MPa)	16,098	21,783

The maximum values of the specified stress-strain state parameters for all calculation options are summarized in Tab. 1.

5 RESULTS

The results of a numerical experiment allowed drawing some conclusions:

Relative deformation of the rod apparatus:

Model from FE: $\varepsilon_c = \dfrac{\Delta l}{l} = \dfrac{0.0273}{235} = 1.162\times10^{-4}$

Model from BE: $\varepsilon_c = \dfrac{\Delta l}{l} = \dfrac{0.0218}{235} = 0.928\times10^{-4}$

Comparison of numerical values of stresses and displacements obtained by finite element analysis of the investigated constructions with the corresponding values of these quantities that are obtained in the calculation by the boundary element method allows making a conclusion about the reliability of assumptions that were adopted at the stages of numerical simulation. This conclusion, perhaps, will be true with regard to the boundary conditions as well as the magnitude and nature of the application of external loads.

The obtained research results can serve as the basis for the development of new constructions for the treatment of diaphyseal fractures of the forearm.

6 CONCLUSIONS

The analysis of treatment methods of the forearm bones fractures is given. It is noted that existing devices are imperfect and therefore it is necessary to use modern and powerful numerical mechanics methods of a deformable solid to analyze the stress – strain state of biomechanical systems in order to improve them.

The analysis of numerical methods that are currently applied is performed. It is indicated that the most promising methods to solve the treatment problems and to improve orthopedic constructions are the finite element method and the numerical-analytical method of boundary elements.

The process of modeling the biomechanical system in the ANSYS professional package is shown in detail. Computed models of one-dimensional and spatial finite elements are compiled. The calculations of the SSS biomechanical system.

For applying BEM solutions of the Cauchy problems of tension – compression, shear, torsion, and bending were involved. A formation algorithm of a resolving system of equations is outlined. Appropriate calculations are made and compare son with FEM results is given where their close match is noted and thus the reliability of the results of both methods is proved.

A comparison of the numerical quantities of stresses and displacements obtained in the finite element analysis of the constructions with the corresponding quantities of these quantities obtained in the calculation using the boundary element method allows us to make a conclusion about the reliability of assumptions that were taken at the at the modeling stages. Perhaps, this conclusion will be true with regard to the boundary conditions, as well as the quantities and nature of the application of external loads.

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Original scientific paper

Gamification Framework for E-Learning Systems in Higher Education

Andrija Bernik

Abstract: This paper explains the concept of gamification, lists the current models according to which educational e-courses can be designed, and proposes a conceptual eRIOOS model aimed at higher education. The aim of the research as well as the purpose of creating a conceptual model of gamification is to standardize the elements of computer games that can be used in educational e-courses at higher education institutions. In the preparation of this research, the emphasis was placed on the invention and analysis of professional and scientific literature for creating a conceptual model. The model contains a logical representation of two levels of complexity. Three separate e-courses have been created in different courses within the two University institutions, which serve as a tool to check the correctness of the conceptual eRIOOS model. The result of the research is a confirmed conceptual model that is suitable for creating Moodle e-courses of IT teaching orientation in higher education institutions.

Keywords: e-course; eRIOOS; gamification; model; Moodle; University

1 RELATED WORK

In this part of the paper are listed the researchers and their model proposals for the development of gamified systems that can be used for educational purposes. [1] in their paper present a Dynamical Model for Gamification of Learning (DMGL). [1] refer to [2] who founded the MDA model (Mechanics, Dynamics, Aesthetics). The MDA model is based on elements of mechanics, dynamics, and aesthetics. [3] complemented the MDA model with challenges, imagination, control, and curiosity. The result of DMGL is a system that is very different from traditional teaching. [1] state that educational efficiency in the case of gamification is significantly lower in relation to traditional teaching, but this indicator is valid only in the initial stages of teaching. It is concluded that time is needed for getting used to and adapting, followed by a rapid increase and surpassing the effectiveness of traditional learning. [4] present in their research a model for gamified activities. The model includes some of the key elements such as content, tasks, levels, feedback, top lists, and group preferences. In addition to the above-mentioned elements, it is suggested to use rewards and penalties, time-limited tasks, and auxiliary units that are in the function of scripts. The model presents a series of links and guidelines in the form of a kind of simple activity diagram. The model is a theoretical proposal on how to create a functional unit focused on teaching in higher education institutions. [4] mention this as the next step in their research. [5] in his research lists the steps that should be taken into account when planning and implementing gamification in business systems: Identifying organization goals, Identifying the main objective of the gamification system, Identifying users, Identifying content, Designing and selecting elements of computer games, Defining measuring instruments, Defining communication methods, Monitoring efficiency, and system improvement. The same principles could be applied to education systems. [6] describe a model called Octalysis developed by Y. Chou [7, 8, 9]. The Octalysis model represents a systematic model that puts the visualized elements of a certain system into a visual interrelation. The model is based on the assumption that almost any game or game-based system is fun because it affects the basic motivational traits of the user. The result is the encouragement of pre-planned activities. The Octalysis model is based on eight motivational drivers, which, according to Chou, are arranged in an octagonal shape as shown in Fig. 1 of this paper. The elements of the Octalysis model that are in the right part of Fig. 1 represent a stimulus for creativity, self-expression, and sociability. These elements are related to intrinsic motivation, as opposed to the elements on the left side, which relate to extrinsic motivation. The elements of the left side are associated with goals, rewards, goods that can be earned or won. The elements at the top of the system are considered to be positive motivators that encourage the improvement of knowledge and skills through meaning and various incentives. The elements at the bottom of the system are considered negative motivators that encourage bad emotion and should be minimized when planning and implementing the system. [10] and [11] state a division that focuses on designing a gamification educational course. The division is simplified and consists of five steps: Understanding the content and users - the first step in which the administrator or teacher of the gamification system is introduced to possible problem situations depending on the teaching units and target groups of e-course participants.

Defining goals - refers to any set of elements that can improve knowledge and motivation or encourage a change in the behavior of e-course participants. Goals are closely related to learning outcomes which are approached as challenges that contribute to a meaningful unit. Structuring the experience - the system is analyzed in parts with the aim of identifying which units are more difficult for e-course participants, and a special user incentive is planned in these units. The incentive has a positive effect on the motivation of e-course participants and the continuation of learning through points, certificates, virtual currencies, or other incentive elements.

Resource identification - resources mean anything that is measurable, e.g. points, passed knowledge tests, or time. In this phase, the rules and feedback related to the activities of e-course participants are defined. Defining the elements - the last step is to connect the rules and resources with regard to the e-course participants and the teaching units. The selected gamified elements should be clear enough and accepted by the e-course participants so as not to create the opposite effect when using the system. Some of the more used elements from computer games are: avatar, interface personalization, bonus materials, forming of teams, feedback, rewards, points, virtual currencies and stores, motivational story, transparency of system points, etc. [12] proposes a model for gamified system development, within a book called: "For the Win: How Game Thinking Can Revolutionize Your Business" in six interrelated steps. The model he proposed is called the 6D model. It includes six words with the first letter D and hence the name: define business objectives, delineate target behaviors, describe your players, devise activity loops, don't forget the fun, deploy appropriate tools.

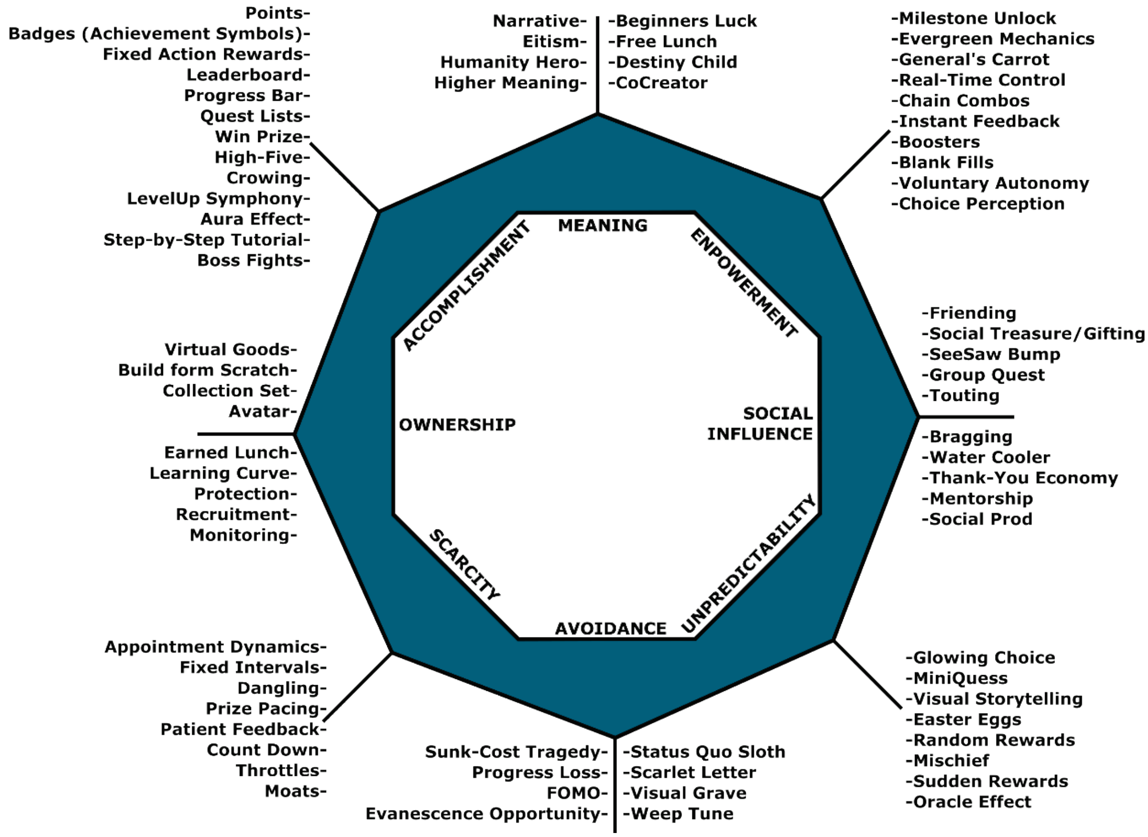

Figure 1 Octalysis and its basic gamified elements (Based on: Economou, 2015; Chou, 2017)

The mentioned gamification model includes a component of emotion that is based on fun, play, and user experience, as well as a sustainable system in which the result and activity of the user are measurable, all in order to achieve predetermined goals. [13] adds that the entire 6D model consists of guidelines on how to use modern technological advances (computer games elements) in specific situations. Schönen points out that success can only be achieved with the correct selection and application of computer game elements, explaining that the first five elements of the proposed Werbach 6D model consist of planning activities and describing the target group of subjects.

2 RESEARCH METHODOLOGY

In this part of the paper are explained the procedures used in planning and conducting the research, and listed the subjects who voluntarily participated in the research. The research was conducted through two phases which are listed below. The first phase - Theoretical research - the implementation of research begins with the analysis and research of professional and scientific literature in order to find specific guidelines for creating a conceptual model focused on research topics. A list is created of gamified elements for the Moodle system which are listed below.

The second phase - Development of a conceptual model - a conceptual gamified eRIOOS model is developed. The conceptual eRIOOS model is a condition for creating an experimental, gamified system on the basis of which scientific research is carried out. The conceptual model is aimed at improving and applying computer games elements in the online education system.

For the purposes of the research work, a computer server was used on which separate Moodle e-courses were installed, which were supplemented with computer games elements. The installed version of the Moodle system at the time of conducting research supports 1137 external add-ons. All 1137 add-ons are, before being selected and implemented in a gamified Moodle system on a separate server, viewed and compared with the mechanics and dynamics of computer games discussed in the previous chapter. Some of the additions are listed below [14]: Simplified graphical interface, Dynamic graphical interface, Story as an introduction to the e-course, Epic meaning, Visual presentation of all obligations, Tasks and challenges, Collecting points, Progress within the e-course, Synchronous communication Chat, Asynchronous communication Forum,

Nonlinear use of teaching materials, Joint collaboration, Discovering the system and teaching materials,

Surprise elements within the e-course, Conditional access to teaching materials, Countdown, Simplified graphical interface, Dynamic graphical interface,

Story as an introduction to the e-course, Epic meaning, Visual presentation of all obligations, Tasks and challenges, Collecting points,

Progress within the e-course. The accessories included in the gamified system influence the mechanics of computer games and the visual impression of the system in order to create an interesting virtual space and the preconditions for a positive impact on student motivation.

3 PROPOSAL AND IMPLEMENTATION OF THE CONCEPTUAL SOLUTION

An analysis of the subjects was made and the selection of subjects was carried out in accordance with the principles of scientific research. The time of the experiment and the intervals in which the subjects were acquainted with the obligations and possibilities of the research were chosen. Subjects were not told anything that could impair correctness in subsequent measurements. The time of conducting the research also defined the teaching unit, considering how the research was conducted during the academic year. For the selected teaching unit, it was necessary to define the teaching contents for classical and experimental e-courses in all three research. The classic e-course contains teaching materials, knowledge testing, and feedback on success, which is visible to the e-course participant after the knowledge test. Teaching materials are in most cases static and factually oriented without giving insight into the wider practical application. At the end of the teaching process, the student is expected to have knowledge, regardless of the motivation or feeling that the student had while using the classic e-course. The benefit of such an e-course is the transfer of information and the availability of teaching content at all times.

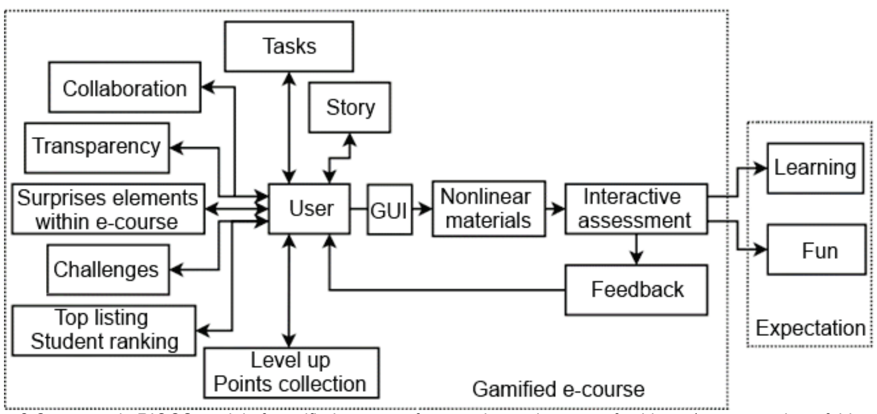

Figure 2 Conceptual eRIOOS model of gamified e-course for experimental groups of subjects (source: author of this paper)

Fig. 2 shows the gamified e-course for the experimental groups of subjects that will be used in the development of gamified solutions for the e-courses of this research. It can be noticed that the student is deliberately surrounded by gamified elements, i.e. elements of computer games that are included in the e-course in order to motivate and entertain the participants of the e-course. The student uses a more intuitive user interface that is clearer, visually richer, and easier to manage and use. Before starting to use the teaching materials, the student is introduced to the meaning of the e-course through a story and practical examples, which achieves a deeper meaning and a positive impact on intrinsic motivation. At the time of using the e-course, the student can approach solving problem tasks related to the teaching unit or accompanying bonus teaching or non-teaching content that reveals hidden elements or parts of the e-learning system. Within the e-course, transparency is ensured in terms of course obligations, as well as in terms of the achievements of other students. The student has at its disposal the interaction with other users of the system (teachers and students) whether it is a competition or mutual cooperation. The result of student activities is visible through the Top lists, but also through other indicators such as the number of badges, the number of points, and the level at which the student is. Progress is provided in terms of system levels and the association of certain symbols to the participant. Expectations from students are knowledge and higher motivation to learn, which are ensured by greater freedom of choice of access to teaching materials, and more visual or auditory guidance and feedback information on the performance of student activities. E-learning system designed in this way should allow students to achieve a sense of comfort, fun, and autonomy over their learning process, and achieve a state of the flow in which learning is fastest.

The eRIOOS model shows the use of a number of computer games elements that aim to achieve greater flexibility and dynamism of e-learning systems. Regardless of the e-learning platform, the student should be provided with a modern graphical interface that supports simple menu animations, background music, and similar multimedia elements that can evoke the ambiance or moment in the story. The mentioned functionality is related to creating a simpler and more intuitive user atmosphere that provides the student with a feeling of comfort and relaxation. Each teaching activity should start as a practical task or problem situation in which the student is introduced to the possibilities of the e-course as well as the possible results that are the consequence of the student's activities. Given how the eRIOOS model is aimed at students of higher education institutions, the story, i.e. the problem situation should follow the generally known, contemporary situations in the field of e-course. The story should put the student in the role of researcher, collector, winner, or socialite, and guide him through the e-course with the aim of activating intrinsic motivation.

The story can be related to the planned knowledge tests, and according to the results of the participants, it can be further upgraded or changed depending on the achievements of the group. The mentioned is not easy to achieve, and teachers are expected to harmonize teaching content and stories with real events in the business world. Harmonizing teaching content and story with real events leads to achieving a higher goal than simply collecting points and learning for routine knowledge tests. This ensures the so-called. an epic meaning that is lacking in the classic e-course as well as in traditional education.

In addition to the teaching materials that are the foundation of the e-learning system, the aim is to provide as many meaningful knowledge tests as possible so that students question the knowledge of teaching topics, and think about certain problematic situations. Tasks and challenges should be related to the points, badges, or certificates awarded to the student depending on the difficulty of the task or the scope of the challenge. As one goes through the system, the tasks and challenges should become increasingly difficult thus ensuring a virtual passage through the teaching units. Points, badges, certificates, or awards in other forms should be publicly visible to all participants, thus ensuring the transparency of grading as well as the recognition of knowledge among e-course participants. In computer games, there are often situations when a player has to face a big obstacle in the form of the main enemy (Boss Enemy). In the e-course, such an element can be achieved through a story in which the student is put in a stressful situation where on the one hand there is a time limit to solve the problem situation, and on the other hand, there is an opponent in the form of artificial intelligence or the teacher himself. An example of this can be a case in which an individual or a team of several participants, and even a whole group of participants, come to a situation where they need to "hack" the exit or entrance to a certain space that is extremely important (according to the story presented at the beginning of the e-course). On the one side are the participants of the e-course, while on the other side is the "opponent" (program or teacher) depending on the level of gamification of the e-learning system. An epic meaning can easily be achieved by such an example. In this case, the synergy and motivation of users to win is achieved, which in a positive way affects the direction and development of the story that supports the educational process in the e-learning system. A similar effect is also achieved with educational games that are already available in e-learning systems but at a slightly lower level of abstraction. It is important to provide multiple access to interactive repetition and the above knowledge tests so that students can master certain teaching units as well as improve existing knowledge.

According to [15, 16] as well as according to other authors [17, 18] there are the following types of players: researcher, collector, winner, and socialite. Players rarely belong to only one of these profiles, it is more common where the player has the characteristics of all four types of players where each element is developed to some extent, which is why it is necessary to provide the ability to personalize e-learning systems.

The simplest way is to enable the use of profile pictures followed by personal information and social statuses, which ensures the sharing of interesting or student-important information, as well as the sharing of status about certain achievements. This is visible within social networks that ensure the sharing of status, social interests, and personal information with other users of the system. The e-learning system should ensure that users are connected as well as sharing their achievements and status at a given time. Supporting information can also be available to all e-course participants if the student wants to share it via his personal status or through synchronous (chat) or asynchronous communication systems (forum or personal information). Synchronous and asynchronous communication enable the dissemination of information between all participants in the e-course, where teachers are required to take on the role of "administrator of communication messages". On the one hand, it is necessary to ensure autonomy in terms of communication between users, while on the other hand, it is necessary to direct the flow of data and written information in the direction of desirable teaching activities. With the assumption that the group of participants is serious enough, it is enough to set notes and guidelines for communication at a certain time and follow the course of the conversation.

It is useful to set time limits for a particular teaching topic to ensure emphasis on a particular topic. It is also advisable to provide virtual meetings in which students are discussed about their achievements and to announce future events and introduce students to the benefits if the task is successfully completed. In this way, it is possible to further encourage students for greater joint cooperation and engagement, as well as to provide a project approach to the teaching unit or problem task that can be seen in business environments.

Students come to the e-course with different prior knowledge as well as with different ambitions. The speed at which a student can go through the teaching materials should not be limiting, however, it is up to the teacher to decide whether to provide certain obstacles in the system or not. Also, it is not excluded that students master the complete teaching unit before the end of the semester, and they should be provided with bonus materials and additional activity that would ensure the need for advanced knowledge. It is not good to slow down such individuals to the speed of the group average because they lose interest in the topic as well as the desire to further participate in teaching activities. If the student is excellent, he needs to be provided with extracurricular or bonus materials that will not be visible or accessible to other participants. All participants have certain teaching and non-teaching materials at their disposal. When creating an e-course, the teacher determines the time periods in which unannounced changes will occur in the system in terms of visual surprise or in terms of new, until then hidden teaching or non-teaching materials. These elements are surprise elements that are planned to cheer up the participants of the system, and at the same time motivate them for further teaching or non-teaching activities.

Feedback on the activities carried out by the student in the e-course as well as other feedback related to the status of progress, the status of completion of teaching obligations in the e-course, as well as a visual presentation of points and other positive achievements that the student accomplished over time are an important element of the gamified system. E-learning platforms, such as Moodle, provide a certain level of feedback on the success of student activities that encourage the student to further improve and go through teaching and non-teaching materials. Given that additional elements from computer games are introduced into the e-learning system, special attention should be paid to providing feedback also for these elements if they are important for motivating or work of students.

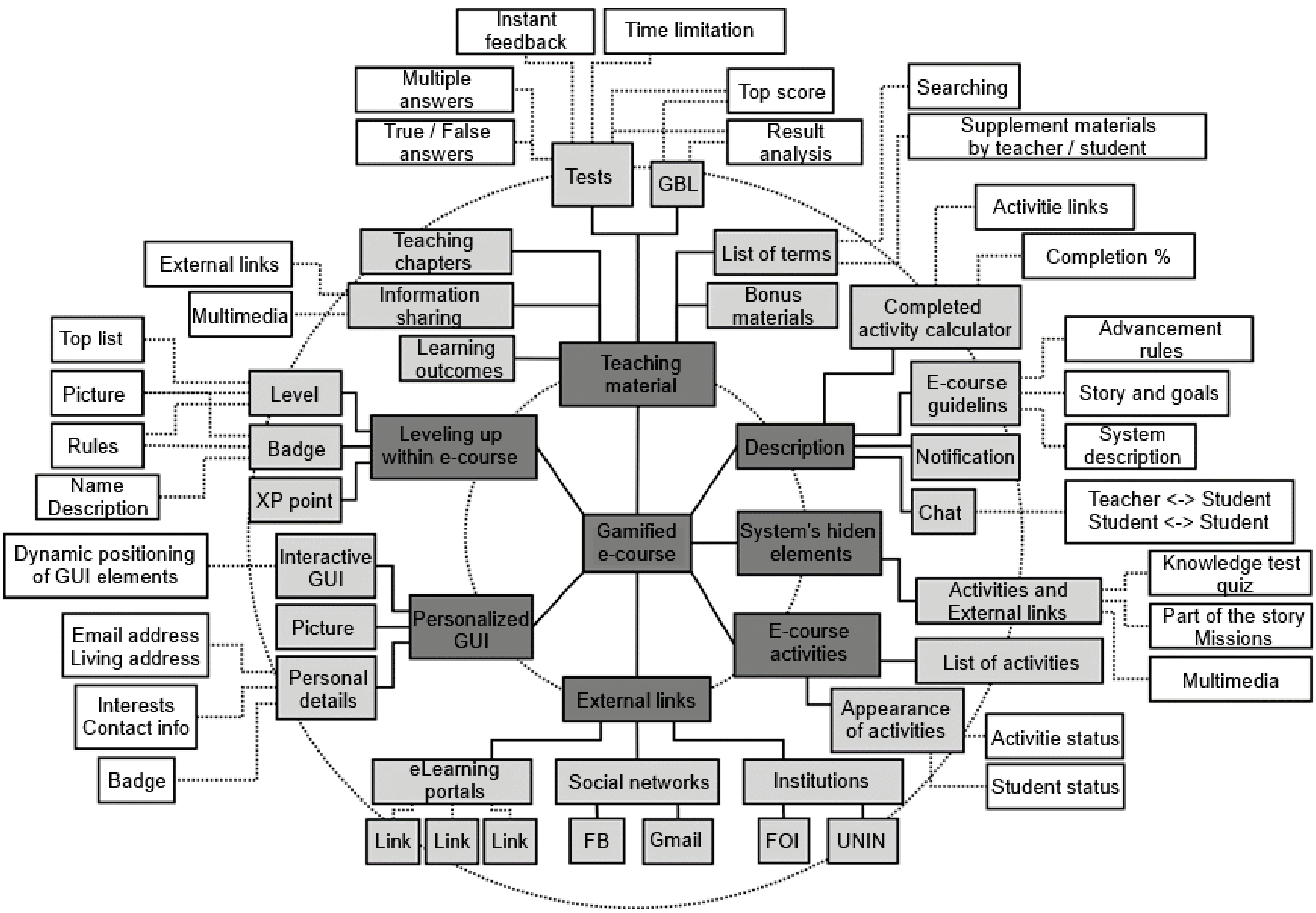

Figure 3 Conceptual solution created according to the eRIOOS model (source: author of this paper)

The eRIOOS model is oriented towards the student with teaching or non-teaching activities that are available to the student within the education system. The eRIOOS model does not bring significant changes for the teacher in the form of facilitating teaching or monitoring the teaching process. On the contrary, the teacher will have more obligations in the planning and initial creation phase of the e-course if he wants to provide all the possibilities recommended by the model. The conceptual model of the gamified e-course, shown in Fig. 2, also serves as a basis for the development of a conceptual solution created for research within this paper. The developed conceptual solution can be found in Fig. 3 and contains seven main units (Teaching unit, System description, Hidden system elements, Course activities, External links, GUI personalization, and Progress within the course). The gamified elements presented in the e-courses for the experimental group of subjects in the first and second main research are marked with white color. Each of the seven units is explained after the picture of the conceptual solution in the continuation of the paper. Fig. 3 shows an example of the computer games elements included in the eRIOOS model and how the elements are connected and organized within the platform intended for e-learning.

The conceptual solution from Fig. 3 makes the structure to which it is necessary to add teaching materials and contents. The student directly interacts with the eight elements of computer games and indirectly with feedback, which has a big impact on his experience of the educational environment. If the system is designed correctly, the student creates a sense of comfort that can lead to a state of flow in which the learning process is optimal. The goal to be achieved was to ensure the state of the flow in which the student learns the fastest while reducing the feeling of fatigue and stress that occurs in the case of a uniformly structured e-course.

4 MODEL TESTING AND VALIDATION

The effect of the conceptual model, as well as the verification of whether the application of computer game elements enabled the achievement of higher results in the knowledge test in the experimental group of subjects was conducted in three independent research (on three separate e-courses). To achieve the mentioned, based on the conceptual eRIOOS model, gamified Moodle e-courses were created for experimental groups of subjects. In parallel with this, classic versions of the Moodle e-course have been developed intended for control groups of subjects. Gamified e-courses for each research were created again because e-courses are conducted in different courses (North University, Faculty of Organization and Informatics) and on different servers (unin.hr, foi.hr). Teaching materials are adapted for the purposes of this research and do not differ from each other in their content. Subjects who participated in the research (N = 309) voluntarily agreed to research activities and actively participated in the validation of the conceptual model. Validation, as well as testing of the conceptual model, is carried out according to pre-agreed rules that must be followed with each group of subjects in each of the selected courses.

In the first step, the subjects were exposed to a pre-test based on which the participants were divided into groups. The second step was to check that the groups were statistically equal. The statistical significance is checked and a conclusion is made on satisfying the initial conditions of the research. In the third step, the subjects use one of the assigned e-courses (experimental or control) within their groups and are exposed to a post-test, i.e. a written test of knowledge that tests the knowledge from the teaching contents used in the experiment. Depending on the average result from the posttest knowledge test, it is concluded based on t-test analysis, with the possibility of an error of 1% or 5%, that there is or is not a statistically significant difference between these subjects. Each research has identical steps and at the end of each research, conclusions were made about the success of the measurement.

For the purposes of this paper, a part of previously published research in [14, 19, 20] is cited.

The conceptual model was tested on two main hypotheses that were tested through the experimental and control group on a total of 309 subjects. Testing was conducted three times on three different courses, academic years, and 2 higher education institutions. The hypotheses are:

H1. An e-course designed with the application of computer game elements has a positive effect on the interest of the participants in that course in relation to the course of the same educational content but without the presence of computer game elements.

H2. An e-course designed with the application of computer game elements enables the achievement of better results for students compared to traditional approaches to e-learning, having in mind the level of acquired knowledge from certain teaching content.

The indicators obtained by the analysis are as follows:

- In the first series of measurements, student activity was almost 65 times higher in relation to the control group of subjects, and the average number of points of the experimental group in relation to the control group was higher by 36.55%.
- In the second series of measurements, the difference in activity was almost 5 times larger in favor of the experimental group of subjects, and the average number of points of the experimental group compared to the control group was higher by 15.46%.
- In the third series of measurements, the difference in activity was 13 times greater in favor of the experimental group of subjects and the average number of points of the experimental group compared to the control group was higher by 33.23%.

5 CONCLUSION

Based on the gamified elements of the Octalysis system, and the found guidelines from the literature, the author of this research develops a conceptual gamified eRIOOS model based on which it is possible to develop a complete gamified e-course intended for higher education. Based on the eRIOOS model, suitable elements of computer games are included in the Moodle platform, with a positive impact on the student's behavior and interest in the teaching and non-teaching elements of the e-course.

The conceptual eRIOOS model enables the student: more intuitive Graphical User Interface, achieving deeper meaning through story and practical examples, solving problems related to teaching units, solving problems related to the accompanying bonus content, interaction with other system users (teachers and students), transparency regarding the course obligations, transparency regarding the achievements of other course participants, revealing hidden elements or parts of the system, competition with other system users and visible order in the form of Top list, progress in the form of system levels and joining symbols to the student, greater freedom to choose access to teaching materials, a greater amount of visual or auditory guidance about the learning process, achieving a sense of comfort, fun, and autonomy over the learning process, achieving a state of flow in which learning is fastest.

The conceptual model at the theoretical level has nine additions (advancement, top list, competition, hidden entertainment additions, transparency, interaction, story, challenges, feedback), extended at the implementation level to a total of 24 elements that contributed to the creation of the gamified system. The eRIOOS conceptual model is the basis for the gamified e-course, which was used in the first series of research within the North University (N = 55) as well as the second and third series of research conducted at the Faculty of Organization and Informatics (N = 254). The test results are briefly presented at the end of Chapter 4 of this paper and indicate that all experimental groups of subjects who used the gamified Moodle system have statistically significantly better results. Note that the only difference between the control and experimental groups was in the layout of the e-course. Everything else is identical (order and amount of teaching materials). In addition, it can be seen that the group that used the gamified e-course used the e-learning system much more, which is another indicator that is in favor of the eRIOOS system. The conceptual model has been empirically and theoretically confirmed because it is based on the research of other scientists and respect for their conclusions regarding the use of elements of computer games within the educational system.

Further application of this model is possible in the form of creating e-courses intended for higher education. The field of application is not limited only to IT teaching subjects with regard to the used elements of computer games and the theory of flow according to which the prerequisites for achieving the state of the flow for system users are met.

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Original scientific paper

Knowledge Management as a Business Strategy of a Learning Organisation

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Abstract: Today, knowledge management is used as part of a business strategy by which an organisation adapts to rapid changes in society and the business world, by which it not only becomes more competitive but also achieves goals and remains successful. Organisations have become aware of the importance of the lifelong learning concept. It should be noted that knowledge management is in close synergy with human resource management in the organisation. To achieve the scientific value of the paper, the authors have conducted empirical research by using a survey questionnaire in which the elements of a learning organisation were investigated, along with the implementation of knowledge on the selected organisational model. The synthesis of the results and conclusions of this research will be used to formulate specific critical recommendations and valuable guidelines indicating possible areas of improving the level of learning organisation and motivation to learn, which indicates potential ways and approaches to knowledge management.

Keywords: business strategy; HR; knowledge; knowledge management; learning organisation

1 INTRODUCTION

Globalisation and modern market trends have led to rapid changes and innovations in the market, which in turn has resulted in a higher standard of competitiveness. Products have a shorter life cycle, individualisation of customer needs is required, new business areas are created, and companies that want to be competitive must quickly follow trends and improve their business. Companies today, if they aim to operate successfully and competitively, must know how to use knowledge as a factor of production. Otherwise, they risk falling behind in a turbulent business arena. Knowledge is predominantly linked to the people who make up an organisation, so it is difficult to observe it outside the context in which it was created. It consists of patents, processes, technology, capabilities, skills, information, and other. It is important to emphasise that knowledge management does not represent just companies' internal resources, but also includes customers, suppliers, contractual partners and further external *know-how* holders. Some companies have begun to measure knowledge in the form of intellectual capital, and all this leads to such a practice becoming quite ordinary and necessary in modern management.

2 HISTORICAL FRAMEWORK OF UNDERSTANDING KNOWLEDGDE MANAGEMENT

The idea of organisational learning and knowledge has long been present in the literature, but it was not until the 1930s that the first significant work on organisational learning appeared. In the 1970s, there was more productive academic work on this topic, and since then, interest in this topic has increased exponentially [1]. Since the early 1990s, knowledge management has become widely known, and many authors believe that the idea an organisation that learns and possesses knowledge as a resource one of the most significant contributions to management theory in the last half-century. According to [2], the transformation into a global information and knowledge society is confirmed by the notion of Kondratieff's fifth cycle. Kondratieff found that the economic development of nations can be described in periods of 40 to 60 years, and critical innovations are usually the drivers of each period. Prosperity, recession, depression and recovery always follow one another.

The first half of the 19^{th} century was marked by the discovery of the stationary power of steam, which started the industrial revolution. The second wave began in the middle of the 19^{th} century and lasted to its end. It was caused by the know-how about the power of steam and steel. Kondratieff's third cycle began in the early 20^{th} century and lasted until the outbreak of World War II. That period was based on knowledge of chemistry and electricity, and the fundamental innovation was the automobile. 1945 was followed by a fourth wave that brought television and mass traffic. It was the beginning of a developed world economy with mass production and high growth in labour productivity with high consumption of energy and raw materials. Many signs hint at the arrival of a new wave, the fifth Kondratieff cycle. North holds that labour and capital are no longer scarce resources, but information from which knowledge is generated [2]. Tangible goods are losing on their importance compared to intangibles, and investors are less and less appreciative of how physical products are made from physical resources, and more and more about how knowledge is accumulated from information and how that knowledge is turned into business success.

Knowledge management has been studied through numerous theories and reflections by various eminent scientists who have researched throughout history how the success of an organisation is achieved through management, and one part of that management is precisely knowledge. According to Dimitrovski [4] knowledge management can be defined as maximising the use of knowledge in an organisation, recognising information, and strengthening the capabilities and competitiveness of the organisation itself which significantly contributes to the success of the organisation. Another definition of knowledge management is that it is a series of processes of collecting, organising, analysing and disseminating the knowledge of individuals and groups throughout the organisation so that these processes contribute to business success [5]. With the development of technology and the increased dynamism of society, knowledge today is growing at a rate that was once unimaginable. Management that strives to be competitive must adapt to today's conditions. Sustainable competitive advantage can only be created by strengthening the influence and using the collective knowledge bases of the organization, creating and strengthening the learning organization and generally putting knowledge at the center of business and its strategy [6].

Knowledge management is much more than just gathering knowledge; it focuses on enabling the employees of a particular organisation to have access to information so that they can use this information in the performance of their daily tasks and thus contribute to the goals of the organisation. According to Alfirević et al. [7] holds that knowledge management is the art of creating value from organizational intangible assets, while Singh and Anand [8] believe that knowledge management is explicit and systematic management of key knowledge and processes of its creation, collection, organization, diffusion, use and exploitation Wiig (1997), according to Alfirević et al. [7] defines knowledge management as an activity aimed at understanding, focusing and managing the systematic, explicit and thoughtful construction, renewal and application of knowledge. According to the same author, it is a set of clear and well-defined approaches and processes, with the ultimate goal of maximizing knowledge-based organizational effectiveness, as well as the return from organizational cognitive assets (KA), as well as its constant renewal. Knowledge management processes, according to Stipanović [8], are the identification of knowledge, acquisition of knowledge, development of knowledge, dissemination of knowledge and implementation of knowledge. Knowledge management today is treated as a process in which not only the benefits of the organisation's knowledge are maximised, but also the organisation's ability to contribute to the achievement of goals with that knowledge. Therefore, knowledge management is recognised as a means by which to achieve the organisation's mission and goals. Knowledge management is also focused on two specific business directions, namely, people-oriented and information-oriented. Organisations that use knowledge management are more focused on adopting the changes that result from today's society, but also on improving procedures, skills and human resources. By using this type of management as a business strategy, it is possible to enable a more straightforward and better flow of ideas, faster innovation, time optimisation, service improvement, tax revenues increase due to faster trade, costs reduction due to source information, elimination of redundancy, and many more [4].

3 THE LEARNING ORGANISATION CONCEPT

A learning organisation is a modern concept of an organisation's activity that responds to ever-growing changes in the environment and constant processes of globalisation, integration, mass supply and accessibility that motivate organisations to continue learning. By learning, the companies can compete specifically and in the long run and not just through marketing sales strategies and differentiation. Next to the "learning organisation" term, the notion of a "knowledge-creating organisation" can also be found in the professional literature. The concept of an organization learning its development began in the middle of the last century, but it has been the focus of the profession and society in general only for the last ten to fifteen years. Peter Senge made the greatest contribution to this in his book The Fifth Discipline. He points out that a knowledge-based organization is continuously adapting to changes in the environment precisely on the basis of gathering information, researching learning about change. The mentioned trends are related to the advancement of technology, the need to protect the environment and human health, globalization, strengthening the gap between developed and underdeveloped economies and integration, which makes some systems extremely turbulent [7]. It applies to organisations that create their solutions based on learning from practice and innovation. It can be said that knowledge and investing in employees and their knowledge, in general, has become the investment with the most prolonged returns. It can nevertheless be said that it is an organisation that strives to create its future with the help of learning as a continuous variable leading to that goal. According to Sikavica [11], learning organizations manage change because they have certain skills and value systems that include:

1) Skill of motivating for changes:
- Creating readiness for change,
- Neutralization of possible resistance to change.

2) Creating a vision:
- Clear ideology and values and set goals,
- Anticipation and pictorial perception of the future.

3) Developing political support:
- Assessment of the strength of the change agent,
- Identification of key stakeholders,
- Influencing stakeholders.

4) Transition management:
- Activity planning,
- Commitment planning,
- Management organizations and structures.

5) Preservation of the continuity of the ascending path of growth and development:
- Providing resources for change,
- Building a support system for change agents,
- Development of new competencies and skills,
- Establishment of new forms of action and behaviour,
- Maintaining the direction and trajectory of the goals.

Communication is crucial in any organization, and especially in learning because it is the basis of knowledge transfer [12]. Communication of a learning organization must not have noises, vague or ambiguous messages, etc. According to Lončarević [13] communication and style is necessary for:

1) Setting and realization of goals,
2) Making plans for the realization of goals,
3) Effective and efficient allocation of organization's resources,
4) Selection and evaluation of members of the organization,

5) Leading, directing, motivating and creating a motivating climate as well
6) Control over the realization of the organization's goals.

The most important thing to point out is that the learning organisation concept does not differentiate hierarchical levels because they do not exist for the exchange of knowledge. A learning organisation is an organisation in which knowledge circulates without any obstacles. It creates a precondition for the progress, development and self-realisation of employees, which contributes to the management and personnel management. A learning organisation continuously learns, which gives it the flexibility to adapt to change and in that lies its contribution to sustainable business through adapting to demand-based learning [14]. It is essential to point out that a learning organisation does not segment knowledge by individuals because as such, it has no particular purpose. In an organisation that learns, knowledge is dynamic, moving and exchanging and enriched continuously, with the understandings of each of the stakeholders of the organisation, experiences and practices. Once acquired, knowledge is continuously transformed into new ones. Hence the synergistic effects of the learning organisation. Learning takes place in all dimensions of the organisation, at all levels, through teams and individuals and circuits through the company's information system.

The transformation of an organisation into a learning one requires leadership that understands the concept and has a vision of transformation, is aware of the shortcomings of the existing organisation and recognises vital aspects that must be restructured first for a successful implementation of the learning organisation (i.e. the transformation of a traditional organisation into learning organisation [15]. The implementation of the learning organisation concept is not a one-time event, but instead, after the adoption of its values and principles, the restructuring and a continuous process of adjustment, i.e. change management, begins. Adapting to change is necessary because markets, needs, customers, technologies, regulations and even knowledge or the need for it are changing. The learning organisation monitors the changes, and following the possibilities, goals and benefits of the changes, it adapts to them or strives to find an optimal solution. The human resources management in the companies based on knowledge requires a remodelling of basic sub functions of human resources management as the managers will deal more often with people who decide themselves about their aims, who motivate themselves, organize and control [16]. Such employees are called knowledge workers. According to Lendzion [17] the term "knowledge worker" refers to a high class specialist who has unique knowledge and competencies. The appearance of knowledge workers in the organizational structure led to an evolution of human resources management basis towards such values as: competencies, knowledge and intellectual capital. There is definition of knowledge workers [16]:

1) They have a high level of specialist knowledge, education, experience and creation, dissemination or practical usage of knowledge are the most important aims of their work;
2) They can have a high level of abstract, low level of routine and are characterized by a constant need to update their knowledge;
3) They show a need for autonomy, trust, evaluation of work, they need to understand a context and to learn by experience; they understand the need of exchanging ideas with experts. Organizations that value their employees for what they know, and reward employees for sharing that knowledge create a climate that is more conducive to knowledge management. Organizations that enjoy knowledge superiority today may find themselves at a competitive disadvantage in the future if their competitors are more capable of learning within similar domains [18].

4 RESEARCH METHODOLOGY

In order to investigate the importance of a learning organisation as an organisational form, a survey was conducted in the spring of 2020. The respondents were employees of companies operating in the retail sector of Croatian retail chains. Empirical research focused on the exploration of personal attitudes and views of employees about the learning organisation concept. The questionnaire included certain statements being presented to the respondents that they needed to confirm in full (grade 5) or completely refute (grade 1). Since this would limit the respondent's replies between two extremes, a scaling between these extremes was introduced too (grades 2, 3 and 4) which allow conditional confirmation (4) or conditional refuting (2) and neutrality - neither true nor false (grade 3).

The demographic composition of employees showed a slightly higher share of female respondents (54%), which is not surprising if we consider the fact that in the general structure of employees, due to the characteristics of the industry and labour market trends, female employees are predominant. A relatively equal share of both sexes in the sample allows for sample stability and testing of gender impact on the characteristics of the learning organisation.

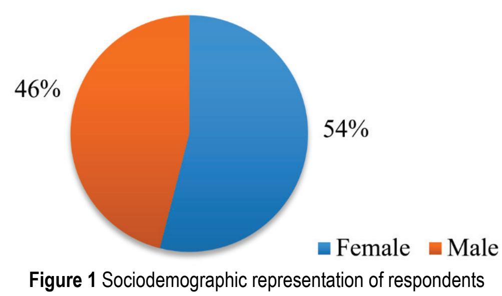

Figure 1 Sociodemographic representation of respondents

Given that the retail network dominates the structure of the organisation, the educational structure of employees is dominated by secondary education in (37%). The secondary education level is followed by higher education with a share of 34%, which is made by employees in retail support functions such as assortment, marketing and sales management. The survey sought to unify the sample's education structure to obtain the most realistic perception possible of employees regarding the learning organisation concept. The share of respondents with a university degree is quite substantial, too - 29%. This share consists mostly of younger employees in the positions of individual functions' heads (marketing, finance, accounting, ICT, etc.) and assistants, independent clerks and directors. The age structure indicates that the average age of the respondents is 3.39, which means in the age class from 34 to 41 years of age, i.e. about 38 years of age on average. The lowest share of respondents is of those up to 25 years of age, with a share of 14%. The largest share of employees is between the ages of 42 and 49. Age is an interesting variable in the analysis of the learning organisation-related topics because it can indicate employee behaviour and preferences over time when it comes to the willingness to learn. The correlation test indicated a statistically significant and positive link, meaning that older employees (as a result of broader experience) have a higher motivation for acquiring new knowledge because it is easier for them to gain and extend it. This is mostly true for professions like accounting and finance, and less so for the retail and supply chain itself.

Along with the employee's age, the length of service is also an essential variable, both the total length of service and the duration of employment with the current employer. The average length of service is 15 years, while the length of service with the current employer is 12, 5 years indicating a low fluctuation rate. This is a good starting point for establishing the learning organisation practices because obviously, employees are retained through specific values and qualities that need to strengthen by providing development and progress to employees through learning.

Table 1 Average values of age and length of service of respondents

		Age	Length of service	Work experience in the current organisation
N	Valid	100	100	100
	Missing	1	1	1
Mean		3.39	3.09	2.52
Mode		4	4	1
Minimum		1	1	1
Maximum		6	7	5

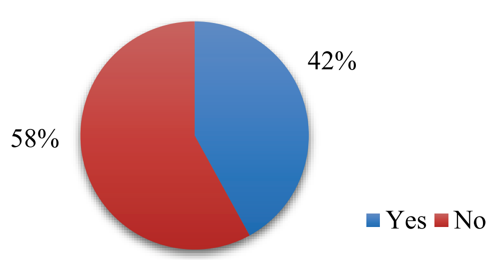

Figure 2 The structure of employees according to whether they were on an additional form of learning, acquiring new skills or training

The first indicator of specific organisation's orientation towards the learning organisation's concept of is how many types of training, seminars, further education or similar broadening of knowledge or strengthening the practice, have been attended by employees, regardless of the employment itself. Fig. 2 shows that 42% of employees had such experience, which indicates a lack of refresher courses improving the knowledge and skills of employees, especially in the retail segment, i.e. employees in the retail network (branch employees). Mostly, employees who are referred to additional forms of training, learning and further education are employees in managerial positions, and employees in support functions like finance, accounting, marketing, ICT and corporate communications.

When asked about the exchange of knowledge within the organisation, over 55% of employees stated that they do not see the continuity of such processes in the form of practice or within the value system. About 43% expressed the view that they notice the exchange of knowledge and experiences. The degree and presence of exchange and transfer of knowledge and experience vary from sector to sector and from department to department, which is determined by many factors. These factors do not represent as much the values of the learning organisation, but more the independent contribution of employees and relationships they have developed with each other. A lower degree of exchange of knowledge and experience is present in the procurement segment, and a slightly higher is present in the system within retail. A possible cause is employee competitiveness. Although a competitive spirit is welcome, it should be result-oriented, not causing close-mindedness when it comes to learning and transferring knowledge and experience within the organisation. The separation of these two views on competition among employees is the responsibility of management, the human resources department and the strategy of the learning organisation. It is needed in order to change employee perception, value system and rules as well as motivation, management and rewarding regarding this topic and to make the learning organisation concept as successful as possible. The extent to which respondents are motivated to acquire new knowledge and skills, and to apply learning for understanding beyond the dry process of performing work tasks can be seen from their level of motivation to acquire new knowledge and skills, which is shown in the table below.

The level of their motivation to learn is 3.37, with the most common grade being 5. This indicates employees' interest and motivation for learning, aimed at achieving higher commitment to the activities and goals of the organisation. The latter is an indicator of a promising outlook for implementing the learning organisation concept. The willingness of employees to learn indicates their value system and work motivation in the development and acquisition of new skills and knowledge. In the long run, this must be accompanied by opportunities for progress, income growth and other incentives, because otherwise there is a decrease in motivation and an increase in turnover rates when employees in which the organisation invests decide to leave it. In the long run, this creates the cost of recruitment, training, training and specialisation and retention of employees, and reduces the effect of these efforts concerning investing continuously and in all dimensions in existing employees.

Employee development and growth with the development of the organisation has synergy effects in the long run and is the basis of sustainable business. The willingness of employees to learn indicates their value system and work motivation in the development and acquisition of new skills and knowledge. In the long run, this must be accompanied by opportunities for progress, income growth and other benefits, because otherwise there is a decrease in motivation and an increase in employee turnover rates, i.e. leaving of employees in which the organisation had invested resources. In the long run, this creates the cost of recruitment, training, specialisation and retention of employees. Furthermore, it reduces the effect of these efforts instead of investing continuously and in all dimensions in existing employees. Employee development and growth have synergy effects with the development of the organisation in the long run and is the basis of sustainable business.

An indicator of the tendencies of a learning organisation is visible in the degree of employee independence and frequency in investing their efforts to improve their knowledge and skills and master the job faster. This can be seen in the table below, which shows that the level of independence for acquiring new knowledge and research practice is only 2.42 with the most common level of 2. It is important to note that there is a lack of transfer of knowledge and practice in the superior-subordinate relationship (average level 2.27 and the most common 2). It further causes the reduced motivation and independence of employees in the research of practice, learning and training. It also reduces employees' willingness to transfer their knowledge and skills and to participate in discussions aimed at improving the process and solving problems (average level of participation is 2.27). Most often, employees who are not formally in charge of this type of cooperation do not attempt to contribute to such processes.

Table 2 Average values of salary amount and degree of motivation for learning and acquiring new skills of respondents

		Salary amount	Does it motivate you to learn and acquire new skills?
N	Valid	100	100
	Missing	1	1
Mean		4.12	3.37
Mode		2	5
Minimum		1	1
Maximum		11	5

Table 3 Average values of process evaluation, level of knowledge and experience transfer and participation in discussions for business process improvement

		How often do you study and research on your own to improve your performance/ master the work tasks?	Is the quality of business processes being assessed?	Do you participate in discussions, meetings, etc. with superiors to improve the processes and solve problems?	Do superiors pass on news and changes and seek to pass on new practices?	Does your organisation motivate and reward teamwork, learning and sharing of experiences?	Do you often use new technologies in the business processes in the organisation?
N	Valid	100	100	100	100	100	100
	Missing	1	1	1	1	1	1
Mean		2.42	3.21	2.27	2.33	2.27	2.76
Mode		2	3	1	2	2	3
Minimum		1	1	1	1	1	1
Maximum		5	5	5	5	5	5

Table 4 Average values of selected variables

		Are new practices or possible innovations being identified? Are efforts being made to implement them?	Do you notice adapting processes and activities to changes and striving for business excellence?	Do you like to share knowledge and experience with others personally (Do you feel capable of explaining in simple terms and transferring knowledge?	In the case of ambiguities, do the superiors try to clarify the ambiguities and give their best to state the best practice and come to the right conclusion?	Do you have enough information within the system of the organisation to learn and strengthen your experience?	Does the organisation invest and provide enough resources (access to portals, journals and other professional literature) for learning and training?
N	Valid	100	100	100	100	100	100
	Missing	0	0	0	0	0	0
Mean		2.44	2.91	2.95	2.88	2.80	2.67
Mode		3	3	3	3	3	1
Std. Deviation		,891	1,093 the most common	1,104 the most common	1,113 the most common	1,035 the most common	1,436 the most common
Minimum		1	1	1	1	1	1
Maximum		5	5	5	5	5	5

Although teamwork is necessary and impossible to avoid, the level of team cooperation, organisation and monitoring of team cooperation and team management as well as the exchange of knowledge and experiences between teams is not standard practice, because the level of such activities is only 2.27. A slightly higher level is observed in the monitoring and evaluation of the process of 3.21. However, this is not enough to realise its improvement in practice. The latter monitoring is only part of the formalisation and insight into work tasks and for job descriptions. Infrastructure is of crucial importance for success and practical application of the principles of the learning organisation, part of which is made of the information system and database, along with its use by employees, as well as new technologies that improve business processes. The degree of application of new technologies does not correspond to the possibilities and is only 2.76. This is because many processes have not been automated (especially those outside the retail chain) as much as they could. Thus, the implementation of the new ERP system was postponed despite the division of the company and a significant larger acquisition. Savings today do not always mean the same expected return on a later investment. Delays in the implementation of ERP have been accompanied by several overtime hours (by ICT, technical services and accounting departments) and thus less efficiency. The limited-time led to less willingness of employees to share knowledge, to research independently and invest in new knowledge. They had less time they could devote to training new colleagues.

A significant link in a learning organisation is communication, style and communication strategy because it ultimately influences the realisation of business processes and enables the transfer of knowledge. Table 5 shows relatively medium and low ratings of clarity in communication and thus, the processes themselves. It is also clear that in situations of learning needs, superiors rarely declare that they do not understand or need the help of a colleague or external expert, which is not acceptable and creates barriers to communication. The unequal conversation leads to reduced quality of the process, which does not exceed the average level of 3. Nevertheless, on average, employees believe that the organisation is professional in its sector with an average score of 3.52, which is only a perception in trade, not the quality of all organisational processes because it is challenging to cover all processes, especially in larger organisations.

Table 5 Average values of agreement with selected statements

		Do you talk on an equal footing with colleagues, regardless of the position they hold, about business issues?	Have you encountered a situation where a superior declares that he does not understand something, and you jointly seek the help of a colleague at a higher level or an external expert?	Is it a problem for you to say that you don't know something and that you need help?	How would you rate the clarity of the business processes in the organisation?	How do you rate the clarity of communication with superiors?	How do you rate the expertise of the organisation, in the industry in which it operates?
N	Valid	100	100	100	100	100	100
	Missing	0	0	0	0	0	0
Mean		2.95	2.23	2.61	2.90	2.80	3.52
Mode		4	1	1	3	3	3
Std. Deviation		1,424 the most common	1,162 the most common	1,456 the most common	, 893	1,015 the most common	, 870
Minimum		1	1	1	1	1	2
Maximum		5	5	6	5	5	5

In the continuation of the research, the influence of gender on specific aspects of the learning organisation was tested. Given the empirical significance of the test, it is observed that statistically, there is a significant impact only in the case of motivation to learn and acquire new skills. The conclusion was made based on empirical significance, which is below the conditions of a maximum of 5% and amounts to 3.6%.

Table 6 Mann-Whitney in a test of gender influence on selected variables

	Does learning and acquiring new skills motivate you?	Do you talk on an equal footing with colleagues, regardless of the position they hold, about business issues?	Is it a problem for you to say that you don't know something and that you need help?	Do you like to transfer knowledge and experience to others personally? (Do you feel capable of explaining in simple terms and transferring knowledge?)
Mann-Whitney U	947	1238	1051	1119
Wilcoxon W	2028	2319	2132	2200
Z	-2,092 the most common	-0.028	-1,359 the most common	-0.881
Asymp. Sig. (2-tailed)	0.036 the most common	0.977	0.174 the most common	0.378 the most common

To find out which of the factors has an impact on motivation to learn and acquire new knowledge, the correlation between motivation to learn and opportunities to acquire new knowledge and education and the salary was investigated. Table 8 shows that the calculated correlation coefficients are statistically significant because the practical level of test significance is 0% for both correlation coefficients. Thus, it can be concluded that there is a statistically significant and even a strong relationship between learning motivation and opportunities to acquire new skills and salary levels because the correlation coefficient is 0.737. This means that with the increase of personal income, the power of motivation of the opportunities for learning and acquiring new skills increase. Employees tend to feel valued and are thus more willing to learn and commit, so these opportunities also make them more motivated in general. The correlation coefficient of learning motivation and opportunities for acquiring new skills and education is 0.458, which also indicates that higher motivation for learning and opportunities for acquiring new skills can be expected from employees with higher education. Such results indicate the connection between some elements of the organisational structure and human capital management. They also indicate their connection with the principles and the foundation on which the learning organisation concept is based. Dissatisfaction creates new dissatisfaction, which means that dissatisfied employees who feel underpaid or are in an unenviable environment in the company cannot be motivated to acquire new knowledge and skills if their basic needs of belonging to the organisation, self-realisation and existential needs (which are realised through their salary) are not met. A learning organisation has different values and goals from a profit-oriented organisation.

Table 7 Spearman correlation test between employees' motivation based on having opportunities for learning and acquiring new knowledge/skills and employees' education and salary

			Qualifications	Salary amount	Are you motivated by learning and acquiring new skills?
Spearman's rho	Qualifications	Correlation Coefficient	1,000	,737 **	,458 **
		Sig. (2-tailed)	.	,000	,000
		N	100	100	100
	Salary amount	Correlation Coefficient	,737 **	1,000	,567 **
		Sig. (2-tailed)	, 000	.	,000
		N	100	100	100
	Are you motivated by learning and acquiring new skills?	Correlation Coefficient	,458 **	,567 **	1,000
		Sig. (2-tailed)	,000	,000	.
		N	100	100	100

The importance of fundamental reorganisation of the organisation from the top to the process, the value system and rules and procedures is manifested in the fact that the state of consciousness, perception of and expectations from the learning organisation is crucial for the organisation's climate, motivation, management and acceptance of the change. Employees with a different view of the learning organisation concept and who are thus more motivated by learning than others, see changes both necessary and existing in the processes that are crucial for the implementation of the learning organisation concept. This is confirmed by the correlation of employees' preference for the transfer of knowledge and experience to colleagues and the ability to identify necessary and existing activities in organising the process of the organisation that makes it closer to the learning organisation concept.

Table 8 Spearman's test of correlation between employee's readiness to transfer their knowledge and experience to co-workers and their perception of process characteristics

			Do you notice processes and activities adapting to changes and striving for business excellence?	Do you like to transfer knowledge and experience to others personally? (Do you feel capable of explaining in simple terms and transferring knowledge?)
Spearman's Rho	Do you notice processes and activities adapting to changes and striving for business excellence?	Correlation Coefficient	1	,469 **
		Sig. (2-tailed)	.	0
		N	100	100
	Do you like to transfer knowledge and experience to others personally? (Do you feel capable of explaining in simple terms and transferring knowledge?)	Correlation Coefficient	,469 **	1
		Sig. (2-tailed)	0	.
		N	100	100

Finally, from this aspect, the perception of employees regarding the organisation to which they currently belong was explored. It was observed that only 9% of respondents believe that their existing organisation has some features of a learning organisation and a sound basis for development in this direction in the future. The fact that it has been observed that there are no favourable prospects in the researched organisations' existing foundations is undoubtedly a shortcoming that will lead to more significant efforts and the risk of deviating from the successful implementation of the concept of the learning organisation. Indeed, organisations must not be rigid and inflexible because the learning organisation changes in line with learning aimed at sustainability and development. Therefore, as such, it cannot be immutable but dynamic and consistent with typical principles of operation.

The results of the research showed that no organisation is, in the full and literal sense, a learning organisation because even this concept is not stable for the entire duration of the organisation. The key lies in the awareness, values of the organisation and motivation for learning, what does not always necessarily mean the highest level of knowledge and the current ability to absorb it. The development of technologies and changes in learning goals can make an organisation a learning organisation in certain aspects and to a reduced extent. The concept of a learning organisation must be embedded in the value system and mission of the company. It is also vital that the company develops skills to continually build and maintain processes on the level of a learning organisation.

5 CONCLUSION

Information and knowledge have never been more accessible, but it is also an increasingly depreciating variable, i.e. a flow variable whose level requires constant investment because it decreases over time. Organisations have become aware of the importance of lifelong learning, i.e. learning organisations concept, so they are increasingly turning to this concept of business. Investments in knowledge, development and innovation are the investments with the highest return through business sustainability and a better perspective. The accelerating development and the need to implement new technologies encourage organisations to change and learn. This is the cause for the learning organisation becoming a way organisation operates, not just an alternative behaviour and concept of business.

On the other hand, new technologies require constant learning to apply and use them within the organisational process. A study of the presence of the learning organisation concept in selected models indicated that this system is still not recognised in Croatian companies. The most significant disadvantage is insufficient investment in strengthening the knowledge of employees and non-participation and communication within the organisation. The advantages and perspectives for the implementation of the learning organisation concept lie within the experience and knowledge of the sector in which they operate and its employees. This is especially relevant in maintaining databases and channels for the implementation of learning processes along with the knowledge base management. The entire knowledge management process affects the improvement of employees' experience and skills, the processes within the organisation, but also the performance of daily tasks and reducing the shortcomings of the organisation. Knowledge management appears as a process carried out by the management of the company. It helps the company in the dissemination of the professional know-how and essential information that contribute to the company goals. Therefore, knowledge management, within the modern business operations of a company, is viewed as an important factor for increasing the competitiveness of Croatian companies.

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Preliminary communication

Measuring Digital Transformation Maturity of Supply Chain

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Abstract: Digital transformation signifies changes in all components and systems of the supply chain. It is also a strategic decision of the organization which, in the long run, can result in the creation of competitive advantage in the market. Digital transformation is affecting all organizations, regardless of their activity. Digital transformation of the supply chain involves the use of industry 4.0 based technologies as well as the replacement of traditional practices with new ones based on digital solutions. The implementation of digital solutions, such as artificial intelligence, IoT, cloud computing, etc., therefore, improve communication between stakeholders in the supply chain, as well as improve efficiency and effectiveness. When conducted, digital transformation must be measured by different levels of maturity. In this paper, authors research current models of measuring digital transformation maturity in supply chain and propose a new model based on identified theories and needs.

Keywords: change management; digital transformation; maturity models; supply chain

1 INTRODUCTION

A supply chain is a group of interconnected stakeholders. Each stakeholder has a task to add value to raw materials that are in the supply chain and to reduce the costs associated with carrying out the activities necessary to add value [1]. To reduce costs and to increase the efficiency of the supply chain, each organization, that is part of the supply chain, can implement some of the technologies that are related to Industry 4.0. i.e. to digital transform the traditional supply chain. Digital transformation means changes in the system that results from implementing technological improvements. The term technological improvements mean the application of automatic and robotic systems which allows the integration of physical infrastructure and suprastructure into a network, as well as the intercommunication between connected infrastructure and suprastructure [2]. The need for digital transformation is arising from increasing expectations from various interested parties that place different requirements on the supply chain, like ensuring the availability of products or raw materials, etc. Furthermore, the requirements of interested parties can be related to the reduction of negative environmental impact, using machines and devices that use alternative energy sources for their work, etc. [3]. All stakeholders in the supply chain must adapt to the described turbulent environment from which are arising different requirements of interested parties. Most important, organizations in the supply chain must develop a competitive advantage and to decrease operational costs and increase efficiency. One way to adapt to that requirement is to digitally transform businesses.

To measure how successful organizations made digital transformation there are different models. In general, the organization can measure the success of making digital transformation through maturity levels. The maturity level is divided into different levels that, in almost all cases, mark level 1 as the beginning of transformation and level 5 or higher as the final stage of transformation. [4]

This paper is secondary research that aims to identify existing models of measuring the maturity of digital transformation and creating a new one.

Paper is divided into six chapters.

The second chapter describes system theory and systematic approach to the organization and its importance within the process of digital transformation.

The third chapter describes the importance of sustainable development of the organization.

The fourth chapter is about digital transformation and Industry 4.0 and its importance for today's busses.

The fifth chapter describes digital transformation of the supply chain.

The sixth chapter describes the practical impact of this research and its limitations.

2 THE IMPORTANCE OF A SYSTEMATIC APPROACH IN DIGITAL TRANSFORMATION

A systematic approach is based on general system theory that is created for better understanding different science disciplines i.e. common language for communication between different science disciplines. System theory describes the system as the group of subsystems and relations between subsystems. All subsystems in the system are mutually related and changes in one subsystem can impact the change in other subsystems. Furthermore, system theory emphasizes that the system exists in mesosystem and mesosystem exist in the macrosystem. All mentioned components are mutually connected and can impact on each other [5]. When it comes to practical implications of system theory, the supply chain can be viewed as a mesosystem that exists within the macrosystem. Macrosystem is related to the general environment from wich forces like legislation, changes in technologies, economic changes and other, act on organization. Furthermore, the supply chain consists of many different stakeholders i.e. organizations that can be viewed as systems. So, in the context of relations that are emphasized in general system theory, if the supply chain is affected with some anomaly, the anomaly will affect all organizations in the supply chain.

Furthermore, system theory highlights:

- every system tends to grow and develop. That is also one of the fundamental characteristics of the supply chain as a system,

- all the elements in the system are interconnected, and as such, the system consists of several different elements that affect each other and interact with each other,
- the goal of each system is to create, i.e. ensure that the desired output is generated, using the resources used at the output,
- entropy in the system is a common occurrence that results from changes in the environment of the system. Any change in the environment can cause a crisis in the system if the system does not develop an adequate response to it,
- each system needs to be managed because if the system is not managed, as a consequence, it may not be possible to achieve the desired system goal [6].

So, according to the system theory, the partial digital transformation of one stakeholder in the supply chain and improvement of its performance will not affect the overall performance of the entire supply chain. It is necessary to optimize and digital transform supply chain as a whole to improve the overall performance of it. Each supply chain tends to grow and develop but it is necessary to ensure its manageability because the loss of control in one of the components will result in the risk of losing control of the entire supply chain.

3 INTRODUCTION TO DIGITAL TRANSFORMATION

Digital transformation involves specific changes that can affect the whole organization. It is also a strategic decision of the organization which, in the long run, can result in the creation of competitive advantage in the market. Digital transformation requires a change in the current organizational business paradigm and a change to create a new organizational culture that will shape the way the organization operates after performed digital transformation [7]. To perform the digital transformation, the organization must ensure technical and technological competence because without such competencies organizations can not implement innovations such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, etc. [8]. Technical competence is related to the existence of machines and devices in an organization, and technological competence is related to the knowledge of how to do something or how to use machines and devices [9]. Accordingly, digital transformation requires major changes in the organization which can lead to resistance of organizational employees. Resistance can occur because of the changes in ways of doing business and fear of losing the control in an organization with implementation of automated systems. For this reason, digital transformation of organization needs to be properly communicated within the organization to reduce the risk of employee resistance.

Digital transformation is done in phases. Current phase of the digital transformation of the organization determines the digital maturity of the organization. So, the digital maturity of an organization is determined with the usage of digital technologies within organizational processes. Furthermore, with a higher level of digital maturity organization can increase the quality of the product or service provided to customers and users and also the efficiency of business processes [10].

It is important to highlight that digital transformation can be determined by the innovations that employees in organization develop [11].

Digital transformation is affecting all organizations, regardless of the product and services they provide. In the context of manufacturing organizations, digital transformation involves the use of automated and robotic manufacturing systems. On the other hand, digital transformation in the logistics sector involves the application of automated warehouse systems as well as sensor-based technologies that enable the monitoring of the performance that logistics processes develop, etc.

4 DIGITAL TRANSFORMATION OF THE SUPPLY CHAIN AND RELATED TEHNOLOGIES

As mentioned in chapter 1, supply chain consists of different organizations that are mutually connected. Each organization in the supply chain has a different task, and the whole supply chain has to procure all raw materials, products, and services that are necessary to ensure the normal functioning of other organizations and society as a whole.

Digital transformation of the supply chain involves the use of industry 4.0 based technologies as well as the replacement of traditional practices with new ones based on digital solutions. Digital solutions can increase the efficiency of the supply chain and also decrease costs. With the usage of some of the technologies, such as AI, organizations in the supply chain can simulate and predict demand for goods and services. Furthermore, AI can help in optimizing transport routes and managing warehouses, etc. Implementation and usage of AI are determined with the technical, technological and competence of employees in the organization.

Other technological innovations, except AI, that can be implemented in the supply chain and organization within the supply chain are:

- collaborative equipment: means the use of automated systems such as robots and drones. Automated systems can be used in the warehouse to reduce the need for human labor which means decreasing costs and higher reliability of the system. If such system is paired with AI, then AI can optimize the functioning of automated systems, like robots. When it comes to drones, drones can be used to transport goods between organizations in the supply chain or to deliver goods to the customer. It is possible to create a system in which AI manages robots to transport goods from the warehouse to the drones and then drones transport goods to the customer [12],
- additive manufacturing: involves the use of a 3D printer for creating products. In other words, an organization that owns a 3D printer can print the product according to the specification that other organization provides. In supply chain that means less need for transportation because it is possible to send a specification of the product to the organization who ask for it in the supply chain and that organization can print product accordingly to specifications that organization receive. But it is

important to highlight the need for raw material which is used to print product i.e. functioning of 3D printer. This kind of technology can be used, for example, in healthcare for printing implants [13],

- Internet of Things (IoT): involves the creation of a network between infrastructure and suprastructure as well as communication between the same. Examples of using this kind of technologies are tracking the goods in the transportation process, tracking the movement of the robots in the warehouse and the possibility of managing the robots, etc. For the normal functioning of IoT, it is necessary to ensure sensors that will be implemented in robots, goods or vehicles. So, based on the sensor readings, certain machines and devices that perform certain activities in the process are activated [14],
- Blockchain: with the development of the supply chain there is a need for better manageability of it and decreasing risks and costs of processes in it. Furthermore, there is also a need for better recording and dissemination of information. One of the technologies that can help organizations within the supply chain is blockchain. Blockchain enables creating an unique database that can be managed decentralized so every organization within the supply chain can make changes in it. One of the main advantages of using blockchain in the supply chain is the fact that all created information have a copy that is stored in databases of all organizations in the supply chain. Furthermore, blockchain enables substitution of traditional systems of communication as electronic data interchange and decreasing risks and increasing the reliability of the supply chain [2].

Therefore, in practice, there are many more technologies that can be implemented in the supply chain such as cloud computing, business intelligence, big data, etc. All of the mentioned technologies can increase the efficiency of the supply chain and decrease costs in the long run [15].

Using such technologies may enable improvements to the logistics processes taking place in the supply chain through the creation of a virtual model of the logistics system. In the virtual model of the logistics system is possible to take different tests related to searching for possible improvements and the testing result of implemented improvements [16].

4.1 Digital Supply Chain

When it comes to defining digital supply chain it must be highlighted that digital supply chain is related to supply chain which uses a different kind of technologies and some of them are mentioned in chapter 5.

The traditional supply chain is based on a functional geographical structure and can often be displayed in silos. Such a structure is often highly formalized through the use of physical documentation, which can significantly slow down the processes in it [17]. On the other hand, the digital supply chain is much less formalized in regards to traditional because of using technology for digital communication. Furthermore, the digital supply chain can be displayed as a virtual structure with all processes that are taking place in it and with data collected using sensors and stored in digital databases. Such data can be used for decreasing costs and increasing efficiency which is the goal of each supply chain, digital and traditional [18].

For making supply chain digital it is necessary to conduct digital transformation and to implement technologies which are described in chapter 4. So, it can be said that the digital supply chain is based on:

- Technology: digital transformation means the implementation of technologies such as IoT, AI, etc. With the implementation of such technologies there is a possibility and chance to increase the performance of processes within the supply chain. Without implementation technologies, the digital supply chain does not exist.
- Integration: indicates increased collaboration between organizations in the supply chain. With increasing collaboration there is also increasing in transparency, better functioning of processes within the supply chain and also the possibility to create better collaboration,
- Collaboration: means better coordination in the process of product planning and development, dissemination of information as well as the overall functioning of the supply chain,
- Coordination: implies coordination of activities carried out in the supply chain with the aim of increasing the efficiency and effectiveness [17].

Implementation of digital technologies also have a higher risk associated with the possibility that the information contained in the digital supply chain may be exposed to external influence, i.e that third parties may be able to misuse such information. Accordingly to identify risk of leaking information, the organization must develop mechanisms to reduce such risk, which is an imperative given the sensitivity of the information in the supply chain and the imperative to protect stakeholder-related data.

4.2 Existing Models of Digital Supply Chain Maturity

The maturity of the digital supply chain is determined by several implemented digital technologies i.e. digitalization of processes within the supply chain. There are many different approaches for measuring the maturity of the digital supply chain and one of the models is described by Salmon (2019).

Accordingly to Salamon [19] the maturity of the digital supply chain can be divided into four as shown in Tab. 1.

Exsisting model that is described by Salamon (2019) do not include all possibilities that tehnologies of industry 4.0 i.e. digital transformation provides. Furthermore, existing model do not include zero level of maturity, holistic wiev and view form perspective of individual organization. Accordingly to that fact, there is need for developing new model for identifying maturity of digital supply chain.

Furthermore, through research it is identified that there is a lack of maturity levels of digital transformation but there are several different authors that are describing what indicators are measured through maturity level of digital transformation. Most of the authors indicate that the digital culture, technology, operations and processes, strategy, organization, digital skills, innovation, etc. are contained in their models of maturity [20].

Table 1 Maturity levels according to Salamon (2019)

Maturity level	Description
1	Collaboration within an organization: As already emphasized, digital transformation is a complex process that needs to be conducted in all of the organizations in the supply chain. For conducting transformation it is necessary to ensure efficient and effective change management that will enable gradual transformation in the chain. So, the first step means identification of opportunities for digital transformation and places in the organizational processes where digitization can be carried out.
2	Networked Supply Chain: The possibility for organizations participating in the market as individuals to develop a competitive advantage in the market is significantly less than the possibility for networked organizations. Accordingly to this, in level 2 of maturity, organizations in the supply chain are networked and are using digital technologies for networking like blockchain, cloud computing, etc.
3	Full integration of customer requirements: The use of digital technologies enables a much better understanding and gathering of information on the requirements that stakeholders place on organizations as well as on the entire supply chain. The supply chain, as such, exists to provide all the necessary resources and to meet the demands of stakeholders. In level 3 of maturity, in the organization in the supply chain use digital technologies as well as software solutions such as computer-aided programs for order prediction, simulation, IoT, RFID, etc
4	Predictability: Forth level of maturity means that organizations in the supply chain are using digital technologies to predict further developments in the market and also to predict risks and possibilities for further development and optimiziation of the supply chain

When it comes to proposed models for measuring digital transformation maturity of the supply chain, it is identified that there are almost no authors that describe models for measuring mentioned maturity.

With development of Industry 4.0 and increasing need for finding out new ways for increasing efficiency and decreasing costs, supply chains are tending to conduct digital transformation. For success in such transformation, there is a need for a model that will provide measuring how successful digital transformation is carried out and also need for measuring the maturity of the organizational system after transforming it into a digital one.

4.3 Proposed Model for Digital Supply Chain Maturity

As described at the end of chapter 4.2, there is a need for developing a new maturity model that will include zero level of maturity and situations in which only one of the organizations that is part of a supply chain, has conducted digital transformation. Furthermore, the new model of maturity described in Tab. 2 includes a synergy that is created through the collaboration between different kinds of technologies that are implemented within the supply chain and using technologies for the fulfillment of specific requirements of interested parties.

Table 2 Maturity levels of digital supply chain

Maturity level	Description
0	Digital transformation is not conducted. The supply chain is traditionally organized. All communication is carried out by traditional ways that in most cases means using e-mails and documents. Level 0 also describes cases in which only one of the organizations within the supply chain conducted digital transformation but the organization can not use its advantage and implemented technology in full potential because other organizations are not implementing digital technologies.
1	All organizations in the supply chain conducted digital transformation but not enough to develop collaboration between each other. Communication is carried out with the help of the new system but in most cases organizations are using e-mails and traditional ways of communication. In each organization in level 1 maturity, the optimization of process and creating a new paradigm of business is carried out.
2	All organizations in the supply chain conducted digital transformation. Communication and collaboration between organizations are developed and carried out with new technologies such as cloud computing. Organizations are using drones to transport products. Warehouses are automated and the efficiency of warehouse processes is increased. Each organization has created new paradigms of business, and started creating synergy within the organization. Employees use new technologies as support for their tasks.
3	In each organization there is synergy between new technologies that are implemented and existing ones. Organizations are using IoT, blockchain, 3D printers, sensors, etc. for managing all processes. There is a start of creating synergy between all organizations within the supply chain. Organizations have significantly increased efficiency and significantly decreased costs of processes.
4	There is a synergy between all of the organizations in the supply chain. All organizations use technologies such as DT (digital twins) which create a digital copy of the physical system for optimizing and simulating processes. The supply chain is in the digital sphere. Artificial intelligence is used for analyzing and simulating risk and market demand. The need for human labor is decreased. The automated system is directed towards substituting humans in the system.
5	The supply chain is the digital transformation. There is no need for human labor. Humans are only needed for maintenance and fixing autonomous systems as well for programming it. Robots are carrying out all activities in the system. AI system is used for managing the entire supply chain with no need for human intervention. There is a risk of self-sufficiency of automated systems and eliminating humans from it.

It is also necessary to emphasize that organizations, that is, the supply chain as a whole, are constantly adapting to new technologies that are evolving and emerging. Adaptation to such technologies is necessary to retain the once acquired competitive advantage but also to create new opportunities for creating new competitive advantage.

As shown in Tab. 1, the maturity level of the digital supply chain is divided into 6 levels. Every level has different characteristics and different level of synergy between implemented technologies and humans or organizational system with different risks. There are five indicators measured within the proposed model and those are as follows:

- Conduction of digital transformation
- Communication in organization and between organizations within the supply chain
- Creation of new bussiness paradigms
- Synergy in organization and between organizations within the supply chain
- New technologies used for processes optimization.

With increasing the level of maturity there is also an increased risk of substituting humans from the system and the possibility for AI to take place in managing the entire system. It should be highlighted that digital transformation has different advantages that are related to decreasing costs and to increase profit. But there are many different kinds of challenges and problems that are related to the role that humans have in such a system.

5 CONCLUSION

The supply chain is a set of interconnected stakeholders who have the basic task of providing all the necessary resources to meet the requirements of the stakeholders, and especially the customer. The impact of the development of Industry 4.0, as a consequence, has the importance of implementing new types of technologies in the organization, and such technologies will allow optimization of the processes taking place in the supply chain. Supply chain optimization is of particular importance because of the need to reduce costs. The implementation of digital solutions, such as artificial intelligence, IoT, cloud computing, etc., as a consequence have improving communication between stakeholders in the supply chain, as well as improve efficiency and effectiveness.

An organization's digital transformation can be viewed through its maturity level. With a higher maturity level, organizations have a higher number of implemented technologies and higher performance of processes. Furthermore, because the supply chain is a system that is compound from many different organizations, for supply chain is general system theory valid, and that theory implies that the digital transformation of one organization in the supply chain will not have a significant impact on the overall performance of supply chain.

To measure the digital transformation maturity of the supply chain there is not an adequate model that is based on a scientific approach. Furthermore, several different models are created by commercial organizations that are in most cases consult agencies for digital transformation. That kind of models are not scientifically proven and there is a need for a new model and proposed model is described in this paper.

With the development of new technologies and an increasing number of organizations that conducted digital transformation there is also a need for measuring the success of the made transformation. The model that is described in this paper give supply chain and organization within the supply chain opportunity to measure their maturity level and success of conducted digital transformation. With increasing in the maturity of digital transformation there is also risk related to substituting the need for human labor in supply chain and organizations at the whole that may lead to creating a self-sufficient system. One of the limitation of this paper is the cost of implementing new technologies in opposite to benefits from the digitalization of supply chain and raising the level of its maturity. There is also a need to quantify each indicator for every level of maturity.

Future researches in this area are advised to upgrade the model described in this paper with methodology that will enable to quantify success in conducting transformation. For example, to weigh all implemented technologies and based on the sum of weigh to give conclusion in which state of maturity level organization is.

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Preliminary communication

Integrated Marketing Communication in Project Activities

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Abstract: The paper deals with integrated marketing applied in project activities. The reason for this is the fact that such activities should refine their offer with a supplement in the project documentation but in the means of a different approach to the market. The amendment addresses recommendations to investors for the future construction and maintenance of facilities, and Lean and BIM in the design, construction and maintenance of facilities. That is why, during market processing, investors are offered an offer that solves the project task, includes design with visualization, and construction supervision, but already at this stage also includes certain maintenance solutions. This is only possible if the customers are approached comprehensively. For this there is an integrated marketing activity or process, where already in the market research, customers are informed about a kit containing everything from design, through construction to maintenance of the facility. Successful application of this process requires appropriate hardware and software support, as well as trained personnel for marketing. In scientific terms, a new method of integrating marketing activities in the business process of project activities is proposed. In application terms, a business process organization model integrated with marketing is presented, which enables the project company to connect with the market more dynamically and efficiently.

Keywords: construction; communication; designing; information; maintenance; marketing

1 INTRODUCTION

One of the most important features of today's global economy is the extremely rapid changes imposed by developed countries, and others with more or less success are trying to follow them. Today, companies face several constraints, such as global competition, highly variable customer demand and increased product diversity in the market, so it is necessary to adapt production as closely as possible to market needs [1]. Specifically, global market changes, new technologies in all industries, new manufacturers and suppliers, but also increasing customer demands, as well as new conditions and constraints on target markets are driving a new style of business systems management. That is why management needs to find effective and fast solutions.

Only systems that continually improve their business and respond to market demands faster can produce accordingly than their competitors have a chance to maintain their status, improve their business and market position. Accordingly, every business must apply everything that the world research heritage has to offer in order to survive in a global and increasingly demanding market. In addition, development is also conditioned by the growth and development of information technology [2].

After political and economic changes, the construction activity of the Republic of Croatia lost part of its domestic and especially foreign markets, which resulted in a fall in employment. In the same time, globalization has led an increased competition. In order to catch up with market trends and rewind the lost market share there is a need to introduce new methods of production and business to raise quality and reduce costs and other losses and increase labour productivity as conditions for greater competitiveness. In such a situation, great advances are not possible, but a constant improvement in all aspects of competitiveness. This is necessary because the demands of the customers are, in addition to the quality, increasingly oriented towards a lower price.

In addition, construction and especially design companies need to expand their offerings and integrate more with investors. This includes the preparation of project documentation, the supervision of construction and certain recommendations for more efficient construction and maintenance of the facility. In addition, there is an opportunity to expand the offering by introducing business methods and tools to increase the efficiency of production and business such as BIM and Lean. In fact, we can say that BIM is one of the Lean tools in the construction industry. Because Lean is focused on waste disposal, the implementation of BIM can ensure waste reduction.

BIM involves building, informing and modelling. BIM is widely regarded as a catalyst for innovation and productivity in the construction industry. In addition, BIM can help a more sustainable construction process, which in turn can contribute to poverty eradication in developing countries. While BIM is increasingly being adopted in developed countries, implementations in developing countries are rare. The survey found that construction firms are struggling with several constraints that must be in line with the socio-economic and technological environment found in developing countries. An example of problems preventing BIM adoption is the lack of IT literacy staff as well as the lack of national programs to implement BIM. Research results show that developing country construction companies rely heavily on outsourcing of IT services [3]. BIM is not just one standalone technology; it is linked to another for example virtual reality using laser technology. BIM, in combination with other tools, is used throughout the life cycle of the construction and connects data and information from the design phase to construction and finally to the renovation and demolition of the building [4]. In addition, BIM provides a platform for visualization, collaboration, automation, integration and communication between different actors in the construction industry [5]. Therefore, the use of BIM technology is used in all corners of the world and is being adopted to ensure greater success in AEC (Architectural Engineering) companies [6].

Lean is a group of new business and manufacturing methods and tools and comes from Japanese business philosophy with the aim of reducing all costs, losses and running time while increasing quality. In the 1980s, for example, the Japanese industry saw an increase in productivity by 15.6%, quality by 36% and a decrease in storage and assembly space by 25% and fifteen times less inventory than in the United States [7]. Studies of changing Lean tools in the design industry have shown that their application reduces cost by 15.6% [8]. Using Lean, project industries can expand their offerings and find the right methods and tools for greater synergy with the market.

Securing an ongoing relationship with investors can be achieved through market research if a tool known as integrated marketing is used. Until 1990, forms of marketing communication were studied and applied individually, but changes in consumer behaviour, caused by general social changes and technological advances, resulted in an increasing need for the integration of all communication activities, as well as for modified and fully customized communication messages [9]. In the coming years, integrated marketing has become the dominant approach that companies use to plan and execute their marketing communications programs [10].

Integrated marketing communication involves different forms of communication with current and potential investors over a certain period of time, in order to ensure maximum information but also the possibility of extending the offer. Therefore, the ultimate goal of this consideration is to define a comprehensive integrated information and communication process so that the project activity is in synergy with the market. There are certain methods and tools for this that enable constant contact with investors that is a long-term relationship. Considering that the project activities are the bearer of the first and most important investment phase, it is necessary to expand the offer through comprehensive communication. This means that designers must be prepared to offer construction supervision as well as additional services, and to maintain a long-term relationship with the target market.

2 PROJECT ACTIVITIES

The preparation of project documentation is an activity or a specific product of professional staff and can be viewed by specific professional types and by stages in terms of complexity of work.

If it encompassed one complete area within the domain of project documentation preparation, then in the expert aspect the projects could be divided as follows [11]:

1) Architectural projects covering the forms of buildings, interior design and landscape architecture, as well as structural projects and budgets
2) Civil engineering construction projects such as railroads, roads, bridges and culverts, tunnels, maritime and river construction, hydro technical structures, and projects related to soil mechanics and earthwork
3) External water supply and sewerage projects
4) Surveying for construction purposes
5) Mechanical installation projects
6) Electrical projects of external and internal installations and equipment or equipment within the facility
7) Special-purpose technical studies on heat, acoustics, various insulations, noise and fire and explosion protection at work
8) Performance projects that are various forms of project documentation that are important when making adaptations and should have documentation for the maintenance of facilities and especially installations.

These can be added to the development of investment programs and studies, construction supervision, construction and maintenance consulting, and other methods of increasing business efficiency, such as BIM and Lean.

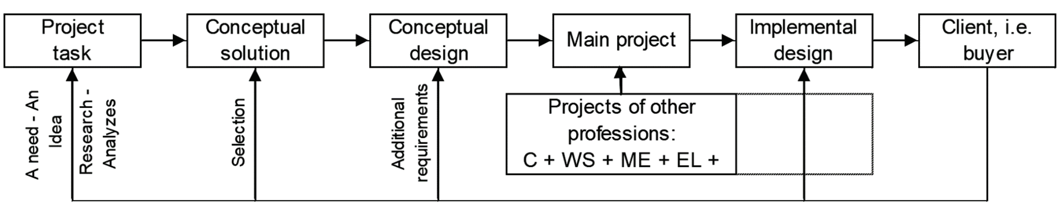

Figure 1 The classic design process (Explanations: C - construction, WS - water supply and sewerage, ME - mechanical engineering, EL - electro, PAW - protection at work).

In terms of content, all of these types of projects will be as complex as a complex object or future construction. According to Fig. 1 (author creation), the first and extremely important step is defining the project task. In most cases, this is done by the architectural design department with additional information from other design professions or departments. Rarely, a Conceptual Solution or Conceptual Design is specifically made. After defining the terms of reference, all departments elaborate on the project and continue with the design after the architects have defined the essential elements and made the foundation for the rest of the design. Subsequently, departmental design is performed almost in parallel with the preparation of the main and implementation projects and other required contracted documentation.

This design approach is common because architectural and static designs are the basis for other design. For all other projects, the company will hire specialized designers in various areas of installations and other necessary projects. This is confirmed by a modern approach to the organization of design as shown in Fig. 2. The figure shows an organization of an Israeli design institute that shows a model with 2D alignment.

The aforementioned design jobs also require an appropriate organizational structure. Fig. 3 (author creation) shows the usual organization of projectile activities. The organization shows that the company is engaged in the design and supervision of construction, because it is done mainly by the personnel who participated in the design.

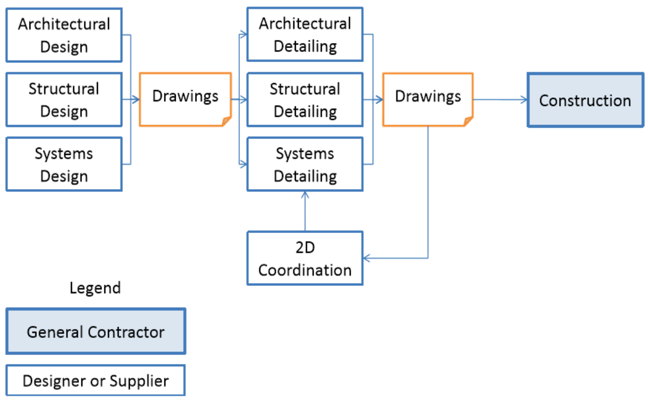

Figure 2 A modern approach to the organization of design [12]

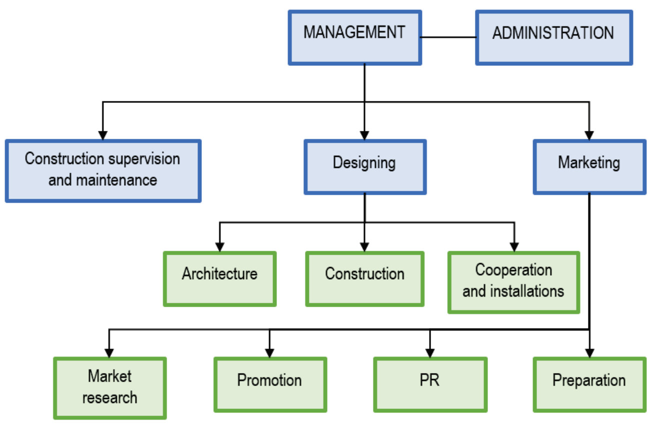

Figure 3 Organizational structure of the project company

In addition, for the supervision of other works, the investor will hire an appropriate specialized company. In practice, if the size of the company and the revenues allow, a commercial or marketing department will be set up with the aim of market research, contracting of projects and supervision, as well as assistance in the preparation of project tasks and other preparatory works for design. From Figure 3, it can be concluded that it is sufficient to have the capacity for architecture in structures, and other types of project can be done through cooperation with an external associate. In addition, project departments can participate in construction oversight activities. Marketing or commercials are given particular attention. In that department, they must have professional construction staff but are additionally educated for modern market access. In this way, this department can carry out market research activities, promotion, public relations and participate in the development of project tasks in preparation for effective design.

The current trends of the economy and globalization impose the need for a different approach and organization, where the wishes of clients and constant communication are to be taken into account. Shortcuts must already have in mind when designing problems that may arise in the construction of facilities and even in their maintenance. Therefore, constant communication with clients is required.

3 INTEGRATED MARKETING

The proposed organization should ensure maximum synergy between the market and the project company. Synergy is possible if the company is proficient in applying new methods and IT tools in the complete process. In this regard, marketing should be accepted first as a process established in the second half of the twentieth century. This process constantly changes its structure and dynamics. Marketing has been defined by many local and foreign authors so we have more access as follows:

1) According to the Chartered Institute of Marketing - Marketing is a management process that identifies, anticipates and satisfies consumer demands while generating profits [13]
2) The following approach defines marketing as the process by which ideas, goods and services, their pricing, promotion and distribution, the goals of individuals and organizations are planned and implemented [14]
3) If marketing is understood as a dynamically irreversible process, it can be stated that it consists of activities of individuals and organizations that enable and accelerate exchange in a dynamic environment by creating, distributing, promoting and pricing goods and ideas [15]
4) Marketing is not only a concept of business, but more importantly, a way of business, and, if we broaden the focus of observation, to think of life, and therefore a way of a kind of philosophy of living [16].

It is clear from the previous definitions that marketing refers to a way of researching and communicating with the market in order to constantly identify the wants and needs of customers, as well as other information that can assist in the promotion and development of products. Marketing activities are conducted through market research and a combination of elements of the marketing mix. Market research aims to identify specific customer groups in a broader field or market segment. Each market segment has a certain capacity relative to the total purchasing power of some products. The ultimate goal of market research is to determine the position or share in the consumption of market capacity in a segment.

It is already known that the elements of the marketing mix are product, price promotion and distribution. Marketing activities are carried out through promotion with the right product and price negotiation. Distribution in project activities may relate to deadlines for the execution of contracted design work or construction supervision.

Marketing has evolved over time in line with the development of technology and technology as well as the market. Marketing development has historically taken place in stages or concepts such as: product concept, sales, marketing concept, consumer concept and social marketing concept. Such a sequence of development shows that marketing or market research has increasingly enriched the connection with the market but also with the wider environment [17]. These phases of marketing development have already survived their peak, so it is necessary to further innovate methods and procedures. In this sense, individual companies with greater intensity are connecting to the market with a view to expanding their supply and permanently linking to their market segment. This is why larger and more structured customer communication is known as integrated marketing. Integrated marketing communication is the transfer of information from the sender to the recipient, provided that the recipient understands the information that forms the basis of the communication process. As a means of modifying behaviour, effecting change, achieving information productivity and achieving goals, information transfer is absolutely essential in any field of activity [18]. He believes that integrated marketing communication is a process of various forms of persuasive communication with consumers and potential customers in a certain time [19].

Fig. 4 shows one modern integrated marketing information system that has feedback and can use different channels with prep code.

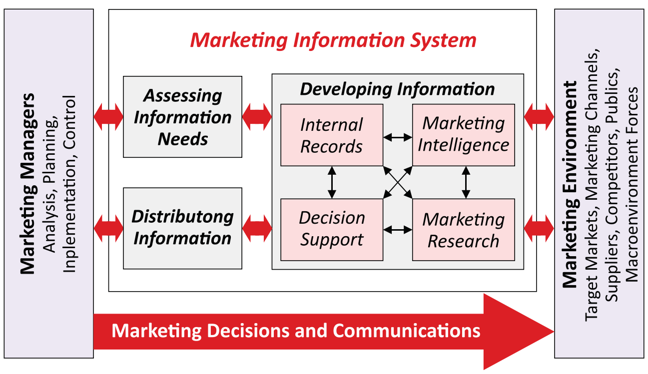

Figure 4 Marketing information system [20]

Fig. 4 shows the synergy between the management of the company through the marketing information system and the target customers. The essence is quality information and communication. Such a system enables constant communication with the target market for the purpose of making decisions about the growing offer or product. Central to the process is an information system where information from markets, institutions and memory is collected and decisions are made. Information gathered from the target market through integrated marketing communication is the input and prerequisite for the application of modern design methods as well as recommendations for construction and maintenance. It is necessary to define a product that is actually comprehensive design documentation but also constant communication of the designer during the construction and maintenance of the facility.

4 INTEGRATED MARKETING INFORMATION AND COMMUNICATION SYSTEM WITH THE APPLICATION OF BIM AND LEAN METHODS IN PROJECT ACTIVITIES

4.1 BIM

The product or design and supervision services should be supplemented with construction and maintenance consultancy work and BIM and Lean tools applicable in construction. The requirements of the market on the one hand, and information technology on the other, create the conditions for the development of design around the world, even in the domestic field. In this regard, domestic and foreign associations are already adopting certain document-directives establishing a method for electronic information modelling of construction projects [21]. Support for the said directive, or its implementation, is supported by the 2014 CEN (European Committee for Electrotechnical Standardization) Program, which initiated the establishment of the Technical Committee CEN/TC - Building Information Modelling, or abbreviated BIM. The aim of these document is to provide a normative framework for the application of BIM technologies in practice [22].

Building in this case broadly implies several substantive terms such as [23]:

- Construction is the design and construction of buildings and the professional supervision of construction
- Construction is the execution of construction and other works (preparatory, earthwork, structural, installation, finishing and installation of construction products, equipment and facilities) that construct a new structure, reconstruct or remove an existing structure
- A structure is an assembly formed from purpose-bound construction products, with or without installations, an assembly with a built-in installation, or an assembly formed by construction.

Information within the BIM method encompasses a set of programs, devices, methods, and procedures through all stages from design to storage. It is a structured set of characters that conveys a message (ethnology and anthropology), as well as information or spoken or written information in a format suitable for sending, storing and transporting [24].

Modelling is the construction of a view or a model, and in this case the following applies:

- A structure or computer record that, when loaded, acts as a real structure or ground and serves to test the load-bearing capacity, safety and usability of the designed object
- Simplified or conscious artificial presentation of reality (ethnology and anthropology)
- Theoretical reconstruction of a set of phenomena for the purpose of visualizing explanations and better understanding of cultural phenomena in the past (archaeology) [25]

There are already some practical experiences, especially in the design work, so the following advantages are highlighted [26]:

- Adding and connecting all design teams
- Better visualization
- Improve productivity by simply sharing information
- Faster design and more accurate documentation with fewer errors
- Cost reduction especially for those who do not create value

- Teamwork
- Errors and omissions are minimized at all stages of design.

BIM is still evolving as a method, so digital tools are available that are based on modelling building information and provide an opportunity to facilitate the assessment of the performance of buildings in the environment. Recently, various tools have been developed that use the BIM model for the automated basis for quantifying life-cycle estimation (LCA) [27]. Fig. 5 shows a simplified method of the process of controlling the implementation of BIM in construction, which, with the help of certain applications, can significantly reduce costs during the design phase. In this way, even at the stage of market processing, a comparison can be offered between a project where BIM has been applied to classical design, which can further increase its competitiveness. The control shown in Figure 5 consists in comparing the cost of applying BIM with respect to classical design.

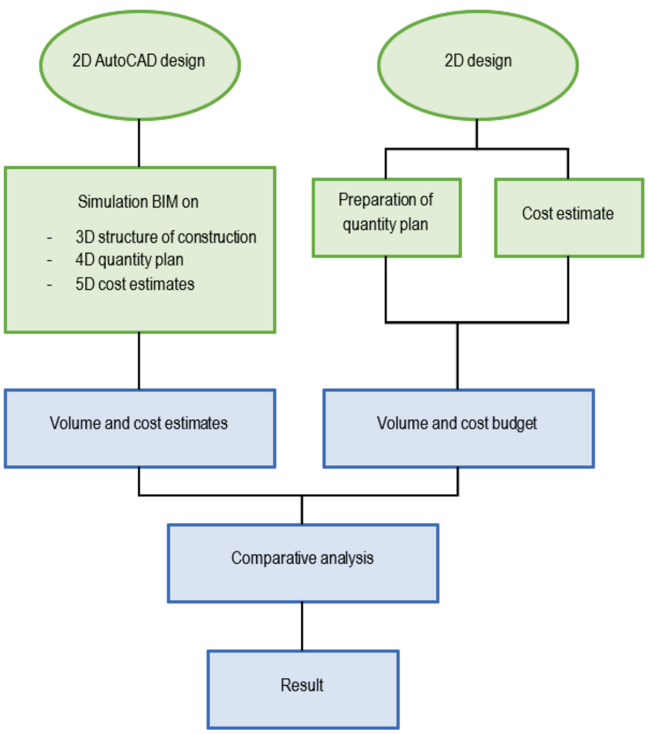

Figure 5 An example of controlling the effectiveness of BIM in design [28]

The difference is that BIM involves the use of a CAD (2D) visualization program, a multi-dimensional (3D) model is simulated, a plan for all construction operations (4D) and a cost estimate (5D) is made. After quantitative estimation and determination of total costs, the costs and effectiveness of the project are analysed and compared. BIM enables the projection of the complete life cycle of a building from idea to exploitation or recycling already at the design stage.

4.2 LEAN Methods in Design

In modern times, new methods are emerging that improve the production, construction and maintenance of facilities known as lean or lean lines, which means less facility, less effort and capital, less time and storage, and therefore less cost and unnecessary losses. In this sense, methods have already been established, of which the following should be paid particular attention in design [29]:

- TQM - a management system focused on continuous improvement of quality
- JIT (Just in time) - delivery of resources at the right time
- "5S" - default model; sorting (sieri), order (seiton), cleaning (seiso), personal contribution (seiketsu), self-discipline (shitsuke)
- Standardizing as many operations and procedures as possible
- Kaizen - continuous process improvement
- Kanban - Inventory management system.

These methods are derived from Japanese business philosophy, and they share a common characteristic that everything goes on continuously with a tendency to increase quality and efficiency. In addition, these methods can be successfully implemented in marketing research and design. A special quality of the company's offer is consulting recommendations with project documentation and later participation in the process of construction and maintenance of facilities.

When defining a product or offer and defining a pricing system and selecting other elements of the marketing mix, especially promotion and PR, an integrated marketing communication system can be defined and applied, which implies a constant connection with customers, ensuring synergy between marketing and operating activities from research markets, through design and construction through to facility maintenance.

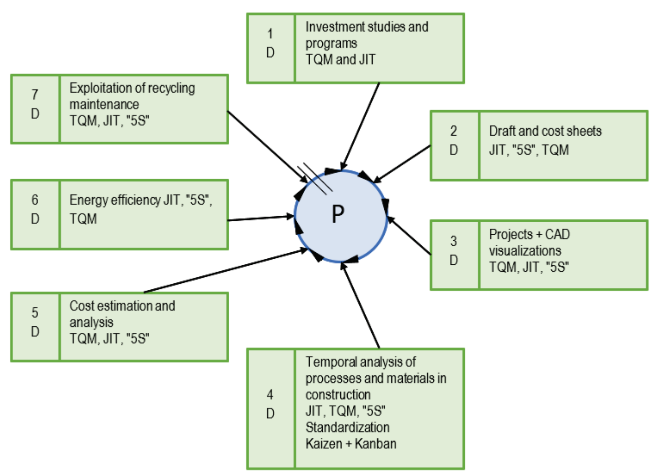

Figure 6 Contents of the complete offer of a modern project company

Project activities can be more competitive by applying modern methods that give the market the opportunity of a project that covers all activities from conceptual studies to exploitation. In this sense, one design sequence can be defined that encompasses all the contents of the design using BIM and Lean methods, as shown in Fig. 6 (author creation). The figure proposes the application of individual Lean tools at certain stages of the project flow. Such a sequence of offers is proposed taking into account past research experience. The proposed product offering (P) can still be supplemented by design software and other new organizational and technological innovations, but the offer must constantly respect various restrictions.

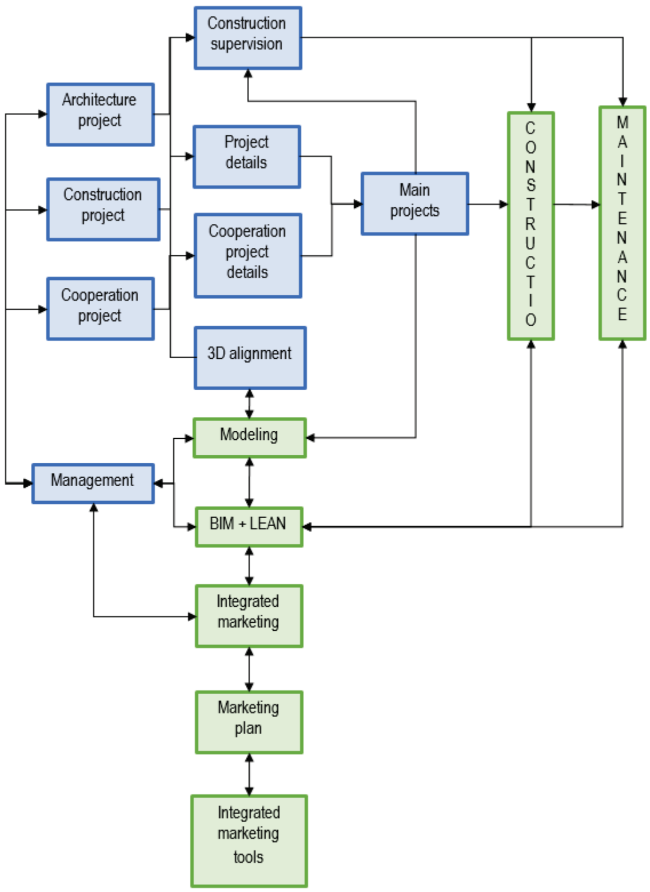

Figure 7 Integrated marketing-communication process in a project company

5 OVERALL INTEGRATED MARKETING AND OPERATIONAL COMMUNICATION PROCESS WITH THE APPLICATION OD BIM AND LEAN METHODS

Once the company is fully prepared to submit a design offer with the latest methods and recommendation to construction and maintenance, everything is ready to apply the integrated marketing communication process. In this respect, the possibility of synergies of the BIM method with the application of Lean method, especially with the Kanban tool is shown in Fig. 7 (author creation). The aforementioned tool, in particular in combination with JIT, is applicable to construction work. The essence is in very precise software called electronic card. The card contains information on equipment and supplies, storage in the dynamics of needs. The software signals in a timely manner the needs for the inputs to the site to be delivered at the exact moment of the start of the defined work of construction. In addition, the complete flow of activities from the beginning of the design to the completion of construction is virtually covered. Other lean tools such as kaizen, "5S" and standardization of procedures can be applied in this regard. The basic lever of this system is a lean-principle called "pull" or marketing feedback. So do not accumulate supplies but also allow for a lack of input.

In this case, this means, for example, that any request for a change during construction, as well as an error or other loss, is immediately signaled to be incorporated into the modeling and in virtual form accepted into the construction.

The proposed communication system can be successfully implemented especially in the design, construction and maintenance of complex facilities, and can be successfully operated permanently with appropriate IT support and highly educated staff. Successful application of the proposed process requires the creation of a plan and defining the tools of the promotional mix. Fig. 8 shows one common integrated marketing plan. According to the picture, the immediate and global environment of the company should be analysed first. In this sense, various positive and negative elements of competition and their own strengths and weaknesses are identified. It is especially important to have a variety of information on the political, financial, developmental and legislative conditions that prevail in the global environment. After that, the market segment and target group of investors can be defined, and their position or part of the market capacity in the domain of the company's supply can be determined.

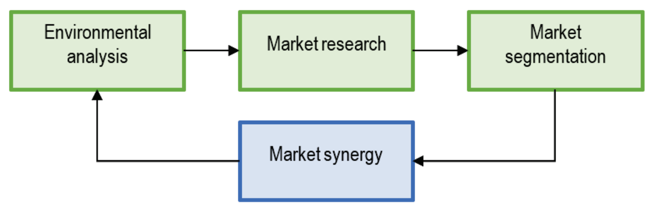

Figure 8 Integrated Marketing Plan [30]

The concept of integrated marketing communication begins with the consumer or potential customer is directed back to the enterprise with the aim of defining the forms and methods through which a convincing and effective communication process will be developed. A successful integrated marketing application depends on the implementation of the appropriate promotional tools shown in Fig. 9 (author creation).

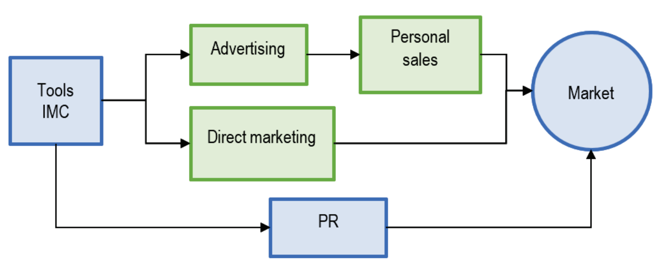

Figure 9 Promotional tools

Fig. 9 shows the essential promotional tools of integrated marketing communication for the purpose of ongoing collaboration and synergy between the company and the market. The basic tool is advertising that serves as basic information. Direct sales involve the personal contact of marketing staff with potential customers through a professional presentation of past projects and new offerings. Namely, for some particularly interesting clients, they should be approached directly and aggressively in terms of informing on the details of the offer. For example, the conceptual design should inform the client about various professional problems and solutions in construction and even in maintenance. In this regard, a range of BIM, visualization and lean construction solutions can be offered. This form is a continuation of advertising, i.e. it is already a sales activity where specialized personnel are involved in accordance with the complexity of the offer. After contracting, there are jobs that can follow the life cycle of the facility according to the agreed cost.

As defined by the American Direct Marketing Association (ADMA), direct marketing is "an interactive marketing system used by one or more advertising media to influence a measurable response and / or transaction at any location" [31]. From the above definition, it can be concluded that in project activities this refers to communication between past clients and those where larger jobs are expected. The communication itself is performed most efficiently by the Internet and in the stages of construction and maintenance by direct contact of appropriate personnel. PR is a constant activity with goals, enhancing the reputation of the company, creating a positive climate and acting on overcoming the negative to positive views of the company. Communicating with the public online or online can be divided into three categories [32]:

- Communication activities within the web site
- Communication with online news media, or
- Social networks.

Integrated marketing in project companies can only be an important factor in competitiveness if these methods and procedures are accurately applied, thereby ensuring synergy with the target market, both locally and globally.

6 DISCUSION

The above text shows that some change is needed in the organization of project activities in order to increase efficiency, especially avoiding idle for some capacities. The above-mentioned example of organization of processes at the Israeli Institute shows that all remaining project work except architecture and construction is outsourced. In addition, the size of the company and the amount of work make it possible to expand IT to construction and maintenance consultancy, but all in outsourcing. The development of marketing with the help of information technologies enables the symbiosis of the market with the company to be expanded in such a way that marketing integrates information with the development of other activities. Thus, the already researched scientific methods of market research can be fully in the function of product or service development. The direct connection of the company in the construction and consultation in the application of BIM and Lean, and especially in maintenance, establish a permanent relationship with the client-investor and thus long-term business cooperation. In addition, such symbiosis opens up numerous opportunities for exploring new methods and procedures and constantly incorporating them into the offer of the project company. In such processes, new scientific methods in the field of marketing and design can be changed, which represents an interdisciplinary scientific approach to this work. Essentially in this consideration, the design process is linked to marketing into one whole. This opens the possibility for flexible behaviour in relation to increasingly demanding clients in the global market. Therefore, in the market research phase, all the answers to the client's questions are possible in all stages of design, construction and maintenance of the facility. This topic can be expanded to include new scientific advances in design, BIM, Lean and other manufacturing and business processes, but with the use of new information technologies. The development of informatics should be especially emphasized as it can be a great support or a tool in the application of new methods in designing as well as in the application of other organizational procedures that can contribute to the integration of marketing with the business process in designing. New information technologies, especially the Internet, will in the future enable even faster and better-quality information between the business of the project company and the market. This will enable faster better-quality information transfer between market and marketing and development of project services. In such synergy with clients, a project firm can over time complement its business program and new ways of integrating with the market.

7 CONCLUSION

Based on consideration of the content of this topic, more conclusions can be drawn. First of all, it is a warning of rapid changes in the economy and globalization. In such a situation, all and even the project activities must constantly expand their product and service offerings with better market connectivity. This means that the project company must define and expand its range of products and services, as well as marketing activities that enable faster contacts and that also create the conditions for long-term cooperation. In practice, this means that designing should be an input activity that continues during construction and is permanently carried out during the maintenance of a building. In this regard, an integrated marketing communication process is proposed, i.e. a system that ensures long-term cooperation of the project activity with the investor. The applied researched scientific methods and procedures of integrated marketing are proposed. By linking marketing with business, a new method in the business of project activities is proposed in a scientific sense, with the aim of increasing competitiveness. Accordingly, the application of scientific marketing heritage in combination with the business of project activities achieves one of the important scientific features, which is in addition to scientific and useful.

In this regard, the latest development results in the business of project activities were investigated, as well as Lean methods and procedures applicable in construction, which in relation to BIM represent an innovation in both theoretical and practical terms. In order to improve the proposed methods and procedures, special attention in future research should be paid to the education of companies engaged in project activities, and especially to greater synergy with scientific research institutions.

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Preliminary communication

Key Tasks and Competences of Spatial Data Manager in Local Self-Government

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Abstract: The article addresses the spatial data manager domain in local self-government units. The scope of the article comprehends typical tasks and required competences for conducting the usual spatial data manager job tasks in local self-government. Furthermore, in the research described in the article, the tasks are systematized and mapped with required competences. Based on the research on tasks and required competences, two types of profiles of spatial data managers in local self-government with its specializations are proposed and described, which are recommended to be considered when developing both, occupation standard and qualification standard of spatial data managers.

Keywords: local-self-government; spatial data manager; spatial data manager competences; spatial data manager profile; qualification standards

1 INTRODUCTION

The aim of this paper is to analyse the profile of spatial data managers in local self-government units in the Republic of Croatia. A representative institution, the City of Požega, was chosen for this, which best reflects and shows the need for the occupation of such a profile, shows the activities performed in it, and are related to spatial data management. Furthermore, in accordance with the Methodology for the Development of Occupational Standards developed by the Ministry of Labor and Pension System, it is necessary to define the list of tasks covered by this occupation, and map them to the appropriate competencies required to perform these jobs. To connect the labor market and the education system, tasks and technical requirements and competencies are elaborated. Research shown in this paper is a support for the development of occupational standards of spatial data managers, which is necessary to develop an optimal qualification standard.

2 DESCRIPTION OF INSTITUTION PROFILE (LOCAL SELF-GOVERNMENT)

According to the Law on Local and Regional Self-Government [1], local self-government units can be municipalities or cities. Cities are all units with more than 10,000 inhabitants and county seats, and represent an urban, historical, natural, economic, and social common coverage.

There are 555 local self-government units in the Republic of Croatia, and the system of local self-government is characterized by an unbalanced structure. This large number of units contribute to this imbalance. An even bigger problem than the number of units is the fact that within each of these categories it is possible to find very small and very large units. Thus, there is a municipality with 137 inhabitants (Civljane), but also a municipality with almost 13,000 inhabitants (Čepin); among the cities there are those with less than 2,000 and those with almost 200,000 inhabitants. Split is 113 times larger than Komiža [2].

For municipalities, given the financial and other capacities, but also competencies, it is not realistic to expect that they will be an organization that develops a system with specialized experts for spatial information management. In municipalities, such mostly specific services are procured from external contractors, and for many jobs they rely on cooperation with regional self-government units (counties). Mostly, there are up to 10 employees of administrative character within one municipality. These are mainly social professions (economics, law), and very rarely they are technical professions.

The category of large cities can be emphasized as the most interesting category for analysis in this research. Large cities are the seats of counties and cities with more than 35,000 inhabitants. For this research, the representative organization which belongs to this category, City of Požega, was selected. Large cities have a very wide range of different authorities. in countries where local self-government developed mainly under the influence of the German tradition, including Croatia, public authorities and tasks performed by local self-government units can be classified into tasks from emerging from their own, self-governing, original scope, and state administration tasks transferred to local units, i.e. entrusted to local self-government [3].

Because of autonomy, and the ability to perform their own self-governing scope, large cities are the most dynamic organizations, which do not have such a large-scale and complex human resource structure as public administration, but on the other hand they perform a wide range of different tasks. In many cases, it can be said that they act both as private investors and as public bodies. Due to the characteristic number of employees (with the exception of the City of Zagreb, which has several thousand employees and is a large-scale organization, applying the analogy of categorizing the size of organizations in the Republic of Croatia for companies), employees of large cities are typically required to apply wider knowledge. A comparison of small and large organizations shows the existence of significant differences in several dimensions of their business. Large organizations are characterized by a global orientation and a rigid structure with a detailed and deep division of work tasks. A high degree of horizontal and vertical complexity, teamwork and professional management are also characteristics of large organizations. On the other hand, small organizations have a regional or local orientation, organic and flexible structures that are usually very simple, and entrepreneurs, i.e. most often the founders of the organization (in the context of this research: mayors), have strict control and hold key roles within the organization. Small organizations are characterized by jobs that have a wide range of activities and tasks to be performed, while in large organizations executors need to perform usually one or a smaller number of specialized tasks [4].

The scope of large cities is also determined by the Law on Local and Regional Self-Government. In their self-governing scope, they perform tasks of local significance that directly meet the needs of citizens, especially tasks related to: organization of settlements and housing; spatial and urban planning; communal economy; child care; social welfare; primary health care; upbringing and education; culture, sports; consumer protection; protection and improvement of the natural environment; fire and civil protection; traffic; maintenance of roads; construction and location permits, other acts related to construction, and implementation of spatial planning documents; and other activities in accordance with special law regulation.

To perform these tasks, the state-of-play is that the most common occupational profiles are social profiles, and to some extent also the profiles of the technical profession. As a support (backoffice), there is a need for a profile of experts in the field of information and communication technologies.

3 SPATIAL DATA MANAGER PROFILE

To properly define the profile of spatial data managers, within this research, the labor market is analyzed, which sets requirements for future staff. Business social networks and global employment portals, as well as the national labor market in the Republic of Croatia, were reviewed by searching published job vacancies through the official employment office, and well-known employment portals Moj-Posao.hr [5], and Posao.hr [6].

On the LinkedIn business social network [7], examples of job advertisements for vacancies such as Geospatial Data Analyst, Geospatial Data Manager, Geospatial Operations Analyst, GIS & Location Analytics Manager can be found. In addition to the LinkedIn network, similar examples of job ads can be found on the global portal indeed.com, such as GIS Manager.

The profile of spatial data managers, and synonyms, in the world, from the analysis of processed job ads includes experts with the following common characteristics: technical background of education, skills in computer operations, work in GIS environment, knowledge of spatial data processing, soft skills - primarily communication.

Furthermore, on the employment portals in the Republic of Croatia, and on the official web portal of the Croatian Employment Service [8], for the following searches by keywords, the results do not appear or the results that appeared are not relevant (not related to spatial information management): *spatial information management; GIS expert; spatial data manager; spatial data* (for the purpose of expanding the search); *geospatial*. These keywords were searched in Croatian language as well.

Only for the keyword "geoinform" just one search result appears, which we can say is relevant - expert associate in the Department of Geoinformation System Development at the Central Bureau of Statistics. This shows that in the Republic of Croatia the profile of "spatial information manager" or "spatial data manager" is not recognized by employers.

State-of-play with a job positions in this profile is currently such that in the Republic of Croatia there are experts employed in local governments working on spatial information management, but these jobs are not formalized by systematization of work, or regulations on job titles, or regulations on internal organization. The formal names of these positions are more traditional, like geodetic expert, etc.

4 KEY TASKS OF SPATIAL DATA MANAGER

The tasks of spatial data managers in local self-government could be categorized into several categories. As in all organizations, there are the most important basic tasks - key (core), then tasks that due to their knowledge, experience and competencies the employee performs, and background tasks that relate to the necessary tasks according to internal procedures of the organization. These background tasks consider certain records and reports about their own work, e.g. records of business trips. The subject of this research are just key (core) tasks which can further be categorized into several categories as well.

4.1 Special Projects

The basic task of the spatial data manager is establishing a spatial information management system for various purposes, as well as its maintenance and upgrade. Some examples of such works realized in the representative institution - City of Požega are: establishment of GIS for communal taxation; design and implementation of the Unified database of unclassified roads; establishment of a spatial register of real estate owned by local self-government unit; establishment of a cadastre of telecommunication lines with participation in negotiations; development of web applications for citizens; establishment of the Communal Infrastructure Register.

These are directly obligatory for local self-government units according to certain legal provisions. Thus, the establishment of a real estate register owned by local self-government units is regulated by the Decree on the State Property Register [9], which regulations define the obligation for local self-government units in the development of real estate registers. Furthermore, the current state of technological development imposes the establishment of, no other than, a spatial real estate register in digital form. The establishment and maintenance of the Register of Communal Infrastructure is mandatory in accordance with the Law on Communal Economy [10]. The structure of the register is prescribed, i.e. the data that the register must contain are defined. The basic data in this case is the spatial reference in the form of the cadastral parcel. So, the logic to apply is also to establish indeed a spatial register in digital form. Local self-government units must establish and maintain a database of unclassified roads, in accordance with the obligation prescribed in the Law on Roads [11]. This database enables and simplifies the process of creating acts on city council regarding unclassified roads. This is an obligation under the same Law, but local self-governments are also encouraged to establish such a database with the propositions of various tenders for financing and co-financing of infrastructure investments. Therefore, without the list of roads in the formal Act, which arose from a database of unclassified roads, it is not possible to apply for investment co-financing in the construction of a particular road, and thus it has a direct impact on the development of the city.

There are also tasks that are not directly stipulated by law but are necessary for the practice of a good management of the city. An example is the establishment of a cadastre of telecommunications lines. Such a cadastre is necessary for the local self-government because it determines the condition of the length of telecommunication lines on cadastral parcels owned by the local self-government, and property relations and positive regulations stipulate that the local self-government has the right-of-way compensation from the operator, or the owner of the telecommunication underground infrastructure. Some examples of the establishment of such a cadastre of telecommunication lines show positive consequence as a direct increase in revenue from compensation fees based on increasing the total length of lines for which it is paid for. The increase in representative institution was as much as 31 km [12].

All mentioned special project tasks are certainly a necessity for the realization of efficient management today for every local self-government unit, and their implementation is imposed with the inclusion, participation and guidance of the profile of spatial data managers.

At the same time, there is an issue that most of legal regulations do not explicitly state that prescribed registers and obligations consider that they are in fact spatial registers, although it is clear that all these databases contain entities located in space, and the main reason is to have an overview of them in georeferenced way. This fact is one of the obstacles in formalizing the occupational standards of spatial information or spatial data managers, and their recognition in the labor market by employers.

4.2 Regular Tasks

The key tasks of the spatial data manager, in addition to the above-mentioned special projects, also include regular daily tasks, which can be divided into several different types of tasks as in Tab. 1.

Repeating tasks are those everyday minor tasks that employee typically perform.

As the main work tasks in local self-government, various reports, reviews, and analysis generally appear. Given that a large part of the institution authorities can be related to spatial data management, the spatial data manager is mainly in charge of preparing and conducting analysis. He should have analytical and statistical skills. As with the above-mentioned repeating tasks, each of the analytical tasks is based on the obligations defined in the positive regulations of the Republic of Croatia.

Typically for technical staff in public administration, a significant part of the work tasks is related to the support of other departments in the organization. It has already been mentioned that in one local self-government it is possible to have various departments and sections as internal organizational units. For example, the Department of Finance, which keeps analytical records of assets as part of the balance sheet, regularly needs to provide excerpts from the Spatial Real Estate Register, given that real estate is the most valuable assets. Also, the up-to-date status of the Real Estate Registry is important to the Department of Finance because the value of the property has an impact on the credibility of the institution. Furthermore, when resolving ownership relations, and when disposing of real estate, the department that announces and conducts tenders must be served with data about characteristics for individual real estates (spatial-planning purpose, existence of infrastructure, zoning, etc.).

Table 1 Types of regular tasks

Task type	Tasks examples
Repeating tasks	System maintenance-inserting new data, data updates
	Forms development
	Spatial planning procedures involvement
	Asset management
	Cadastral and land book procedures for the city
Analytics	Investment justification analysis
	Report about state of space
	Revision reports on ownership objects
Support to other departments	Technical background design for EU funding applications
	Different drawings and spatial maps creation
	Preparing data (spatially related) for public procurement
	City council materials preparation (maps, visualizations, etc.)
Strategic level tasks	Suggestions for National physical plan in prescribed format (GML)
	Participating in development of Strategy for management of city real estate
	Participating in development of Traffic Masterplan
Other tasks	Negotiations with different external authorities
	Acquiring different official documentation for construction
	Coordination with building process stakeholders
	External database inputs

An important task of spatial data managers in local self-government is to participate in work at the strategic level. This requires knowledge of the situation in general, knowledge of public policies, and setting goals for the improvement of a certain part of processes under the authority of the organisation. This requires knowledge of the organization's capacity, as well as methodologies for drafting strategic documents, and knowledge of state-of-the-art technologies for drafting proposals for concrete measures, but also the necessary investment to solve identified problems. The strategic level considers the use of managerial skills and knowledge of the state of the profession even more than it requires technical skills. This shows, on the example of a city from the category of large cities, i.e. medium-sized organizations (see Chapter 2) that the spatial data manager in local self-government in the Republic of Croatia needs both, specific technical knowledge and narrow specialization, as well as broad management knowledge and soft skills.

4.3 Categorization of Key Tasks by Required Competences

To relate the occupation of spatial data manager in the local self-government and the tasks he or she performs, with the required qualifications, a categorization of key tasks with emphasized related competencies is created (Tab. 2).

For the categorization of tasks by required competences, the information from the City of Požega regular work processes were analysed. The documents, existing domain regulations, work systematization and work inputs and outputs were considered, and with deduction and experience of all authors based on the knowledge about work processes in similar organizations, and in City of Požega as sample organization, were synthetized to categories. The mapping process was not simple and straightforward. Certain tasks can belong to several categories, and in that case such a task is classified into a category according to its predominant characteristics and required competencies.

The categories by competences are divided into 1. development, 2. Maintenance and upgrade, and 3. Usage and manipulation. Those categories are then mapped to required competences which are divided by the way of gaining the competence (Tab. 2).

Table 2 Categorization of tasks by competences

Category and mapped type of task	Competences gained through	
Development - 4.1 Special Projects	Existing education programmes	General competences: Command of computer usage, CAD and GIS software usage, database knowledge, spatial data processing, knowledge of English Specific competences: data modelling, query language, topological data processing, knowledge of spatial data formats, basic geodetic principles, knowledge of spatial data reliability, accuracy, and precision Cartographic rules knowledge, spatial referent systems
	Long-life learning	Knowledge of UML (both class diagram and activity diagram), computer networks basics, mapping spatial data applicability in different work processes, ability to interpret correctly domain laws, fast cost/benefit decisions on certain operations, quality control methods, familiarity with state-of-play and state-of-art in geospatial technology, familiarity with norms and standards (OGC, ISO, INSPIRE)
Maintenance and upgrade – 4.2 Repeating tasks – inserting data Other tasks – external database integrations	Existing education programmes	General competences: Command of computer usage, CAD and GIS software usage, database knowledge, spatial data processing Specific competences: Cartographic rules knowledge, topological data processing, spatial data formats, basic geodetic principles, knowledge of spatial data reliability, accuracy, and precision
	Long-life learning	Computer networks basics, intermediate knowledge of web technologies, ability to use API or software plugins for web app development
Usage and manipulation – 4.2 Analytics, Support to other departments, Strategic level tasks, Other tasks	Existing education programmes	General competences: Command of computer usage, CAD and GIS software usage, good command in MS Office package Specific competences: GIS analysis, multi-criteria analysis, cartographic rules, knowledge of SDI, ability to use web services, basics of real property evaluation methods
	Long-life learning	Statistics, data visualization skills, knowledge of reporting rules, orderliness, self-control methods, ability to understand needs even when they are not clearly communicated by the superiors, knowledge of regulations, good knowledge of office administration procedures, good knowledge of organization of the state and public institution division of authorities

5 DISCUSSION

Considering previous categories of tasks and required competences, for defining the profile of spatial data managers in local self-government, two possible theses appear - one is in the direction of creating a unique comprehensive profile, and the other is in the direction of specialization of the profile of spatial data managers in local self-government. From the analysis of required competencies and job descriptions presented in this paper, we conclude that two specializations are potentially possible – an engineer developer and an advanced user of spatial data.

5.1 Unique Comprehensive Profile

It is already clear that extensive and broad knowledge, an interdisciplinary approach to problem solving, and knowledge of various professions are required to perform spatial information management tasks in local self-government units.

As an argument that supports this profile, it is possible to briefly describe the process of establishing the cadastre telecommunication lines under administrative area of the representative organization - City of Požega.

The City of Požega charges a fee for the establishment of right-of-way for telecommunication lines based on the valid Agreement with the operator, and based on the estimated length of lines, and a later supplement based on geodetic survey of existing lines. The task was to determine all lines laid under the ownership of City of Požega in order to determine the length or area of easement. Only after determining the existing situation based on available data, it will be possible to start arranging the relationship with the infrastructure operator with exact new numerical data.

In the procedure, it was necessary to recognize the need and define the project task, to know the methodology and architecture of the systems already established in the City administration, as prerequisites for this task.

The list of parcels with line lengths in the survey reports does not contain all parcels owned by the City on which the lines are, due to the passage of time and other circumstances. In the overall procedure, the person who manages the spatial information in the City of Požega recognized the need to update the list of lines based on the same survey reports. Furthermore, it was necessary to analyse and process the input data of survey reports, created by classical geodetic survey and present in the classical dwg files, with corresponding Excel tables.

In the process, the input spatial data were in the HDKS (old Croatian official coordinate reference system) and it was necessary to know and operationally carry out the process of transformation into the new coordinate system HTRS96 (Croatian Terrestrial Reference System 1996 – new official CRS), using the software which is available in the organization. After processing the input data, the next step was to conduct GIS analysis and spatial intersection of several layers with selected entities that were previously defined. Through the process, it was necessary to identify and appropriately address special cases such as the mismatch of the administrative border and the border of the cadastral municipality which do not always coincide, and cases in which parts of one cadastral parcel represent several different categories of roads (i. e. they are under different regimes). This presupposes knowledge of various areas and road management, and administrative arrangements, and regulations of land registry law and the establishment of easements. From the completed task, it was further necessary to create a clear report, and a clear list of telecommunication lines to update the easement agreement with the operator, so that the same report is a clear proof and basis for clear and effective communication in negotiations with the operator. The spatial data manager was in charge of approaching the telecom operator in negotiations as well.

The whole described process of this single example, argues in favour of defining a unique profile of managers who should have almost all the competencies that can be found in Chapter 4.3, i.e. to know classical geodesy, GIS analytics, model and structure of other related systems, to widely know the regulations of many technical and other areas in order to link and recognize the need to carry out this task, the ability to decide and choose the methodology, to actively use GIS tools to implement the process, the ability to compile concise report, communicate and negotiate for a complete process leading to the final result, which is increase of revenue.

5.2 Specialization of the Profile of Spatial Data Manager

Considering the task categories from Chapter 4.3, and the necessary competencies, we can conclude that it is possible to develop two specializations of the spatial data manager profile.

5.2.1 Advanced User of Spatial Data

The first specialization could be called "advanced user of spatial data in local self-government". This specialization is characterized by tasks which could be defined as maintenance and upgrade, as well as use and manipulation tasks. It is clear that these categories have in common a group of competencies, in fact the traditional, classical geodetic group of competencies - CAD and GIS software, knowledge of the basics of geodetic principles, understanding of reliability, accuracy and precision of certain spatial data, skills in other software which are widely used such as Excel, and to a certain extent the basics of computer networking and the basics of web technologies, which are the skills that are acquired at the basic level on higher education institution (faculty). This specialization of spatial data managers is more oriented to the usage and manipulation of already established spatial information management systems, but in various applications. This type of professional acts more as a service staff who serves and provides support to other areas of authorities in the local self-government.

5.2.2 Engineer Developer

This specialization is characterized with knowledge specific for modern studies of geoinformatics (with emphasis on informatics and data modelling). The engineer developer has the role of developing new spatial information systems. He also needs to have a broad knowledge of different areas, to be able to connect needs, rules, and final solutions that bring improvement of work processes. It is not so crucial to know the classical geodetic principles for this specialization. For development, the emphasis is on the database, and on data modelling, not just class modelling, but also workflow diagrams, as well as knowledge of higher geodesy. It is necessary to know the standards and norms, and to have the way of thinking at the program and strategic level.

5.3 Forming (Educating) Spatial Data Manager

From the conducted analysis, it is evident that the profile of spatial data managers by the name is not recognized by employers in the Republic of Croatia. This leads to a mismatch between supply and demand in the labor market. The employers have the need for the experts with competences of this kind, which is proven with wide range of tasks described in Chapter 4., but still, they do not have common information about what kind of qualification degree which would comprehend all the necessary competences should they seek.

The process of modernization and reform of the qualification system in the Republic of Croatia is carried out through the Croatian Qualifications Framework – CROQF [13], which establishes a mechanism for recognizing the mismatch between supply and demand for workers at the level of competencies.

In order to harmonize the supply and demand on the labor market in accordance with the CROQF related to the geodesy and geoinformatics sector, i.e. the area of spatial information or data management, it is necessary for employers to recognize the possibilities of this profile of employees and to develop occupational standards. From that, it is then possible to develop a qualification standard for the profile of spatial data manager, or its specialization.

Occupational standards and qualification standards have been introduced in Croatia through the CROQF, which can cover all levels of education. The Occupational Standard is defined by law as a list of all jobs performed by an individual in a particular occupation and a list of competencies required for their successful performance, while the Qualification Standard is defined as the content and structure of a particular qualification. It includes all the information needed to determine the level, scope and profile of the qualification and the information needed to ensure and improve the quality of the qualification standard. According to the Rulebook on the CROQF Registry, the occupation standard contains a list of key jobs in one or more jobs that define the occupation and associated individual competencies and a list of sets of competencies and related individual competencies required to work in one or more jobs. Therefore, occupational standards should contain a list of key tasks and a corresponding list of competencies, and a list of competency sets with associated individual competencies required in a particular occupation [14]. From this it is further possible to develop a standard of qualifications.

In order to develop qualification standards for spatial data managers in local self-government, it is necessary to monitor the necessary competencies, and take into account the fact of the need to increase the importance of informatics in the coin "geoinformatics" or "geomatics". Also, the spatial data manager is a multidisciplinary occupation. There is a strong focus on new technologies and the need to gain knowledge, especially the fast-growing Industry 4.0 (Cloud, Internet of Things, Big Data, Artificial Intelligence), and new 5G technologies. These topics will certainly need to be addressed when developing the qualification standards of spatial data managers in the local self-government, otherwise the developed qualification standard will become obsolete at the same moment when it is defined.

Recently, because of the digital transformation process, the activities in local self-government units on the development of smart cities (SmartCity concept) has intensified. The solutions commonly applied in the transformation of cities into smart cities, mainly relate to information systems with a spatial component, because space is the largest and most important resource available and managed by a city. In this trend, geodetic and geoinformatics experts can see the opportunity and apply their knowledge and increase the share of their activities within the system of local self-government units, unlike the previous paradigm of geodetic staff, where the largest share of professional geodetic and geoinformatics staff worked in the state administration, i. e. the cadastre [15].

Accordingly, great significance in the future education and qualification standard of spatial data managers needs to be given to technologies belonging to Industry 4.0.

Finally, the strategic framework in the Republic of Croatia defines the need for new qualification standard development harmonized with the needs in economy. Smart Specialization Strategy (S3) [16] is an integrated strategic document for economic transformation of Croatia based on new emerging technologies and innovation. That document mentions that lack of skilled labor is the second most significant obstacle to innovation, although only 44% Croatian companies acknowledge that they have difficulty finding a skilled workforce. According to the study, employees often have a lack of experience (80%) or the education system does not allow them to acquire the necessary skills (40%). In terms of human resources, the Republic of Croatia is going through a difficult and slow transition, primarily due to the recession created long-term unemployment and reduced the relevance of workers 'skills also due to very slow reforms of the education system that continues to produce qualifications that are not in line with labor market needs. Combined with low investment in lifelong learning in general, skills structure has become a limiting factor for the development of competitiveness, innovation and growth. The conclusion is that there are not enough study programs, i. e. qualification standards for the adequate occupations of the new modern employer's needs.

Furthermore, Industrial Strategy of the Republic of Croatia [17], as the second priority defines encouraging strategic cooperation between industry and the education system, science and technology. Knowledge, skills and abilities of human resources are the basis for achieving a competitive advantage of companies, industry and economy. The greatest contribution to the development of industry and the economy of the state can be made through a quality education system. The basis for attracting any investment, with a stable political and macroeconomic environment, lies in the availability of an educated workforce. It is important that the state directs investments in the education system in areas that are important and necessary for the future needs of industry development. Given the rapid and frequent changes that occur in the environment, and thus create a continuous need for new knowledge and skills, it is extremely important that the education system "collects" information from the environment and industry and continuously adapts the education system to new knowledge needs, with the aim of encouraging new employment through new knowledge.

The Strategy for Education, Science and Technology [18] as primary goal for high education stipulates the need to harmonize the number and profile of study programs social and economic needs.

Forming (educating) the spatial data manager, i. e. development of qualification standard for spatial data manager is in line with all those strategic documents.

6 CONCLUSION

Local self-government units in the Republic of Croatia are characterized by quite heterogeneous internal structures. Nonetheless, they all share a wide range of different authorities. The most important activities which are conducted within authorities are related with spatial management as the most important resource of a city or municipality. Accordingly, there is the need for qualified staff for spatial information management. In the Republic of Croatia, such staff as a spatial data manager is not clearly recognized by employers, despite the fact that such qualified staff "covers" many tasks, from special projects to establishing certain spatial data management systems, analytical work, data service support and information for other departments within the local government, to work at the strategic and program level. The employers evidently have the need for human resources with this kind of competences, but it is not clear for them which formal qualification degree should they seek.

It is important to point out that the categorization, but also the nature of tasks due to the autonomy and heterogeneity of local government can be different. This research presented a realistic comprehensive example of tasks and work processes involving staff who can identify with the future spatial data manager. For the efficient development of standards for the qualifications of spatial data managers in the higher education system, it is necessary to consider the highlighted needed competencies, and to develop a standard of occupation. It should be noted that the interdisciplinarity is a common feature of all tasks of spatial data managers. It is necessary to cooperate across various professions and areas to achieve comprehensive approach. The essential competencies of thinking at the strategic level, reporting rules, data modelling and process flow, and familiarity with many related mainly technical professions, as well as strong knowledge and law interpretation skills, are emphasized as a novelty in the required competencies list.

In the future education and design of qualification standard of spatial data managers, 4.0 Industry themes should be significantly represented since geodetic profession is by nature technologically oriented and technologically advanced. Moreover, the geodetic profession is intensively developing in the direction of emphasis on geoinformatics, or geomatics.

Ultimately, by setting up spatial registers and the right approach in using existing data and available spatial information management technology, it is possible to achieve direct effects of increasing revenues for budgets, as shown by one example. This indicator clearly proves the need for today's trends in local self-government units to go in the same direction, which is regular structuring of existing data into spatial registers in order to directly contribute to the budget with the help of GIS spatial information management technology. Finally, financial benefit is the strongest argument for decision makers. All tasks that belong to the domain of spatial data managers in local self-government either contribute directly to the financial benefit for budgets, or are conditioned by mandatory regulations, and therefore the recognition of spatial data managers in local self-governments and occupation standard development should not be difficult to realize.

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Preliminary communication

Autonomous Charging of Electric Vehicles in Industrial Environment

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Abstract: Modern industrial manufacturing involves several manually and automated driven vehicles - not only for logistics and production purposes, but also for services, maintenance, resources supply and cleaning. These different types of vehicles are increasingly driven by electric powertrains that operate in the production halls, warehouses and other involved areas. Today, electric charging of these mobile devices is accomplished mainly manually and by use of a number of different not standardized charging interfaces, which leads to increased time and cost efforts. The paper evaluates different charging technologies for the use in industrial environments and introduces a new approach for automated, robot-controlled charging of electric vehicles, which is based on a standardized charging interface. The technology has been developed to fully automated charge different types of cars and other vehicles and consists of a vision system to identify the vehicle and the charging connector position in combination with a fully-controlled robotic system that plugs-in and -off the charging connector. In this way, the system is universally applicable for different types of autonomously and manually driven vehicles in a professional context, e.g. in production, logistics and warehouses.

Keywords: automated charging; autonomous driving; electric vehicles; industrial services; robotics

1 INTRODUCTION

Electric propulsion systems in mobile industrial applications have a long tradition and can be found in multifarious types of use. Fig. 1 shows selected examples of electrically driven vehicles as they are applied in logistics, manufacturing plants and other types of professional facilities. Besides transportation systems, e.g. fork lifters, logistics manipulators and floor-borne vehicles, further applications are common, e.g. cleaning, maintenance and service inspection.

Figure 1 Exemplary manually driven electric vehicles for professional applications [1, 2]

In the past years, robotic systems are increasingly used in industry and logistics, e.g. for moving materials and components, in warehouses and also for services and cleaning. Fig. 2 shows a selection of fully automated vehicles for industrial use.

Figure 2 Selection of autonomous industrial robots [2, 3]

Regardless of manually or autonomously driven, the powertrain of such vehicles includes an electric energy storage system, typically based on high voltage lithium-ion technology, power electronics, electric motor(s) and a vehicle controller, an electric converter for charging, and eventually wireless data communication. As a status of today, the vehicles are charged by manually plugging-in charging cables or by use of type-specific charging sockets, being connected at a defined vehicle parking position. Especially for self-driving vehicles, manual charging represents a very non-practical approach, but also human-driven vehicles would benefit from a universally applicable, automated charging solution. Previously used company- and vehicle type-specific charging sockets come with the disadvantage of non-universal applicability and these systems are not certified for general use. In this context, it is a target of research and development activities to provide a universally applicable fully-automated charging solution that makes use of a robust and standardized charging interface. One of such solution has recently been introduced by the company Cleanfix [4]. This system combines a standardized charging interface from the automotive industry with a robotic arm to charge an autonomous floor-cleaning vehicle. In addition, services can be provided during the charging process, e.g. draining of waste water and refilling of fresh water for the next cleaning sequence.

Robotic service vehicles in industrial applications only make sense in combination with fully autonomous charging technology. And even for manually driven vehicles, the use of automated charging has a great potential to support safe operation and efficient processes. In this context, the present publication introduces results of a research project, which was focused on the development of a fully-automated charging system for a broad range of applications [5].

2 OVERVIEW OF ELECTRIC VEHICLES CHARGING TECHNOLOGIES

Various techniques enable electric charging of vehicles. In the following, the three most important charging principles with potential for automation are presented: conductive charging, inductive charging and battery swapping.

2.1 Inductive Charging

Inductive charging enables wireless power transfer and is derived from the basic principle of a transformer, where energy transfer is provided via two oppositely positioned coils. Today, the technology is common in different consumer products with relatively low transfer power, e.g. smart phones or toothbrushes. In the case of vehicle charging, higher charging power is required, which arises several challenges. The arrangement principle of inductive charging systems for vehicles is similar to those of consumer product solutions: a primary coil is stationary installed at the charging station and a secondary coil is mounted at the vehicle's underbody. Advantages of this technology include contactless charging and high comfort, because no manual operation is necessary for connection. Furthermore, there is a low risk of unintended damage or vandalism because the system does not involve freely movable cables - just flat plates at the station and in the vehicle. Weaknesses of inductive charging are based on the electric principle of inductive power transfer. In this way, charging efficiency decreases with the size of the air gap between the coils and potential deviations of centric positioning of the charging pads. In addition, electromagnetic radiation is produced, which can lead to problems regarding electromagnetic compatibility (EMC). While progress in research and standardization is done towards higher charging power for automotive applications, maximal charging power is restricted to 3.6 kW today because of both EMC and the limited size of the charging pads. Nevertheless, there are a few applications in the automotive industry, e.g. introduced by BMW, Fig. 3 [6]. Because of limited charging power, issues with highly accurate positioning and relatively high system costs, inductive charging has not been considered as an option for an industrial applicable automated charging system in the course of the present research project.

Figure 3 Serial application of inductive charging of cars [6]

2.2 Battery Swapping Systems

In battery swapping stations, the empty battery is decoupled from the vehicle and replaced by a fully charged battery unit. The battery exchange process takes just some minutes and the vehicle is ready to go. In the station, the battery can be recharged, checked for proper functionality and then provided to be implemented into another vehicle. In this way, battery swapping stations seem to be an attractive alternative to fixed mounted vehicle-internal batteries. The technology has been tested in the automotive industry since several years, e.g. by the company Better Place in a joint project with Renault [7]. A Chinese car manufacturer, Nio, has introduced battery swapping in mass production cars recently and also provides a number of battery swapping stations in large cities and on main highways, Fig. 4 [8]. Challenges and limitations of this technology are characterized by the relatively high investment to make the system running. Besides an automated robot-controlled battery swapping mechanism, a number of pre-charged batteries have to be provided to enable uninterrupted operation of the system. In addition, the vehicles have to be prepared for battery swapping, which requires stiff vehicle structures as well as a specific design of battery mounting and connecting systems in the cars. Finally, the battery swapping system has to manage and provide different battery sizes and formats to support all vehicle types involved. Because of these limitations - especially the high investment costs and the limited variability in view of servicing different vehicle types with varying battery sizes, this technology has not been considered as an option for an industrial applicable automated charging system in the course of the present research project.

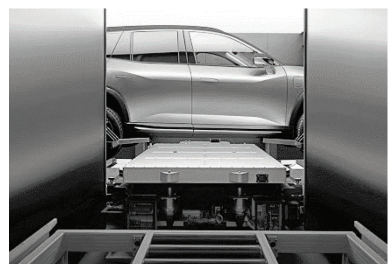

Figure 4 Serial application of automotive battery swapping [8]

2.3 Conductive Charging

Conductive charging is characterized by direct electric connection by use of cables or specifically designed conducting elements. Due to the direct flow of electricity, high power can be transferred with very good efficiency. In this way, modern conductive charging systems enable up to 43 kW alternating current (AC) and 500 kW direct current (DC) charging power. Once the connection is established, the power transfer is safe and reliable. In general, conductive charging technologies distinguish between underbody coupler and so-called side-coupler. A special case represent pantograph systems with coupling over the vehicle's roof. This technology is well-known in railway systems and now under development for heavy truck and bus applications. Due to the large size of the pantograph systems, they are not considered further in the present work.

2.3.1 Conductive Underbody Coupler

Underbody coupler consist of a movable or fixed charging device that is placed on the floor of the charging station and a movable or fixed opposite unit mounted on the underbody of the vehicle. Entering the charging station, the vehicle is placed in a way that both units are aligned, whereas parking misalignments of about 0.5 × 0.5 m are allowed.

Connection is established by the motion of a connector at the movable unit onto the fixed unit. Fig. 5 exemplary shows two underbody coupling systems: The matrix-charging system from Easelink [9] has a moveable trunk mounted in the vehicle, which "screws" down to a fixed plate on the floor for contacting. The Volterio system does it the other way around: a robotic arm, mounted on the floor, moves up to a fixed connector in the vehicle [10]. Underbody couplers have the advantage of robustness and safe operation, because there are no cables hanging around. However, the integration effort is relatively high. In case of technologies with moveable stationary units, the robotic kinematics and control is complex, and in case of moveable units in the vehicles, the vehicle integration requires installation space and complex control of the kinematics. These aspects might be the reason why underbody coupler technologies have not been brought into mass production vehicles so far. In case of professional use in industrial environment, underbody coupler cannot be used for some specific vehicle types, e.g. flat manipulation robots or cleaning machines. For this reason, they are not considered further as a potential technology in the present project.

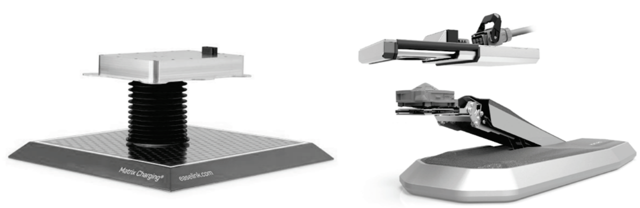

Figure 5 Underbody coupler charging system of Easelink [9], left, and Volterio [10], right

2.3.2 Conductive Side Coupler

Manual conductive side charging by use of cables and plugs is the most common method today. In automotive applications, different standardized interfaces are used, as exemplarily shown in Fig. 6.

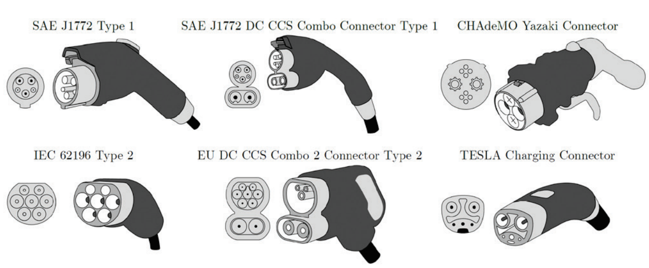

Figure 6 Selection of standardized charging interfaces in automotive applications [11]

Standardized interfaces provide several advantages, such as compatibility, certification for predefined charging voltage and current as well as broad availability of systems and components. In the present work, the Combined Charging System (CCS) Type 2 system [12] was considered in more details. This interface enables both AC and DC charging, and that with a wide power range of up to 30 kW for AC and up to 350 kW for DC at a voltage level of up to 1000 V. The interface design is standardized according to the IEC 61196 and the operational use is certified according to IP44. Besides transfer of energy, the interface also allows communication and data exchange, e.g. between the charging station and the vehicle according to the IEC 15118. In this way, the CCS Type 2 is not only applicable for automotive charging, but also for the use at commercial vehicles and in industrial facilities.

While conductive charging standard interfaces have been developed to provide a safe and reliable charging connection by manual operation, they have not been developed for automated robot-controlled plugging. This brings several challenges for the development of automated charging systems, because design details of the connectors hinder smooth automated plug-in and plug-out processes. Exemplary, pre-positioning of plug and socket is not supported by markers or lights, so that an automated charging device has to operate with highly accurate vision systems, able to deal with different surface- and light- conditions. In addition, the shapes of plug and socket are not optimized for automated fitting, e.g. by use of tapered or conical wall shapes that would support self-centering effects. Contrary, the walls are designed in parallel to the moving direction and do not support the fitting process. In this way, the development of an automated robot-controlled charging system represents a challenging task and requires to integrate a precise sensor system for position detection and control in combination with an accurate robotic actuation system for conduction of the necessary motion during the plug-in and plug-out sequences. Due to the high complexity, no serial production system has been introduced so far. However, different car manufacturer and supplier have published their research and development activities in this field during the past years, e.g. Volkswagen [13], Tesla [14], Kuka robotics [15]. Fig. 7 shows a selection of prototype systems for conductive side coupling.

Figure 7 Selection of prototype systems for conductive side coupling. Left: Tesla charging snake [14]; middle: VW charging robot [13]; right: Kuka Carla charging connect [15]

3 AUTOMATED CONDUCTIVE CHARGING SYSTEM USING STANDARDIZED CONNECTORS

The different charging technologies, introduced in section 2, have been evaluated regarding their potential use in large-scale industrial applications. Boundary conditions for the evaluation included:

- Compatibility with different types and sizes of electric vehicles
- Compatibility with both manual driven and fully autonomously operating vehicles
- Safety and reliability of the technology
- Easy operation and maintenance

- Costs of installation, investment and service
- Availability and maturity of the technology.

As a result, the conductive charging technology with standardized interfaces reached the highest scores and has been selected for further consideration. Convincing strengths of this technology include the applicability for a fleet with very different types of vehicles (referred to Fig. 1 & 2), the possibility to use proven standardized interfaces from the automotive sector, low electrical losses and EMC in operation as well as high safety and reliability of the technology. In addition, state-of-the-art charging converters can be applied and installation, operation and maintenance can be conducted with reasonable effort. One critical aspect in the evaluation included the missing maturity of the technology: automated conductive coupling with standard interfaces is not available as a mass production product and thus beyond today's state-of-the-art.

In this context, this publication introduces results of a research project that focused on the development of a fully automated charging robot, using the CCS Type 2 standard interface [16-18]. The charging robot consists of a vision-based sensor system, a 6-axis robotic arm including a CCS plug as well as a system control unit.

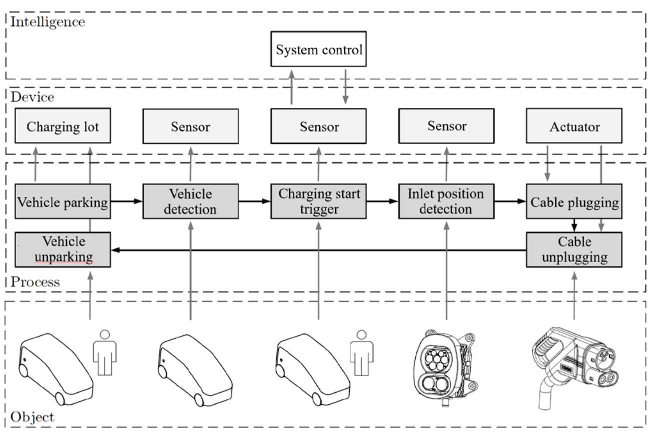

Figure 8 Overview of the automated conductive side coupler charging system

Fig. 8 shows the operational sequences of the automated charging process, including involved components. "Sensor" represents a camera system, "Actuator" the robotic arm and "System control" represents the station controller, including data communication interfaces. As a part of the charging process sequence, the "Objects" are represented by involved manually or automated controlled target vehicles, and in subsequent phases of the plugging process by the charging socket and the charging plug.

At the beginning of the charging process, the target vehicle approaches to the charging station and parks in a pre-defined position. Due to a given operating range of about 1 meter, different types of vehicles with different charging socket positions can be processed. It can be stated that the necessary parking position accuracy is relatively low in comparison with inductive or conductive underbody coupling. The charging system detects and identifies the vehicle on the spot by use of a camera-based object recognition system and allocates the specific vehicle characteristics from a database. In this way, vehicle charging requirements are set, e.g. actual position of the charging plug or electric parameters of the charging process. In the next step, the charging process is started; this can be done manually or fully automated - depending on the type of vehicle to be charged. In the first step, the charging plug is roughly aligned to the vehicle's charging socket and in a second step, precisely motion sequences perform very accurately the critical plug-in process. Both steps are controlled by use of a camera-based object detection and identification system [5]. After the battery is charged to a pre-defined level of State-of-Charge (SOC), the robotic system unplugs and the vehicle can leave the charging station. The entire procedure is recorded and key data are stored in a database system to support the vehicle fleet management.

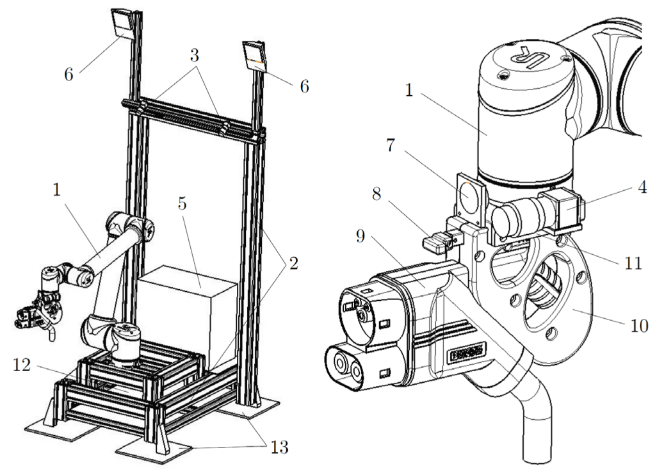

Figure 9 Left: overview of the charging station, right: connector unit with CCS Type 2 connector, camera, LED, actuator and adapters [5]

Fig. 9 shows the configuration of the automated charging station and the connector unit. The station consists of robot (1), frame (2), cameras (3, 4), robot control box (5), LEDs (6, 7), actuator (8), CCS Type 2 connector (9), two carrier adapters (10, 11), rubber damper (13) and a microcontroller board (frame-integrated, 12). The integrated robot (1) is a collaborative UR10-CB3, [19]. The 2D-cameras (3 and 4) are responsible for the identification of vehicle and inlet pose detection. Two LEDs (6) on the frame (2) and the LED (7) on the robot head tool support the vision system in case of insufficient light conditions. An additionally integrated actuator (8) enables closing of charging lids, if required. Two adapters, whereas one is made of aluminium (11), the other one (10) is made of 3D-printed plastics to reduce weight, improving robot control and cable handling, are integrated and hold the parts in a compact system that is connected with the robot. Besides this stationary configuration, the charging robot has been designed for mobile application, too (Fig. 11).

The movement of the robot head - and thus of the charging connector - results in a sum of sectional performed movements of the robotic system. The total accuracy of the movement is influenced by the accuracy of vision system, control and motion accuracy of the robot, as well as by mechanical deviation and tolerances of the components.

Additionally, influencing factors include temperature extension, vibrations and environmental impacts. All these factors have to be considered in the system control to enable safe and reliable operation.

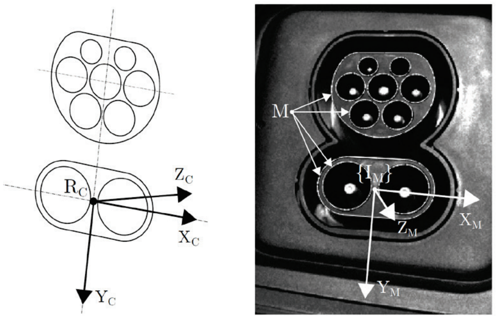

Figure 10 Left: CAD-model for shape-based 3D-matching, right: matching result of an image from the robot-head camera [5]

A specific challenge for successful operation represented the development of a highly-accurate position detection and object matching process. The matching process is based on a vision-based algorithm, using a CAD-model of the specific connector surface shape for processing in the vision software Halcon [20]. In this way, the position of the coordinate system of the shape model (X_C, Y_C, Z_C, R_C) is aligned in relation to the position and orientation of the socked in the camera image (X_M, Y_M, Z_M, $\{I_M\}$). Fig. 10 shows the CAD-model including the pre-defined coordinate system and a positive matching result during tests.

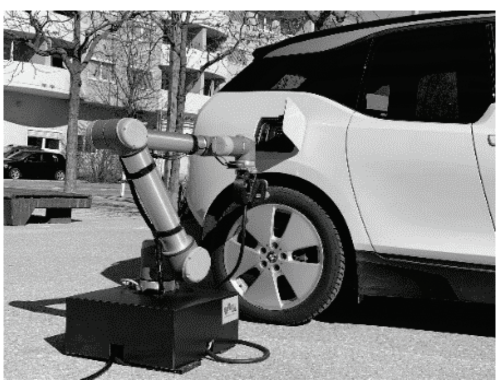

Figure 11 Exemplary test case at an electric car

The automated charging station has been tested at different vehicles under various boundary conditions in buildings and outside. It was shown that the introduced technology enables safe and reliable plug-in and plug-out processes with a very high rate of success. In case of errors (which occurred in less than 1% of the test cases), the system automatically goes back to the initial starting position and re-starts the plug-in process. The robotic system can be combined with different types of electric charging stations, according to the actual charging performance requirements. Fig. 11 shows an exemplary test case of charging an electric personal car at a parking lot and the compact design of this charging robot version. In this context, the system is applicable in various positions and can be even mounted on movable platforms or robotic vehicles to charge a number of vehicles in a subsequent order by plugging-in the cable at on car and then driving to the next one.

4 CONCLUSIONS

Automated charging of electric vehicles in industrial environment represents an important upcoming technology to enable effective operation, safe and reliable charging processes and maximum comfort. Considering emerging autonomous vehicles, automated charging is mandatory to enable holistic management of fleets. A detailed study of the different electric charging technologies showed, that automated conductive charging by use of standardized charging interfaces has the greatest potential for successful implementation. In this context, the paper presents a novel automated robot-controlled charging station that is universally applicable for different charging standards and different types of vehicles. In the present work, the station has been equipped with the CCS Type 2 connector standard. However, the technology is not limited to this example and can also be equipped with different connector standards and also different main actuators (robots). A comprehensive process has been introduced, covering all sequences of the charging process, including approaching the vehicle to the charging station, detection and identification of vehicle and charging socket, automated plug-in process, charging sequence as well as automated plug-off and vehicle exit. In addition, communication between vehicle, charging station and data management supporting comprehensive fleet management applications, has been introduced. In this way, a system for autonomous charging of electric vehicles is provided that can significantly support service and management of vehicle fleets in different types of industrial environments.

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Notice

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Preliminary communication

A Knowledge-Based Digital Lifecycle-Oriented Asset Optimisation

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Abstract: The digitalisation of the value chain promotes sophisticated virtual product models known as digital twins (DT) in all asset-life-cycle (ALC) phases. These models. however, fail on representing the entire phases of asset-life-cycle (ALC), and do not allow continuous life-cycle-costing (LCC). Hence, energy efficiency and resource optimisation across the entire circular value chain is neglected. This paper demonstrates how ALC optimisation can be achieved by incorporating all product life-cycle phases through the use of a RAMS²-toolbox and the generation of a knowledge-based DT. The benefits of the developed model are demonstrated in a simulation, considering RAMS² (Reliability, Availability, Maintainability, Safety and Sustainability) and the linking of heterogeneous data, with the help of a dynamic Bayesian network (DBN).

Keywords: criticality analysis; digital twin; dynamic Bayesian network; knowledge-based maintenance; RAMS²

1 INTRODUCTION

Today digitisation and Industry 4.0 significantly influence on management and operation of industrial companies. Over the past years, a multitude of enabling technologies for a digital transformation has been introduced to the industrial context, like Digital Twin (DT), which also raises new challenges and opportunities for asset management [1]. An efficient use of the capital-intensive resource of asset is becoming increasingly important, especially in the view of rising automation and the associated substitution of the production factor labour (human) by the production factor asset (machine) [2-4]. In addition, the digital transformation is bringing major changes to the industry through rising data volumes from networked production systems (e.g. industrial internet of things and cyper-physical production systems) and the ability to analyse them. These could be opportunities for qualitative growth and shape the idea of sustainability within a company, especially if resource consumption is reduced from an overall economic perspective and thus environmental relief is achieved through e.g. CO_2 reduction [3]. The aim of anchoring the concept of sustainability in the asset management is to minimise the cost incurred over the life cycle of an asset – life-cycle-costs (LCC). For functional asset management, it is vital to consider the entire asset-life-cycle (ALC), starting with the planning-/development- and ending with the disposal-phase. This holistic view enables a reduction of asset LCC by aligning all processes and decisions [4]. In the best case, a cooperation and continuous data exchange between the asset manufacturer and the asset operator exists. This is the basis for a transparent, dynamic adjustment of maintenance strategies, optimal resource utilisation and improved LCC with end-to-end knowledge protection using data linked across all life-cycle phases.

This paper presents the WissensFab model and addresses the concept and related steps for developing a lifecycle-oriented asset optimisation through a knowledge-based DT. This goal is achieved by a dynamic asset evaluation, considering RAMS² (Reliability, Availability, Maintainability, Safety and Sustainability) and the linking of heterogeneous data from the considered assets and their life cycles with the help of a dynamic Bayesian network (DBN) to develop a DT. Furthermore, the model is validated by means of a simulation in laboratory character with real machine data. In the run-up to the selection of the machine data, a criticality analysis of an asset park, which is part of the RAMS² toolbox was carried out by an asset operator. The most critical assets were analysed in detail and the input data (asset index/KPIs) were transferred to DT. The results of the simulation from the WissensFab model are discussed in the last section.

The paper is structured as follows: In chapter 2, a state-of-the-art analysis of the current literature in the field of DT, DBN and asset valuation is done. In chapter 3, the WissensFab model is presented in detail and its results are finally discussed in chapter 4.

2 THEORETHICAL BACKGROUND

This section looks at the theoretical background around the terms DT, DBN, asset management especially at criticality analysis and LCC.

2.1 The Digital Twin in Life Cycle Environment

Digitisation in the value chain is one of the main driving forces in the use of sophisticated virtual product models, called DT at all stages of the ALC, according to "Gartner's Top 10 Strategic Technology Trends for 2017". DT as initially defined by NASA is "an integrated multi-physics, multi-scale, probabilistic simulation of a system, that uses the best available physical models, sensor updated, feet history, etc. to mirror the life of its flying twin" [5]. Over time, this simulation-based understanding evolved. However, it is ambiguously introduced in the literature. The German Industry 4.0 platform defines a DT as the "digital representation of a […] product […] within a single life cycle or across different life cycles using models, information, and data" [6]. This means that virtual models are created from physical objects in a digital way and linked to simulate their behaviour in real environments using data streams [8, 9].

According to Grives [7], DT is composed of three components, the i) physical entities in the real world, ii) the virtual models in the cyber world and iii) the connected data linking the two worlds. Fig. 1 expands these components to six dimensions, based on Uhlenkamp et al. [8-10]. These identified dimensions are derived from frequent occurring application areas.

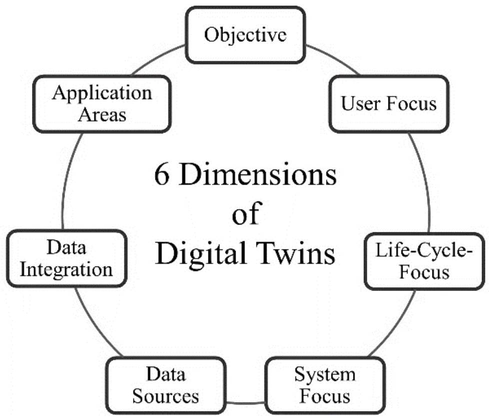

Figure 1 The 6 dimensions of DT

The application areas of a DT range from the use in i) product design [13] specifically in simulation [14], to ii) production, iii) maintenance [9] and iv) networking and communication across asset manufactures and operators [15]. The DT used in simulating production applications often includes data of the asset operators, material, equipment, tools, environment, behaviour, rules and dynamic models, derived from expert knowledge, which can be optimised by the DT [14]. A core aspect of a DT are digital and seamless information flows, which are an essential aspect [16] to efficiently and effectively run through the ALC-phases. Furthermore, the vertical data integration across the ALC-phases, as well as horizontal integration are necessary [17, 18].

For the design phase, the interaction between the physical and the expected virtual world is represented in the DT [13]. The virtual model can reflect both the designer's and the customer's expectations, as well as the practical constraints in the physical world [19]. Especially in predictive maintenance [9], the collection of static and dynamic machine information (e.g., master data and motion data) plays a crucial role, however, the collection turns out to be particularly complex. This leads to wrong results in proven analysis models, because of the missing possibility to combine static and dynamic machine data. This underlines the need to combine up-to-date data and information with the content of technical documents in dedicated analysis models [20]. The combination of these different data sources becomes even more important when a DT is used across the ALC phases. In this case, data exchange between asset manufacturer and operator is a necessity [15].

2.2 Knowledge Representation Using Dynamic Bayesian Networks

To create a DT representing the ALC, appropriate methods for linking those heterogeneous data and information sources, including a temporal dimension, are needed. In particular, to link newly extracted knowledge with prior knowledge and documented experience to achieve a higher degree of data integration, this is essential [9]. Knowledge-based methods are an essential part of artificial intelligence (AI) research, which has been increasingly integrated into production management systems in recent years, especially in knowledge-based maintenance [21, 22]. In this context, particularly in maintenance, it is important to combine various objectives from industrial companies' technical, functional and economical areas [23]. Maintenance measures that are carried out at the right time are key in ensuring the asset's availability, product quality, and process efficiency in modern manufacturing systems [24, 25]. However, it is increasingly important to add a cost dimension to these classic targets [26].

Bayesian networks (BN) are graphical methods for knowledge representation. Their advantages to other AI methods are the possibility of graphical visualisation, easier traceability of cause-effect chains, as well as the possibility of using knowledge-based inferences [27-29]. Important steps towards the use of BN in ALC-assessment have already been set by Dienst [27], as well as their use in knowledge-based maintenance [28]. Dynamic BN (DBN) can be created from an object-oriented BN (OOBN) by selecting a learning algorithm and a DBN by adding a temporal component [27]. The use of DBN for creating a DT [28] in maintenance [29] shows the great potential of this method. The possibility of semantic linkage and the possibility of generating knowledge out of the represented data are particularly noteworthy. BN is also increasingly used in product development [30] and in the design of sustainable product lines under consideration of the multi-life cycle [31].

2.3 Asset Valuation under Consideration of Life Cycle Costing

Numerous holistic approaches in asset management contribute to minimising LCC and increasing resource efficiency in asset management. One of the best-known approaches is the Total Productive Maintenance (TPM) concept. The overall goal of TPM is to maximise the asset effectiveness with respect to the entire life cycle [32]. Furthermore, the Lean Smart Maintenance (LSM) philosophy focuses on a value-added-oriented design of maintenance management. LSM is taking into consideration the latest technological advancement (aka Industry 4.0), with the goal of a resource-efficient asset management over the entire ALC (planning, use, retirement) [33]. By optimising LCC and downtime costs, LSM follows a dual approach to increase efficiency and effectiveness of maintenance [34], which are reinforced by the standards and norms ISO 55000 and DIN EN 16646. Regarding the area of sustainable development of corporate management, there are standards and norms such as ISO 14001 or EMAS, which are increasingly used in companies to consider or comply with environmental aspects.

Life cycle assessment is described by international standards ISO 14040 and ISO 14044. Furthermore, there are also legally required benchmarks, for example the European

Parliament Regulation (2018/842) which sets annual climate targets. These factors influence the company's value system, their activities to elaborate, design and steer a sustainable economic, environmental and social development [3]. Another methodology that has become established is RAMS (Reliability, Availability, Maintainability, Safety), which can be used to prevent errors already in the planning phase of projects. RAMS management ensures that systems are defined, risk analyses are carried out, hazards are identified and detailed checks and safety certificates are produced. To perform a detailed risk analysis, the first step is to identify critical assets to narrow the scope of consideration. There are some methods used to identify critical assets, such as FMECA (Failure Mode and Effects and Criticality Analysis), ABC classification [35], risk analysis [36], Analytical Hierarchy Process [35], fuzzy analysis, CEIM (cost-effective maintenance measure) [37], and Weibull analysis [38]. Another example of an already existent methodology is the criticality assessment adapted from Kinz et al. [39], which consists of the steps of asset selection, criteria assessment, identification of critical assets and detailed analyses for cost and risk reduction [40, 41]. Through the implementation of Life-Cycle-Assessment (LCA), these detailed analyses enable the consideration of environmental goals and contribute significantly to a holistic decision-making process. An experience-based assessment methodology causes human errors and long decision paths due to uncertainty of the people involved. The more important it is to reduce the human influence and to carry out the assessment automatically, based on quantitative criteria [42].

The methodologies currently used in literature usually only shed light on maintenance per se and its impact on the asset availability. Factors such as data quality, production, company- and sustainability-related influencing factors are disregarded, as shown in the work of Adams et al. [43], Bharadwaj [44] and Crespo Marquez et al. [35]. Usually, two criteria (extent of damage and probability of failure) are used for the evaluation [45]. A holistic view of the organisation and all influencing factors (costs, quality, sustainability, time and flexibility) on maintenance by integrating them in the asset evaluation is currently not existent. The need for such an easy-to-use, quantitative, dynamic, data-based assessment methodology has been identified in the literature, but does not yet exist [46].

In summary, it is noted that currently:

- The experience-based assessment is in the foreground in the literature and no standardised procedure model for criticality assessment based on the existing data quality and complexity of the company exists.
- Furthermore, the combination of criticality assessment with RAMS^2 (RAMS & Sustainability) methods with a DT using DBN, is completely new.

3 WISSENSFAB MODEL

The WissensFab model fills the gap by leveraging the benefits of DBN [47], specifically in knowledge-based maintenance, to preserve and use existing expertise and learn from experience and past events to generate new knowledge [2]. While most data-driven maintenance strategies aim at increasing the availability, the WissensFab model uses DBN, extends this classic approach by a LCC dimension [48]. Due to the ability to represent knowledge from heterogeneous data sources, DBN can also be used for recommended actions. This has been successfully applied in healthcare [49] and especially in predictive maintenance of industrial equipment and production quality management [50]. DBNs are particularly suitable for the extraction of expert knowledge from heterogeneous data sources. The WissensFab model takes advantage of the semantic linkage of heterogeneous data sources and the temporal properties of DBN to introduce another sustainable dimension into the DT in the course of life cycle management.

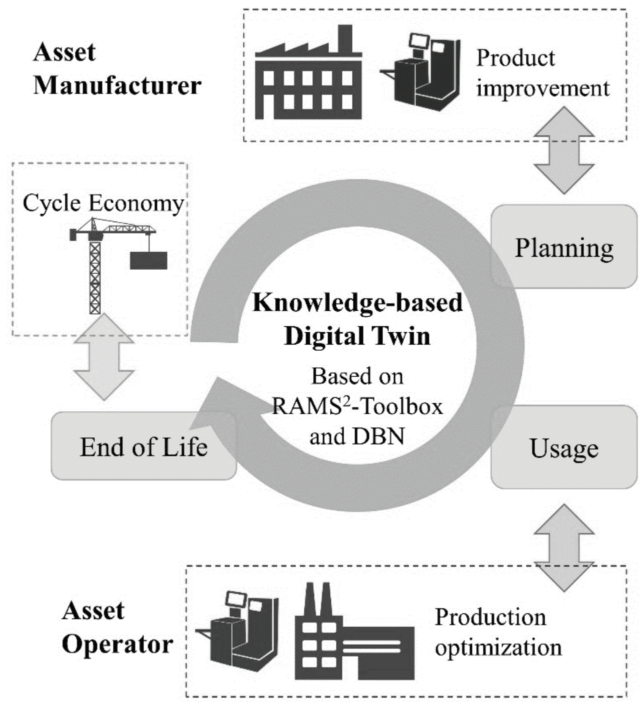

Figure 2 WissensFab Model

The overall objectives of the WissensFab model are to build a lifecycle-oriented asset optimisation based on the results of the criticality assessment through a knowledge-based DT (Fig. 2).

The model contains a set of instruments tailored to the respective asset manufacturer and operator and contributes process and product optimisation from an economic and ecological point of view in the various life cycle phases of an asset. Knowledge is presented transparently through standardised processes. This leads to a reduction in downtime costs, an increase in availability, improved product quality through a reduction of rejects, savings in material and energy resources, a reduction of reworking times and a reduction of LCC through improved product development. By using a knowledge-based DT, these savings potentials can be made visible at an early stage and targeted measures can be taken. The WissensFab model comprises three components:

- RAMS^2-Toolbox

- Innovative Knowledgebase with DBN
- Digital Twin.

All three components are created and tested in simulation, using data from industrial use cases. The individual components are presented in the following sections and the results are discussed at the end.

3.1 RAMS²-Toolbox

For a sustainable asset evaluation, the RAMS model is extended by the aspect "Sustainability" (RAMS²) in order to include environmental considerations in the criticality evaluation. RAMS is defined in CENELEC-Norm EN50126 [51] like:

- **R**eliability Engineering
- **A**vailability Engineering
- **M**aintainability Engineering
- **S**afety Engineering.

It focuses on the use of targeted, product-specific hazard, reliability, maintainability, safety and sustainability analysis (Fig. 3). Life cycle thinking is used to ensure minimisation of potential hazards of humans and the environment and maximisation of reliability and safety of products and processes.

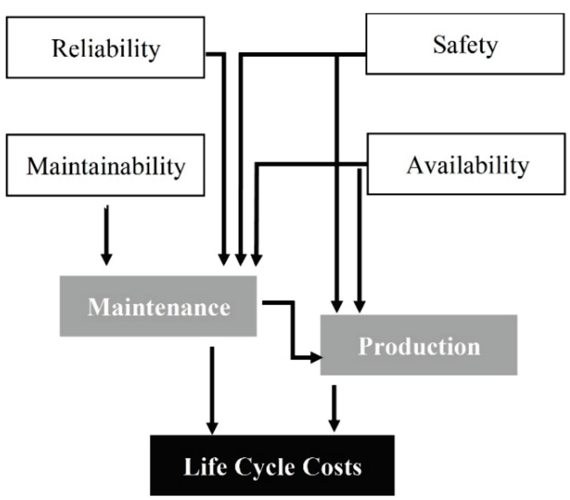

Figure 3 LCC influence through RAMS

RAMS² enables a resource and energy evaluation in the value chain with simultaneous consideration of the LCC. This novel approach enables a fusion of traditional metrics with sustainable aspects, which increases the benefit of the application for industry partners and thus creates a company-wide increase of knowledge. This leads to a transformation towards a climate-friendly, resource-efficient factory.

The RAMS² toolbox (Fig. 4) contains various instruments that can be selected individually for each company. In the course of the requirement analysis, the ALC is evaluated in terms of data quality and risk tolerance by the cooperation of the asset manufacturer and the asset operator, applying the RAMS² toolbox. The performed data quality and criticality analysis in combination with a consideration of RAMS² over the entire ALC represents an innovation beyond the current state of the art.

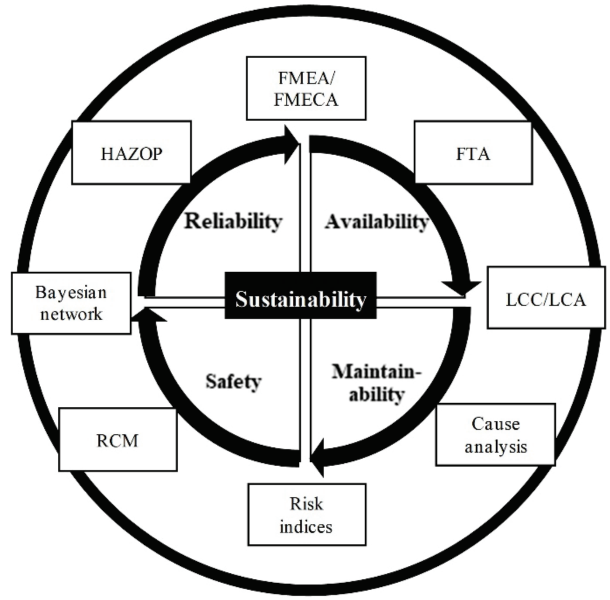

Figure 4 Excerpt from the RAMS² Toolbox

The RAMS² methods are used for criticality and weak point analyses, based on the existing processes and data by selected use-cases. This can ensure a holistic view of assets through technical, economic and sustainability criteria. The output of the criticality assessment (asset index / RPI) serves as input for the DBN of the DT. Furthermore, in turn, the output of the DT is fed back through iteration loops as additional/extended input for further criticality assessments. This makes it possible to derive control mechanisms for decision-making and check which effects decisions have on individual KPIs.

3.2 Identification of Most Critical Assets

The criticality assessment adapted from Kinz et al. [41] is applied in combination with the HAZOP [1] approach to identify the most critical assets. This criticality analysis method includes four steps [49, 1]:

1) Asset selection & Criteria Selection
2) Asset evaluation
3) Creation of an asset priority portfolio
4) Detailed asset analyses.

In the first step, it is important to set limits for the selection of assets for the asset evaluation based on the success factors of the company. It does not make sense to evaluate all assets in the course of the asset evaluation. The larger the asset park, the more important it is to make a preliminary selection on the basis of defined characteristics. These characteristics have direct impact on the success of the production, and in broader sense, on the company. Furthermore, in the first step of the criticality analysis, the preselected assets are evaluated based on the defined criteria, which were derived from the company's success factors. It is important to use criteria from different categories like cost, time, quality, flexibility, sustainability and safety, which are reflected in the different categories of the RAMS². They can include the common time and cost-related criteria, such as asset availability, downtime or maintenance costs, as well as quality-related criteria such as scrap or supplier quality. For sustainability criteria, it is useful to consider the three key areas ecological, economic and social issues, such as environmental pollution, pollutant emissions, the degree of risk to operators, the location of the asset or the criterion of health risk [14]. Tab. 1 shows some examples for criteria for the asset analysis with the assignment to the RAMS² categories.

Table 1 Examples for asset criteria with RAMS²

RAMS²	Criteria/KPIs
R	Product quality, material range, delivery reliability, maintenance requirement
A	Availability, performance level, scrap rate
M	Overdue maintenance, MTTR, prevention rate, qualification level
S	Lost time injury rate, occupational accidents
S	Resource consumption, Facility cleanliness

The asset evaluation (step 2) is an integral part of the implementation phase of the HAZOP approach. In this step, the preselected assets are rated based on the predefined criteria. In the best case, this step is done automatically with a software tool. Therefore, only quantitative criteria can be used. If automated assessment is desired, there must be uniform data availability at asset level and uniform data quality. The result of the asset evaluation is the asset index for each of the assets valued. The asset classification is depended on the asset index. The higher the asset index, the more critical an asset is [34].

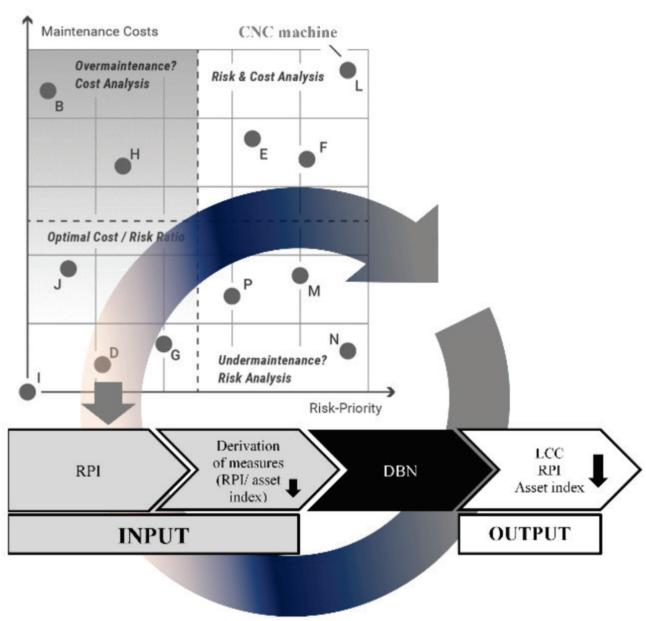

Figure 5 Asset priority portfolio as input for DBN to reduce LCC

The results are visualised in an asset priority portfolio (step three), in which the criticality or in more detail the different dimensions of the criteria (RAMS²) are compared to the direct maintenance costs [49]. Fig. 5 shows an asset priority portfolio, where the CNC machine was identified as one of the most critical assets.

The fourth step is to examine the assets identified as most critical in detail and try to adjust the maintenance strategy by considering the defined measures for risk and cost reduction. Therefore, each criterion is analysed in detail and the consequences of such high-risk level are considered. Potential as well as already occurred risks of the respective critical asset (CNC machine in this case) are assessed at component level according to the probability of occurrence, the extent of damage and the potential consequences (quality, safety, time, …), the probability of detection as well as the effort to be expended for risk reduction with the maintenance risk prioritisation tool. The result of the evaluation is the risk prioritisation index (RPI), which gives a rating of how critical the respective error is. The higher the calculated RPI, the more important it is for this risk to implement the intended risk reduction measure as quickly as possible. The measures for risk reduction can be derived at component level.

The detailed cost analysis includes the division of the costs in their cost types to identify the largest cost drivers. Generally, for both analyses-types (risk- and cost-analyses), measures are derived and the saving potential is considered in the reduction of the asset index/RPI. This regular automated system evaluation as the basis for detailed analyses supplies input data (RPI/KPIs) for the DT.

3.3 Innovative Knowledge-Base with DBN and Digital Twin Demonstrator

A DT for the simulation of the industrial use cases is created from the heterogeneous data sources spanning the ALC with the help of DBN. The classical simulation approach will be extended by the dynamic aspect of a BN, as well as by a semantic linkage, to map the temporal component in the process and to extract relevant KPIs. The example discussed in this paper represents the simulation of a CNC machine and its LCC over the ALC. The CNC machine has been identified as the most critical asset in the analysed asset park by the criticality assessment. In the example shown in Fig. 6, sensor data from the asset operations (motor rotation, electric current, oil pressure, oil temperature, and main spindle speed) are linked with data from the operation (output power, feed and operating hours) and asset components (motor and cutting tool). An asset failure consists of the combined inputs from sensor data, operating data and asset data. In the simulation use-case for example, the cutting tool, combined with the feed, the electric current and the motor rotation represent combined an asset failure. The failures are derived from the criticality assessment (detailed CNC risk analysis). The modelling of these failures is done with experts from the asset operator.

Two types of KPIs can be derived from these failures namely from the:

- Operational phase
- Quality

- Reliability
- Availability
- MTTR
- Lost time injury rate (LTIR)
- Resource consumption (RC)

• Design phase

- Motor power
- Intended use
- Efficiency.

The KPIs from the operational phase also reflect the RAMS^2. The results of the KPIs of the operational phase can be used to optimise the ongoing asset usage by using the identified measures for risk reduction. The results of the KPIs of the design phase can be used in the next product iteration. Once the KPIs of the operational phase have been optimised, this will have an impact on the sensor and asset data of the next time period. Based on the changed parameters, the failure frequency occurrence and the potential extent of damage also change in the following time period. This leads to adjusted measures in the risk assessment. In the case of different potential measures to optimise the KPIs of the operational phase, the DT also helps to select the most efficient measure, as it simulates the effects of the measures and therefore provides a data-based decision-making tool. The knowledge-based DT therefore represents a continuously self-improving system.

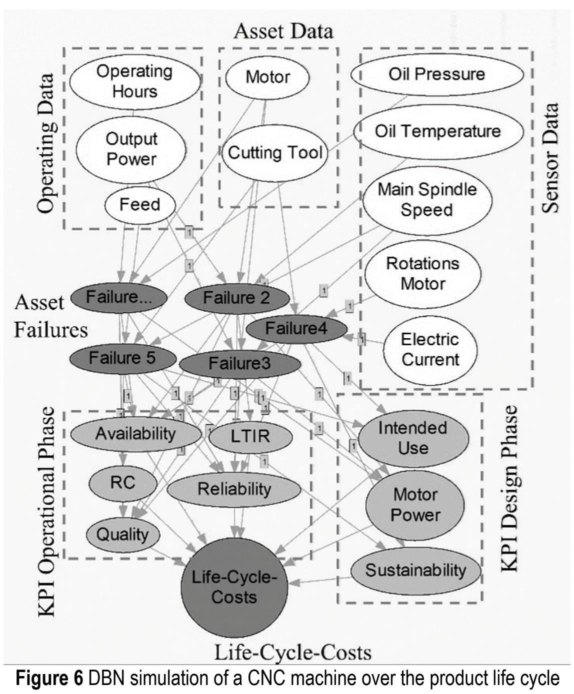

Figure 6 DBN simulation of a CNC machine over the product life cycle

This happens in analogy by the improvement of the KPIs of the design phase. These do not automatically have an effect on the next period of the machine in operation, but they significantly improve the machine data in the next product generation. Those KPIs can be used in the next product iteration, e.g. to adapt the asset to the real usage profiles, the results of the sustainability analysis or the required engine power. In combination the KPIs from the operational and the design phase are used together to calculate the LCC. Their continuous adjustment leads also to a decreasing asset index. By optimising the operational KPIs in each time period, as well as the KPIs from the design phase the LCC of the asset can be reduced continuously by optimising the maintenance strategy based on the results of the simulation. This innovative approach enables knowledge representation, the derivation of KPIs for each ALC-phase, the derivation of product design recommendations and the calculation of life-cycle costs in a dynamic model. For the data exchange required in this case, it is necessary that both the asset operator and the asset manufacturer can access the DT at all times. If this is the case, the model presented here makes it possible to dynamically adjust various KPIs and furthermore adapt the maintenance strategy over the product life cycle and product iterations.

4 DISCUSSION AND OUTLOOK

The result of the simulated knowledge-based DT using DBN serves to prove the functionality of the combined use of the RAMS^2 toolbox and the DBN, which enable a lifecycle-oriented asset optimisation by including heterogeneous data sources. With the help of the demonstrator, asset manufacturers and operators will be able to achieve a use-case dependent reduction in maintenance costs, an increase in asset availability, a reduction in LCC by means of improved product development, a continuous safeguarding of knowledge, as well as a simultaneous reduction in CO_2 emissions and an optimisation of decision-making with increasing transparency.

LCC has a great advantage for both asset manufacturers and operators. By knowing the LCC, the asset manufacturer can design the assets in a more targeted way to have lower operating costs during the utilisation phase. The DT results also enable the asset manufacturer to systematically improve the next generation of the machine, considering the asset operators' needs and production conditions (see Fig. 1 planning phase).

The advantages for the asset manufacturer regarding the optimisation of machines in the planning phase for future applications is evident. This enables the asset manufacturer to become even more familiar with his customers and to react to trends and changes in the markets of the customer group. The difficulty here for the asset manufacturer is not to use the data obtained to optimise a manufacturer's production settings for a product but to convert this data into a product development strategy from which all customer groups benefit. The asset manufacturer can use the reduced LCC as an argumentation basis towards the customer and build up economic service concepts or new business models.

The DT provides an opportunity for a continuous improvement of the assets and dynamic adaption of the maintenance strategy in the operation phase for the asset operator (see Fig. 1). After each optimisation of the KPIs during the operation phase, the optimised parameters of the asset operation, consisting of machine, operational and sensor data, are available in the following time step. In the following validation cycle these parameters serve as input for the next improvement of the operational KPIs. This continuous improvement of the asset operators KPIs of the operational phase in combination with the periodic improvement of the asset manufacturers design phase KPIs leads to a continuous reduction of the LCC. The asset operator can use the optimised LCC to select and procure assets and plan the total costs at an early stage. LCC can be used to derive maintenance concepts and thus optimise maintenance.

The knowledge-based DT clearly shows the advantages of combining criticality analysis based on $RAMS^2$ with a DBN to continuously reduce the LCC and reduce the asset index/risk potential of the critical assets. The presented approach has the great advantage of representing a generic method applied to almost any domain. The domain-specific adaptation takes place using the expert knowledge of the employees involved in the design of the DT. However, this can also be seen as a limitation, as the approach can only be automated to a limited extent. It still requires human expertise to apply the criticality analyses and $RAMS^2$ toolbox and to model the DBN.

In future research, the end-of-life phase needs to be studied in more detail. For the asset manufacturer in particular, this represents a very large untapped potential with recycling and after-use concepts. However, the asset operator can also make further use of this phase, e.g. by building up synergies with downstream users.

Notice

The paper will be presented at MOTSP 2021 – 12th International Conference Management of Technology – Step to Sustainable Production, which will take place in Poreč/Porenzo, Istria (Croatia), on September 8–10, 2021. The paper will not be published anywhere else.

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Preliminary communication

Development of a Generic Framework to Assess Asset Management Maturity within Organisations

Hans Thomas Maier*, Oliver Schmiedbauer, Hubert Biedermann

Abstract: With the comprehensive Lean Smart Maintenance philosophy and its associated maturity model, organisations were given a tool to reach asset and maintenance excellence. This paper discusses the approach used to transfer the scientifically based methods and concepts of the Lean Smart Maintenance Maturity Model into an assessment structure to generate a generic tool to collect the complete and correct information necessary to determine an organisation's maturity level. Research results show that a standardised assessment process combined with continuous improvement cycles, a more accurate assessment of the company's maturity is possible. A well-structured MM assessment supports less experienced assessors whereby experienced assessors will not need a full questionnaire but only a well-structured list of items and their maturity levels.

Keywords: Assessment; Asset Management; Expert Evaluation; Instrument Validation; Lean Smart Maintenance; Maintenance Management; Maturity Model

1 INTRODUCTION

The last decades, especially the last years with the challenges that arose from the global COVID-19 pandemic, have shown that the ability of companies to change and adapt to volatile market conditions is more important than ever. A central part of ensuring competitiveness in such environments is supporting production with a lean (efficient) and smart (effective) organisation. This is especially true for asset-intensive industries, where the asset management organisation is seen as a key enabler in this and smart factories contexts. Against this background, the Lean Smart Maintenance (LSM) concept, which takes a value-added perspective, focuses on dynamics, organisational learning, and risk orientation. [1-3] Based on these works and past maintenance maturity models (MM), a MM was developed as a tool to guide organisations towards LSM, with a strong focus on current developments in the fields of digitalisation. [4-6] For the LSM MM's trouble-free utilisation, a standardised assessment based on semi-structured interviews combined with a document review is used. [5]

This scientific contribution intends to answer the question that repeatedly arises in reorganisation projects, which is, 'How must a maturity assessment be structured to obtain the greatest possible density of information (complete & correct) for the maturity rating of the organisation being surveyed with the most efficient use of human resources?'

The publication is structured in 8 different sections: after the introduction in section 1, a theoretical overview of the LSM MM and maturity assessment are given in section 2 of this paper, which includes an explanation of the assessment process in detail, the applied question types and the improvement process applied during the organisational analysis. Section 3 introduces the selected methodology, section 4 the expert and interview mode selection process, section 5 an in-detail case description. Section 6 results are presented and discussed, and section 7 concludes the paper with a summary and an outlook into possible future research.

2 LSM MATURITY ASSESSMENT

MMs are defined as artefacts with elements arranged in an evolutionary scale with measurable transitions from one level to the next and are used for benchmarking, self-assessment and continuous improvement. [5, 7, 8] Their basic architecture can differentiate MMs: capability maturity models, which focus on the organisation's capabilities and processes, progression models, i.e. evolution of elements and hybrid models, which use the architecture attributes, features, patterns, etc. of a progression model, with transitions between maturity levels defined by a capability maturity hierarchy. [7] MMs can be designed as *descriptive* to describe the as-is state of a system, *prescriptive* as a base for improvement or *comparative* for benchmarking purposes. [9] The LSM MM is classified as a primarily prescriptive, hybrid MM. It uses the Capability Maturity Model Integration (CMMI) base architecture and progressive elements to better understand the model's elements.

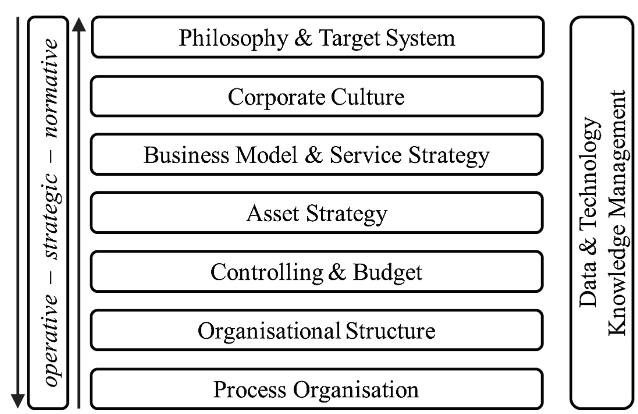

Figure 1 LSM MM categories [5, 6]

It encompasses nine main categories arranged from normative, via strategic to operative management: philosophy & target system, corporate culture, business model & service strategy, asset strategy, maintenance budget

& controlling, organisational structure, process organisation, knowledge management and data & technology, with the last two being designed as cross-sectional categories. [5] The basic structure of the model can be viewed in Fig. 1. In the hierarchical model, structure sub-categories can be found below the category level, which are comprised of items, which in turn form the basis for the assessment questions. The questions are an aid to find the right manifestation of an item over the different maturity levels. The items themselves are directly linked to the maturity levels of sub-categories, meaning that all item descriptions have to be fulfilled until a certain maturity level for an organisation reaches a certain maturity level in a sub-category. The minimum maturity level in of sub-category within a category then sets the maturity level for the overall category. [5, 6] The logic behind the maturity evaluation can be viewed in Fig. 2.

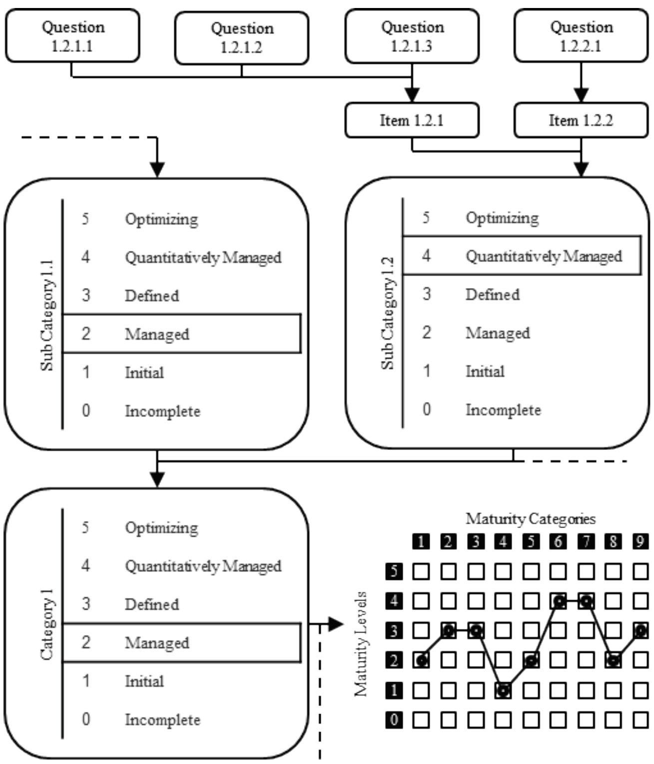

Figure 2 MM logic [6]

Although the main goal of the model was to create a prescriptive and not comparative model, similar asset organisations can be compared with the resulting maturity profile.

The LSM assessment targets to identify the maturity of an asset management organisation within each mentioned management category. For the completeness of an organisational assessment, a structured assessment process, assessment questionnaires and an appropriate team of assessors [10] are necessary alongside the corresponding maturity model. The defined assessment process is based on the ISO/IEC 33004:2015, consisting of seven main, a start and a stop phase. Continuously improving the assessment quality, the defined process was extended by the aspects of the DMAIC-cycle (Define, Measure, Act, Improve, Control). [11] This advancement aims to optimise date respectively information collection and assimilate gathered information alongside the assessment procedure.

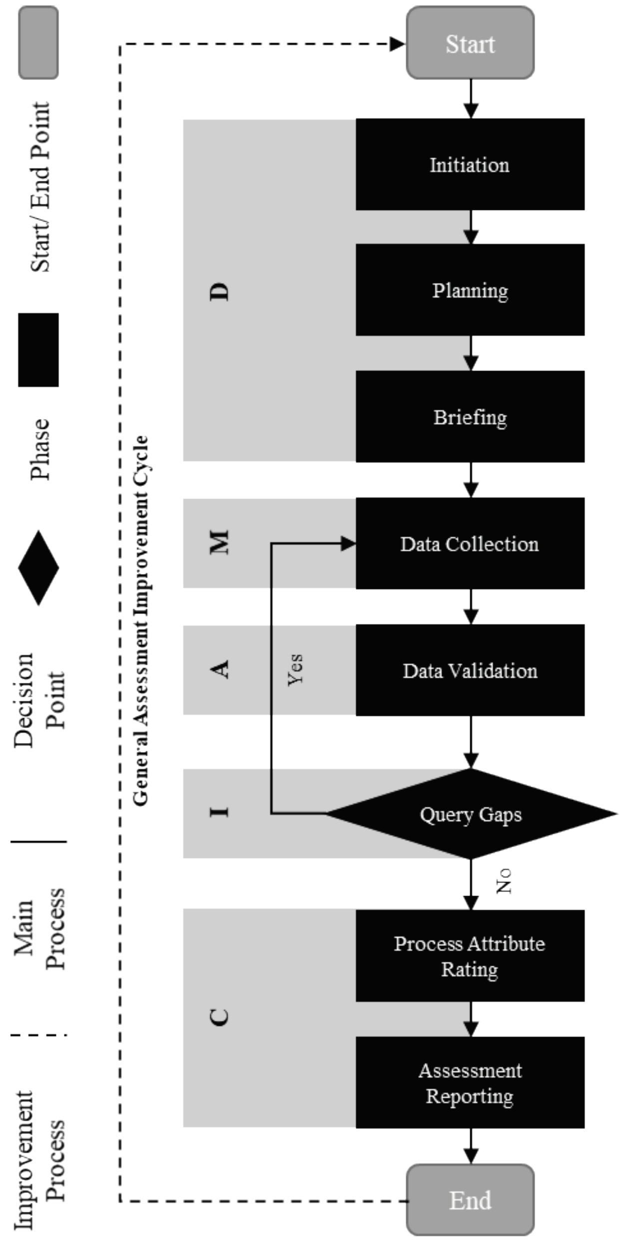

Figure 3 LSM assessment method, adapted after [12]

As shown in Fig. 3, the assessment method includes two independent improvement loops, enabling the organisation that conducts the assessment to perform organisational learning. Organisational learning can be described as identifying gaps and errors and then deriving appropriate measures from them. [13] The first improvement loop is placed parallel to the M-A-I phases. After conducting the first interviews, the gathered information is analysed, and gaps resulting from elements of the maturity questionnaire not being asked are identified. These shortcomings are used as new input parameters for the data collection phase to complete the assessment information. Data collection and the defined assessment questions are scrutinised through this first learning cycle can be categorised as 'double loop learning'. [14] The authors propose a second loop, the *General Assessment Improvement Cycle,* and this represents the approach of deutero learning adapted to the assessment process. The highest characterisation of learning types, the deutero learning, seeks to enhance the learning process, and in this case, the assessment process itself. [13] Typical questions within this improvement step are, e.g., 'Do we have chosen the right types of questions?', 'Is the phraseology of the questions appropriate for the target group of the assessment?' and 'Is the assessment timeframe correct?'

In addition to the assessment process, the assessment questionary is of utmost importance. The employees to be questioned have several tasks to fulfil, e.g. interpret and understand the meanings of the questions asked to provide the right information to the assessors. [15] For the assessment to be carried out properly, the questionary setup was derived by the MM structure. As described before in this section, the model is divided into different items per sub-category, and each item has a certain number of questions to be asked to identify the correct maturity level. Since the LSM MM represents aspects of the normative, strategic and operative management level, the question types must also be comprehensive, reflecting different views, opinions, attitudes, knowledge, and certain organisational behaviours such as value orientation and culture. [16] Therefore the questionary was developed by utilisation of two basic question types. The first one is the closed question with a defined number of possible answers related to the item's content, and the second the open question whereby this type was used to identify processual and organisational details, which are always different between different organisations.

3 METHODOLOGY

The stimulus for this scientific work was provided by several 'lessons learned' from various reorganisation projects. After previous organisational analysis had been completed, the question arose about whether it is possible to adapt the assessment system to acquire more information in the same time frame of an assessment than was previously possible. The LSM MM describes, in its simplest form, current states of, e.g., processes, structures, characteristics of maintenance organisations' and indicates potential development paths to increase efficiency and effectivity by reaching a higher level of maturity. The LSM MM was further developed using Hevner's Design Science Research approach (DSR) [6], and this is also used in this publication as a methodological guide. DSR consists of three research cycles: the so-called Relevance Cycle, the Design Cycle (DC), and the Rigor Cycle. [17] The methodological structure of this contribution focuses on the DSRs' Design Cycle. The LSM MM was validated with existing data from previous projects. [6] To further meet the DC requirements, the derived questionnaire was validated against an actual organisational development project, part of the validation assessment structure and mode described in this publication. The DC is structured as an iterative process that includes the phases of creation and evaluation of artefacts. Therefore, it is represented with the general assessment improvement cycle, shown in Fig. 3 and discussed in section 2. With the requirement for continuous improvement in the highest maturity level of the CMMI architecture, the iterative process transfers the MM requirements to the assessment and maturity model's design.

The general Assessment improvement cycle starts at the end of the assessment process (AP). Here, a survey was created to assess the efficiency and effectiveness of the AP. This survey was sent to the different assessors of the conducted project, further described in section 5. Questions asked in the survey included general information about the assessors, namely the name and role of the assessor during the interviewing process. Besides the general information, five specified questions were asked to identify the usability and quality of the assessment. The first question (Q1) focuses on the data collection process carried out during the interviews. Question two (Q2) deals with the phraseology and clarity of the assessment questions, and thus whether the interview participants, in the opinion of the experts, have understood them correctly, and the answers given are consistent with the context of the questions. Question three (Q3) is focused on the gap analysis between the target data for a holistic picture of the organisation to the gathered data from the interviews (e.g. identification of not used items or sub-categories of the maturity assessment), and question four (Q4) ties in with the result of Q3, and the possibility to determine the maturity level through the collected information. The final question, Q5, evaluated the assessors' ability to produce reports and perform organisational analyses based on the data collected. Furthermore, the assessors were asked which interview mode they used (Q6) (see section 4) and if they could collect enough information with the interview mode chosen (Q7). The result discussion is seen in section 6.

4 EXPERT AND INTERVIEW MODE SELECTION

In this section, the systematic process of expert selection for conducting the interviews and the decision process of choosing the interview mode are described. Choosing the right assessors is one of the most critical aspects of the assessment preparation process. [10] The starting point for selecting experts for LSM assessments is the qualification matrix of the assessing organisation. A staff qualification matrix is used to identify individual knowledge gaps in projects and further training. The staff's ability is analysed, reviewed, and expanded at regular intervals. It thus provides the current qualification status of the employees. [18] In the case described, the organisation, a scientific organisation that conducts scientific projects with industrial partners, offers training for employees of mainly industrial companies and lectures to students, differentiates in four different qualification levels:

- Theory, acquisition of basic literature, training completed (x)
- Project support, first application, first lecture performed (xx)
- Repeated lecture, repeated project application (xxx)

- Expert, several years of experience in further education and projects (xxxx).

The lead assessors in a project should have a level 2, ideally a level 3 qualification in the relevant qualification categories. General assessors should have at least an intermediate level in the different qualification categories. Assistant assessors need to complete at least the first qualification level most relevant to the assessments. The tasks of the lead assessor include interviewing and the aggregation of information gathered by the different interview teams.

Table 1 Qualifications of the possible Assessors

Possible Assessor Nr.	Maintenance Management Projects	MM Assessments	LSM MM Development
1	xxxx	xxx	xxx
2	xxx	xxx	xxxx
3	xxx	xxx	xxxx
4	xxxx	xxx	xx
5	xxx	xxx	x
6	xxx	xxx	xx
7	xxx	xx	xx
8	xxx	xxx	xx
9	x	x	
10	x	x	
11		x	
12	x	x	

The assessor's main task is interviewing. The assistant assessors record the information gathered and lead some first interviews to prepare for possible future roles as assessors or lead assessors. The relevant qualifications for LSM assessments include the following, are however not limited to:

- Expertise based on maintenance- and/or asset management related projects
- Expertise based on conducted maturity assessments
- Scientific expertise gathered by being part of the LSM MM development team.

The qualifications of the different assessors in the assessing organisation are shown in Tab. 1. If further special knowledge is required for certain parts of the organisation, this is further considered when assigning the assessors. Besides the mentioned main qualifications of the assessors, each assessor has a substantial background in moderation and skills in conducting interviews, and the lead assessors have several years of workshop experience.

Due to the LSM MM description's detail with its high granularity, two possible paths arise when interviewing: The first starts with the interviewer filtering the question depending on the interviewees' horizontal and vertical position in the company. For the maintenance manager of a factory, this would, e.g. mean filtering for 'middle management' and 'maintenance'. The interviewer would now only see the questions relevant for this interviewee and question him or her accordingly. The second possibility for the interviewer would be to take the item descriptions in the different maturity levels and think of questions that would generate answers to sufficiently describe the organisations' status regarding the used model. Before starting the interviews, the different interviewers need to be assigned or chose an interview mode.

5 CASE DESCRIPTION

The case selected for this paper is an LSM assessment carried out in a large, central European company from an asset-intensive industry with slightly less than 2000 employees in maintenance. The company sells its products globally and faces strong international competition. Due to its size, the maintenance organisation is designed with a large central workshop, supporting the two decentralised, asset-specialised departments. The central workshop is further split into specialised units, four of which were relevant for the assessment. Reorganisation projects are handled in a standardised process consisting of 6 stages to ensure the sustainable development of an organisation.

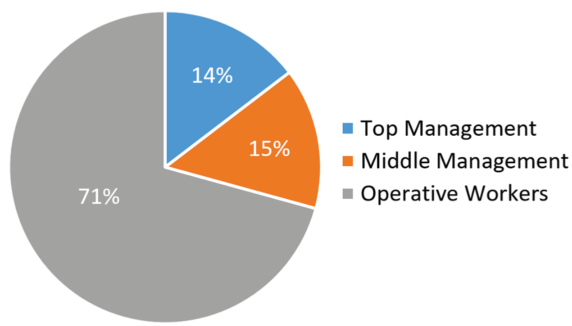

Figure 4 Hierarchical interview distribution

Besides the education and training of the employees on the LSM components, the companies' 'as-is' state has to be analysed. The analysis, in turn, consists of several steps, as shown in Fig. 2. The 'define' phase of the assessment was decided to conduct at least 160 interviews within the organisation. This number was defined to cover all relevant functions and hierarchical levels of the surveyed area with at least two candidates. Based on the defined number of participants, the company and its divisions agreed to make 164 employees available for the interviews. The hierarchical distribution of the different interviewees is depicted in Fig. 4. This approach pursues identifying potential gaps between the management's defined maintenance processes and the operational level's applied to the process and getting a clear picture of all the different relevant organisational interfaces and their potential shortcomings. A further step in the Define phase was to select the lead-assessors, the assessors and assistant assessors, according to the process described in section 4. In the list of possible assessors depicted in Tab. 2, persons 2, 3 and four were chosen as leads, 1, 5, 6, 7 and 8 as assessors and 9, 10, 11, 12 as assistant assessors. From this list, three teams were formed according to the organisational structure: One team for decentralised unit one (DU1), one for decentralised unit two (DU2) and one team for the central workshop (CW) with the size of the teams depending on the number of interviewees per organisation. Furthermore, a flexible team (Flex) was created to support the three other teams.

Table 2 LSM assessment team breakdown

Organisational Unit	Lead Assessor	Assessors	Assistant Assesors
DU1	2	5	9
DU2	4	6	10
CW	3	7, 8	11
Flex		1	12

In the next step, the interview plan was created together with the company's management. This resulted in three weeks of parallel interviews, with interview durations ranging from 45 to 120 minutes, depending on the interviewee’s hierarchical and functional position in the organisational structure. Furthermore, two of the lead-assessors (3 & 4) decided to use the MM items as a base for thinking of questions that would generate answers to sufficiently describe the organisations' status regarding the used model, as described in section 4. All other interviewers used the established process by directly asking questions from the questionnaire.

During the actual interview phase, the three phases measure (data collection), act (data validation), and improve (query gaps) phases were cycled through each interview day. The collection of information was conducted through interviews. At the end of each interview day, the information for each unit was gathered, aggregated, different answers in items compared, and gaps in the information base for the maturity evaluation visualised and analysed to address them during the interviews the following day directly. The check phase included first defining the maturity levels by the assessment team and then validating them in consensus workshops, where experts from the relevant units discussed the results with the assessment team. The workshop participants' years of experience and expertise were contrasted with the assessment results, and small adjustments in the maturity rating were done. However, these workshops pursue two objectives, first, as already mentioned, the validation of the assessment results, and second, employee participation, regardless of organisational level, is increased through participation and voice or voting rights in the maturity level results.

6 RESULTS AND DISCUSSION

The compilation of the first assessment questionnaires was based on the experience of the lead assessors mentioned above. The initial questionnaire consisted of about 80 core questions selected from a total question catalogue consisting of about 580 questions and sub-questions. These questions were selected to gather first insights into the organisation by posing basic questions about each MM item. The first interview day also represented the first M-phase (data collection) and set the assessment-improvement loop (M-A-I) in motion. A total of seven assessment teams were deployed and conducted 32 interviews on the first day. After the first consolidation phase of the collected information, the ratio of ‘essential queries’ to ‘existing queries’ was carried out by the assessment team. Based on this evaluation, which was supported by an Excel tool, it was possible to identify blind spots or contradictory statements from the different areas. Contradictory statements were cross-checked using two different approaches: by comparing them with company documents and repeatedly asking different interview participants for the same information. As the interviews themselves were time-limited (0.75-1.5 hours), those teams that worked with the questionnaire and the predefined closed questions types had a higher response rate than those teams that oriented themselves to the item structure with the open questions types.

The first impression of these differences was examined in detail by the entire team of assessors. These differences in response rates were attributed to three identified factors. Firstly, it was found that the questions were asked 1:1 by the partly less experienced interviewers, which led to misunderstandings and contradictions to the same questions in different areas. The phraseology problem was identified as significant in this context, and it was more prominent at the operative level than at the middle or top management level. Secondly, it was found that there were technical problems in the handling of the assessment tool, which led to limited usability and thus to time that was not usefully utilised. The third and final issue identified was the size of the questionnaire itself. Due to the lack of detailed information about the interviewees' job descriptions, it wasn't possible to adequately predefine the questionnaire regarding the interviewees' knowledge concerning certain parts of the organisation. These three points show the necessity of the authors' improvement cycle, which repatriates the gaps in information identified within the I-phase to the M-phase, enabling the assessment setup's continuous improvement. The M-A-I phases were run through each interview day, which resulted in a significant improvement in the quality of the information received as the interview phase progresses

After finishing the interviews, to close the complete DMAIC cycle, the assessors were subjected to a survey (see section 3) to assess the continuous improvement approach's effectiveness, efficiency, and questionnaire design. Survey responses at Q1-Q5 were captured by a typical 5-point Likert scale (1 = very poor, 2 = poor, 3 = neutral, 4 = good, 5 = very good). First glance at Fig. 5 shows four out of five questions (Q1, Q2, Q4, Q5), a low rating with 1 and a rating of 2 on Q3 was given.

This response was based on the assessor that assessed the maintenance logistics area. Although this project was a reorganisation project of maintenance departments, the logistics area was also assessed, as it is an interface area that closely cooperates with decentralised and central maintenance. However, the results reflect that only parts of the LSM assessment are suitable for logistics organisations. The Q1 and Q2 responses resulted in an average value of 3.73 and 3.90, respectively, whereby focusing on the approach and usability concerning ‘data collection’ and ‘data validation’ of the LSM-assessment. The best rating was given at Q3 and Q4 with an average value of 4.27 and 4.09, which confirmed that the new questionnaire design is very suitable for identifying blind spots that may arise during the assessment. The last question was ranked with an average value of 3.55, reflecting a good result regarding creating a comprehensive report with the interviews' gathered information. The interview results were also based on the type of interview that was chosen. Nearly 20% of the assessors chose the second type of interview (see section 4), and 80% oriented their conducted interview on the detailed questionnaire catalogue. The last question was asked to evaluate the overall satisfaction with the comprehensiveness of information gathered through the chosen interview method to determine the organisation's correct maturity level. More than 90% of the assessors agreed that they could gather all necessary information with the interview mode chosen. The assessment results were validated with the subsequent consensus workshops held with the individual departments and the correspondingly selected representatives from the operational and management levels, which only resulted in slight adaptions of the identified maturity levels in the sub-categories.

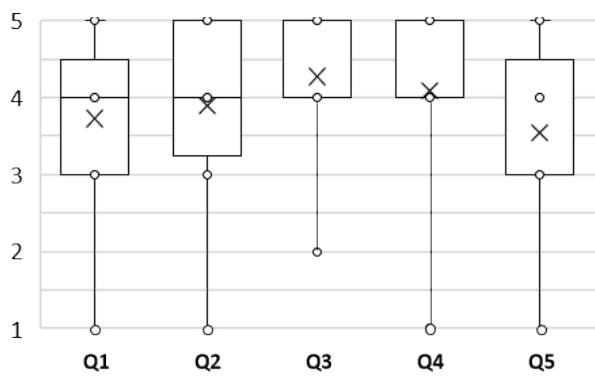

Figure 5 Assessor survey results ($n = 11$)

The general improvement cycle results are the lessons learned from the described case, used to improve the whole assessment. These include that filtering by core questions is less practical than filtering by position and role of the interviewee, that both detailed item descriptions, as well as a complete questionnaire, are necessary for an assessment due to the different qualifications of the assessors and that the assessment has to be further optimised for departments that are positioned at organisational interfaces, e.g. maintenance logistics service organisations.

7 CONCLUSION

This paper presents the methods employed to improve the LSM assessment during the interview phase (double-loop learning) and after the interview phase (deutero learning). The authors showed that the presented model for an assessment process and improvement cycle allows effective assessments and continuously improves the interview guide with the underlying MM structure. Limitations include that the assessment method was validated using the LSM MM in one Austrian asset-intensive organisation with six different units. The assessment team consisted of team members from one scientific organisation, whereas seven out of twelve assessors already had experience implementing maintenance reorganisation projects. Finally, this CIP was applied to the specific LSM MM assessment. Further possible applications include testing the presented process on other assessment types (e.g. Total Productive Maintenance, Total Quality Management or European Foundation for Quality Management (EFQM) model assessments). Further research is needed to effectively implement a systematic change process based on identified MM development steps to reach the ideal LSM maturity level. Other necessary research includes integrating the LSM maturity assessment into a holistic excellence framework and evaluating the value added by moving an organisation towards LSM.

Notice

The paper will be presented at MOTSP 2021 – 12th International Conference Management of Technology – Step to Sustainable Production, which will take place in Poreč/Porenzo, Istria (Croatia), on September 8–10, 2021. The paper will not be published anywhere else.

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Preliminary communication

Robotics in the Modern World of Work - Results From an Empirical Study Regarding Business Ethics

Daniela Ludin, Wanja Wellbrock*, Erika Müller, Wolfgang Gerstlberger, Lea Gray, Sabrina Salat

Abstract: The digital revolution is changing the world. Robots, big data and artificial intelligence are the key technologies of the future and the basis of important innovations for the future development of the economy and society. In companies, this fact requires strategic rethinking and adjustments in ever-shorter time cycles. The creation of an agile and collaborative production to achieve the goals is often a basic requirement. With adaptation to technical progress, requirements and goals change continuously. To be and remain competitive, companies are forced to have at least the same technological standard as their competitors. In order to meet these challenges today, the use of highly efficient mechatronic systems such as robots is necessary. The paper analyses business ethics relevant aspects of robotics by using a survey with 88 respondents.

Keywords: business ethics; digitalization; ethics; robotics; sustainability

1 INTRODUCTION

The fourth industrial revolution is progressing inexorably and is bringing major global and disruptive changes with regard to technologies in use and level of knowledge needed [6, 33, 35]. The progressive use of artificial intelligence (AI), robots, the Internet of Things and Big Data is changing familiar work processes, and might lead to automation of industrial production processes, services and even creative activities [6]. Increasing globalisation is accompanied by the networking of systems and data and vice versa. Among other things, this results in an increased need for communication and information [26].

The speed of this technological revolution is expected to challenge economies and societies [6]. Technological developments linked to computerisation, automation and technological advancement are at the forefront [24]. In companies, this fact requires strategic rethinking and adjustments in ever-shorter time cycles. The creation of an agile and collaborative production to achieve the settled goals is often a basic requirement. With adaptation to technical progress, requirements and goals change continuously. To be and remain competitive, companies are forced to have at least the same technological standard as their competitors. In order to meet these challenges and to stay competitive, the use of highly efficient mechatronic systems such as AI and robots needs to be considered [12]. In addition to the many opportunities associated with this, the impacts of AI and robotics especially on human labour are still uncertain and must be weighed up [6, 11, 12, 24, 26, 33]. Positive impacts might relate e.g. to creation of new jobs, higher productivity and flexibility as well as reduced costs. In addition, the improvement of health and life quality are viewed as a positive effect of using robots especially in routine-dominated or dangerous work places [16, 36]. On the other hand, replacement of human labour especially of untrained workers by AI and robots as well as an increase in income equality are seen as the biggest threats [6, 11, 24, 26].

Benefits and threats of a wider use of AI and robotics may differ related to firm size, sector- and country-specific aspects [11, 22, 26]. This complex interaction needs further investigation in order to identify necessary steps to adapt production processes, training of workers or even political framework conditions to support positive and mitigate negative effects [8]. This paper aims to contribute to research on the influence of robotics on human labour in the German context by combining the perspectives of business ethics, mechatronics, production management and human resource management. A questionnaire was used to collect empirical data from employees working in different sectors. The aim is to examine the fields of application, chances and risks as well as the future development of robotics both in a theoretical and in an empirical way.

An additional goal is to find out the extent to which robotics is already prevalent in the working world and to what extent employees are included and informed into ongoing transformation processes. It is also important to find out how willing people are to collaborate with robots in their working environment and what might be further impacts of robots on humans. This refers to activities, requirements as well as the personal perception of employees, which is to be estimated by the answers of the interviewees.

2 METHODOLOGY

A literature analysis and a fully structured survey are used as basic methods for this study. For the literature review, research texts, working papers and contributions of various authors found and selected were examined and evaluated based on the central problems and questions, which have to be answered in this paper [37].

In empirical social research, a survey is the most diverse and most frequently applied method to collect and analyse data and elaborate on specific topics [23, 32].

A written consultation based on a fully structured questionnaire with partially open questions was carried out to collect empirical data. This questionnaire was created via an online survey portal and distributed via email or directly as a link in order to reduce time and costs for data collection and to allow scalability. Open questions are included in the sense of a partially standardized survey in order to record qualitative results and to give the respondents more leeway to answer [4]. The responses received were analysed using simple statistical methods. Answers to open questions were included in the evaluation in a qualitative way.

3 THEORETICAL BACKGROUND

3.1 Fields of Science

The subject of this study in the field of economic and social research is investigated by combining business ethics, mechatronics, production management and human resources into a theoretical framework (cf. Fig. 1).

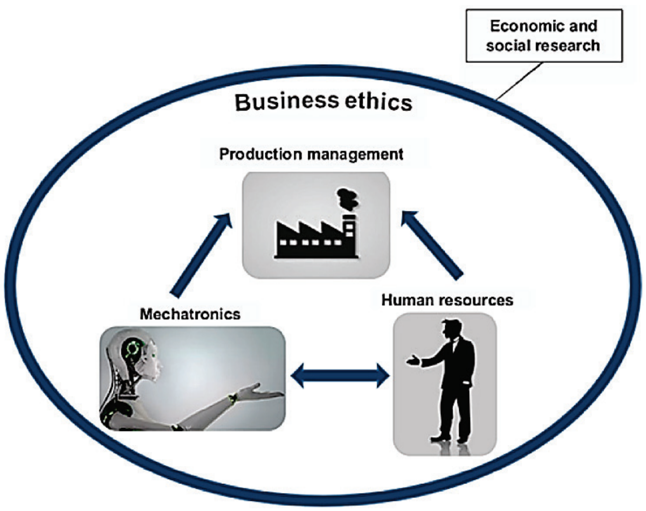

Figure 1 Classification in Science (own illustration)

3.2 Theoretical Background on Business Ethics

Business ethics is a branch of applied ethics and deals with the question how moral regulations and behaviour can and must be in a modern economic system. Business ethics is subdivided in ethical aspects of companies, individuals, orders and consumption [2, 27].

It is, among other things, influenced and guided by the actions of different individuals. Over time, three systems of standards have developed – conventions, morals and law. Conventions are well-established rules in society and are described as "can-be" expectations. In contrast, the moral rules by which actions are evaluated are only right or wrong. They represent "target expectations". Legal norm systems are "must expectations" which must be adhered to under all circumstances and are relatively easy to check.

Business ethics is also divided into various levels of analysis: meta, normative, applied and descriptive ethics. Meta ethics is concerned with the question of ethical or moral judgement itself, for example, under what conditions a fact is judged right or wrong. Normative ethics deals with the question of how one should act morally and has the goal of analysing and evaluating moral norms and deriving possible solutions from them. Based on this, applied ethics provides concrete recommendations for action in specific situations. Existing systems of moral rules are described and explained by descriptive ethics. In contrast to meta and normative ethics, descriptive ethics is based on empirical methods [2, 27].

The fields of action of business ethics are broad and include education, environmental protection, working conditions and human rights.

In everyday business life, many different interest groups are whose demands must be met. There is the difficulty of finding the right balance in the conflict between entrepreneurial success and compliance with self-imposed or legally prescribed guidelines. In business practice, the above-mentioned relationships are often reflected in a code of conduct or, in some areas, in compliance guidelines [9].

The term "machine ethics" reflects a still relatively new sub-area in practice and increasingly subject of operational considerations. At its core, it is concerned with the moral behaviour of machines towards human users and perhaps other machines. Machine ethical questions might be e.g. related to the use of partially or fully autonomous programs and systems such as robots. In concrete terms, the focus is on topics such as safety, job loss and decision-making power of machines as well as necessary regulations is concerned with ensuring that the behavior of machines toward human users, and perhaps other machines as well, is ethically acceptable [1, 9]. Research around machine ethics also deals with possible risks that might arise from "future greater-than-human intelligence machines". In particular, intelligent robots or AI technology might challenge human abilities to understand or regulate machine behaviour, which might lead to negative feelings or trust issues or other reservations among workers [9].

3.3 Theoretical Background on Mechatronics

The fourth industrial revolution results in progressive digitalization, globalization and automation. Mechatronic systems represent essential key technologies and thus also the linkage of human with machine capabilities. In 1969, a Japanese developer coined the term "mechatronics". It is composed of the fields of mechanical engineering, electronics and electrical systems for information processing by using intelligent computer control elements (IT technology). These systems find application in various production processes and operations and should help to improve and/or alter the performance and functionality of mechanical systems by integrating sensors and electronic processing [19, 28].

The replacement of mechanical approaches or simple machine technologies with machine technologies in combination with electronics and IT intends to reduce mental and physical strain on humans involved in production processes that can run autonomously. It also allows broadening control functions and integrating learning-abilities into production processes in order to increase robustness, reliability, flexibility and cost effectiveness [28].

Robotics as a sub form of mechatronic systems is a relatively new form of engineering, but are already omnipresent components in the most diverse areas of our lives and influence our actions. Robotics is characterized by its versatile and flexible applicability – from private households to medical technology and manufacturing processes as Robotics can be understood as "intelligent connection of perception to action" performed by sensors. Sensors help robots to "sense and interact with the changing environment" as well as to gather information, which is then further processed by intelligent algorithms and results in commands that actuate parts of the robots. Robots are characterized by high speed, precision, robustness, power and a long service life. The constant high quality, the unlimited reproducibility as well as the significantly high productivity are fundamental advantages of robots. Robots can provide support by performing non-ergonomic, monotonous, time-consuming and potentially dangerous tasks. Furthermore, robots show no signs of fatigue and apart from maintenance intervals or malfunctions; they are available for continuous operation. They perform handling tasks such as gripping, moving, laying, turning or lifting. Furthermore, some of them already possess the cognitive ability to speak, see and hear which enables them to learn by storing and processing data [13, 28].

On the first level, physical machines are involved, which contribute to the expansion of human capabilities with tool character. The second level states that the robot performs activities autonomously using algorithms that modify themselves independently. The highest degree of autonomy occurs when a robot can act in a human-like manner using artificial intelligence [10].

The interaction of robots with humans plays an increasingly important role, both in industrial processes as well as in service contexts. In this context, a distinction is made between three types. On the first level, the so-called coexistence, humans and robots are in the same workspace at the same working time. The subsequent level of cooperation is extended by a common goal. The highest degree of interaction is achieved in collaboration, where man and robot are connected by close joint action. In addition, it is common in practice for several robots to interact together to perform tasks that cannot be performed by a single robot [3].

The definition and improvement of the so-called human-machine interaction is a complex field of growing research interest and might notice e.g. decision-making and cognitive processes, modelling of human performance, allocation sharing and job design, intelligent interfaces, human operator support, work organization, and selection and training criteria [3, 10, 13, 28]. Also on social and psychological aspects of human and robot interaction that correlate with aspects of human resource management and business ethics [10]. The growing application of robots, their technological development and a growing cooperation between men and robots require a dynamic adaptation of working environments and standards.

3.4 Theoretical Background on Production Management

The focus of production or operations management are all processes around the combination of production factors for the operational production of goods and services considering the economic principle. The main tasks are the planning, management and control of the targeted transformation of objects in terms of quality, quantity and dimensions. Ecological, economic and employee-related aspects are considered [17].

The main influencing factors on production are time, customer, costs, quality and flexibility. With regard to the time aspect, the focus is on increasing productivity and thus optimizing throughput, research and development, replenishment and reaction times. On the customer side, the aim is to increase the logistical performance for the customer by means of high availability of goods and the best possible delivery service. In addition, the company is trying to expand customer benefits through an individualised product range and to bind customers to the company. Together this leads to increased satisfaction, which has a positive effect on sales and profits. Furthermore, it is essential for companies to reduce elementary costs in order to maintain or increase their profit margin. Cost optimisation is becoming increasingly important, especially in the production area, due to the constantly increasing pressure to maximise efficiency. The objectives of the quality aspect refer to the products of a company with regard to their innovation, durability and reliability. In addition, a high degree of flexibility in production must be aimed for. This refers to the reaction time with regard to internal and external influencing factors, especially in the event of fluctuations in demand [17].

The requirements and challenges in production are also changing fundamentally with the progress of the fourth industrial revolution. The integration of the essential elements of the industry 4.0 such as Big Data and analytics, autonomous robots, simulations, system integration, IoT, cyber security, clouds, additive manufacturing and augmented reality potentially drastically transform existing production processes, logistics, handling of resources as well as integration of humans into workflows and processes. The Smart Factory is one form of enterprise for implementing these factors. Here, processes are increasingly standardized and mechatronic systems are increasingly used instead of classic machine elements. There is already a large number of autonomous production processes that would be unthinkable without the use of robots. They mainly take over tasks like transport, assembly and control of production material. Changes in production management might also lead to a need of learning new skills and capabilities [9, 14, 25, 29, 35].

3.5 Theoretical Background on Human Resources

Human resources management, as a further subarea of business administration, deals with the production factor labour. The tasks relate to design and administration and are both personnel and social in nature. Managers and the human resources department pursue the common goal of managing, directing and controlling the personnel considering the needs of the employees and the company [7].

A fundamental trend that is shaping human resources management is demographic change. The shift in the age structure in society towards a higher average age is influenced by the birth and death rates as well as immigration and emigration. This demographic development poses new challenges, especially for the working world, especially in developing countries. Human resources management focuses on the increase in the average retirement age, the lack of junior staff, dealing with fluctuation, migration and workplace health promotion [5].

In Germany alone, there is a shortage of more than 1.2 million skilled workers, according to forecasts, there will already be three million by 2030. This deficiency is one of the greatest critical success factors and, as a brake on growth, has an impact on economic development. An important operational task for human resources management is therefore the long-term securing and retention of skilled workers. This includes, among other things, creating and ensuring attractive working conditions, for example through a fixed income, high management quality, an open-ended employment contract and opportunities for professional development [21, 30].

Besides "classical" aspects of occupational health and safety such as counteracting loss of productivity as well as the impairment of performance and chronic diseases and to increase employee motivation, further issues related to change working environments in the industry 4.0 might arise. Human resource managers need to consider adaptation and innovation of occupational health and safety systems in order to meet these new requirements [2, 8].

In addition, the education system has undergone many changes in the past. New qualification profiles and competence requirements have emerged, particularly because of the ongoing digitalisation, automation and globalisation in the course of industry 4.0. These new educational contents are increasingly being addressed both in school education and in the world of work, particularly in human resources development. However, pose questions how to qualify elderly workers according to the new requirements of the emerging complex knowledge-intensive work processes that need technological and robotic assistance [31, 34, 38].

Accompanying the expected transformational change of industrial processes lead to new aspects to be considered by human resource managers. For instance, questions of re-education, development of new skills of workers that collaborate with robots as well as anti-discrimination matters might arise [18, 28].

4 EMPIRICAL STUDY

As part of this paper, a written, partially open survey was conducted using the online platform ‘Survey Monkey’ to collect data. This type of survey was chosen to quickly reach a large number of people regardless of location, to give respondents enough time to answer and to provide anonymity. The only condition for participation in the ‘Robotics in the World of Work’ survey was employment. The intention was to receive a cross-sectoral general view on the use of robotics and its possible effects on labour. To ensure this criterion, the online link was sent directly to personal contacts of the researchers, which covers the parts of the area of the federal state in Germany the questionnaire comprises ten mandatory questions, which had to be answered within one week.

In order to be able to make a basic classification, personal details such as age, school education and the sector of employment were asked at the beginning. This resulted in a response of 88 persons with a very broad range.

Besides finding out to which extent robots are already part of people´s work settings, this study also tries to get an insight in people´s perceptions and feelings of robots. It might deliver useful guidelines for decision-makers. To consider machine ethic aspects is important for engineers and (human resource) managers in order to ensure a successful implementation of machine technologies into production processes and to stimulate supporting measures to ensure positive social outcomes [9].

4.1 Empirical Results on Business Ethics

One aspect of business ethics is the fear of robots replacing jobs. In the questionnaire, the employees were asked to indicate whether and why they have this fear regarding their job or not. 9.1% of the respondents said that they were afraid of losing their jobs within the next twenty years. The arguments are that companies can save costs in the end by using robots and that the job profiles will change as industry 4.0 progresses. Especially activities with high repetition frequency and low complexity are affected by this change.

Five of the eight respondents who answered ‘yes’ are active in the service industry. One possible justification for their assessment is that, for example, in banking, administrative activities or travel booking, algorithms are increasingly being used to initially facilitate these activities and finally completely replace them.

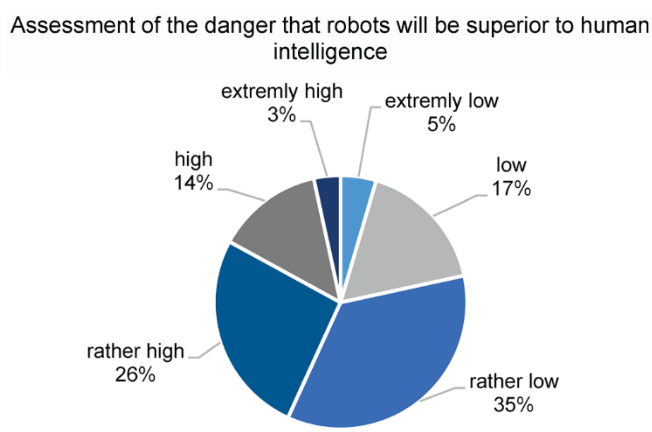

Figure 2 Danger that robots will be superior to human intelligence (own illustration)

In contrast, 90.9 percent of the participants are not afraid of losing their jobs. The main argument is that there are many individual activities where factual and often quick action and decisions are required. Furthermore, expertise, experience, creativity and empathy are often required to accomplish tasks. Some of the interviewees are of the opinion that technology is not yet mature in some areas or that investments are not profitable. Others justify their nonexistent fear by the fact that the use of robots creates new jobs or that they are about to retire.

Business ethics also deals with the question of whether there is a danger that robots will be superior to human intelligence. Fig. 2 illustrates, in percentage terms, the assessment of the risk by the employees from extremely low to extremely high.

In the survey, 54 out of 88 employees, well over half, classified the risk as medium, with a tendency towards low risk. Since the risk cannot be fully assessed, the assessment of the employed persons is nevertheless divided.

For example, the proportion of those who assess the risk as low to very low (19 persons) is only slightly higher than the proportion of those who assess it as high to very high (15 persons).

A detailed examination of the age structure, educational attainment and sector does not reveal a clear trend in terms of the answers. This can be explained by the fact that it is a vision and depends on the range of actions and personal feelings of the individuals.

4.2 Empirical Results on Mechatronics

In mechatronics, the application of robotics is discussed. In order to find out whether and to what extent this is common in companies or directly at the workplace of the participants, a partially open question was asked on this subject. The interviewees had the possibility to choose between use and no use and then to indicate in categories in which areas robots are used or not used for which reasons. The specified areas were assembly, transport, service, packaging and quality control.

21.6% of the respondents stated that robots were used in their assembly operations, for example in processes such as welding, milling or screwing. In transport, for example picking up, turning or setting down, robotics is used in 14.8% of cases. The third area of application is the packaging sector with 12.5%, which includes processes such as picking or gluing. At 10.2%, quality control is supported by robots during activities such as scanning, measuring or weighing. Only a small proportion of 4.6% use them for service tasks such as cleaning or repairing.

On the other hand, 44 respondents stated that they do not use robots, firstly because human thinking and knowledge is required and secondly because human experience is necessary. 42 indicated that the responsibility and decision-making power could only lie with humans. For almost one third of the workforce, the need for empathy or creativity is a justification. Fewer than eight people are of the opinion that robots are not used because of high investment, lack of profitability, immature technology, safety aspects or insufficient legislation.

Due to the fact that the respondents had the possibility to choose several answer options, the result is that a total of 56 times "Yes, in the range..." and 210 times "No, because..." were selected. This shows that in companies the reasons against the use of robotics clearly predominate. This is particularly the case in health and social services and the service sector, this contrasts with results from other studies see a huge potential for the use of AI and robots in health and social services.

In the further course of the questionnaire it was necessary to prioritize in which of six predefined areas the use of robots, according to the personal opinion of the respondents, brings the greatest benefit. In the evaluation, the area with the highest percentage of respondents prioritizing was selected for each priority level. Thus, 69.3% placed industry in first place, followed by medicine with 37.5% in second place. In the middle field are the transport sector with 31.8% and trade with 28.4%. The respondents see a smaller advantage of robotics in the education sector with 35.2%.

The service sector was classified by 33% as the area where robotics brings the least benefit. The clear prioritisation of industry in the first place confirms the previous findings that robotics can be implemented and used more easily and effectively in this sector than in other sectors. Potentials in medicine are probably seen in precision, research and permanent applicability. The prioritisation of transport in third place is also related to the further development of topics such as autonomous driving. The human factor plays an indispensable role in the areas of trade, education and services, so that robots are seen as having less advantage in these areas.

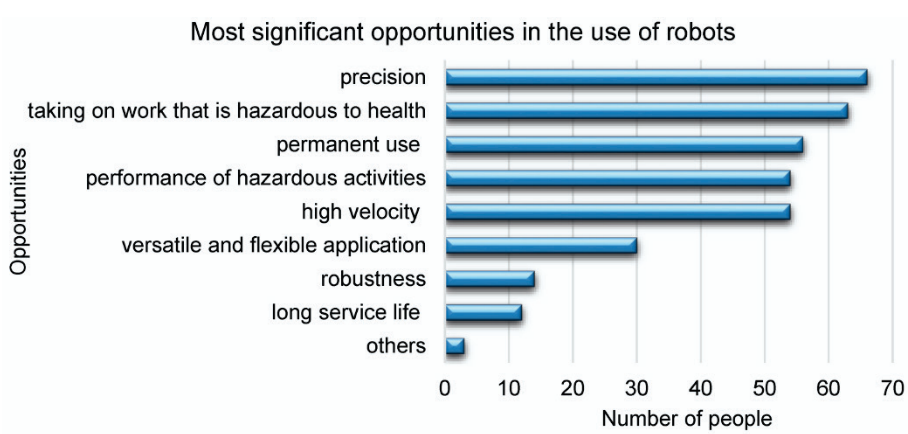

Figure 3 Most significant opportunities in the use of robots (own illustration)

4.3 Empirical Results on Production Management

There are many advantages and opportunities in the use of robots in the working world. The respondents were asked to select the four most significant opportunities in their opinion. Fig. 3 shows the results of this question.

75% of all respondents stated that the precise operation of a robot is of great importance. This was followed by 71.6% who took on work that was harmful to their health. In addition, 63.6% of all respondents see the permanent use of robots as an opportunity. With 61.4% each, high speed and the execution of hazardous activities also play a more important role. It can be deduced from this that employed persons see opportunities in those areas in which they are clearly inferior to robots. In many areas, robots are able to work faster and more precisely than humans with consistently high productivity [11]. As a result, production targets of the factors time, customer, costs, quality and flexibility can be better implemented. Furthermore, they see a benefit in the fact that robots perform activities that are harmful to health, dangerous or monotonous. As a result, employees are relieved of physical strain, can focus on other activities and develop personally or dedicate themselves to tasks that require creativity or human attention, for example.

On the other hand, there are also some risks and disadvantages associated with the use of robots. Fig. 4 shows the answers to the question of the four most significant risks.

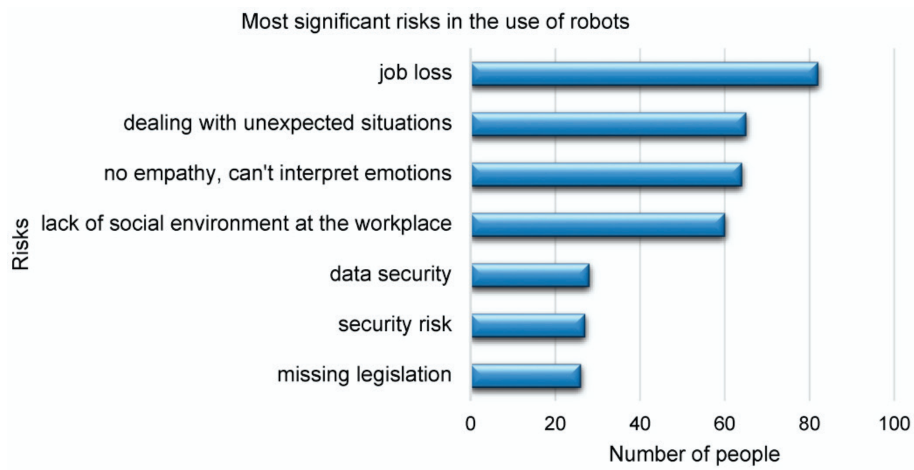

Figure 4 Most significant risks in the use of robots (own illustration)

The risk of losing one's job due to a robot was rated as high by 82 of the 88 respondents. In contrast, only eight of the respondents had previously stated that they were afraid of losing their jobs within the next twenty years. This striking deviation shows that the respondents assume that a large number of workplaces could be replaced by robots, but that they themselves are not affected for the reasons described in point 4.2. This corresponds to the statements of various scientific sources that robots replace jobs depending on the activity, but in return, new jobs are created. These include activities that require, for example, responsibility, cognitive skills as well as training to foster interaction or collaboration between humans and robots [8, 15, 27].

In addition, 65 respondents perceive dealing with unexpected situations as risky. This shows the necessity of security systems, legal regulations, wide-ranging algorithms and clearly defined decision-making leeway [8].The rate of more than two thirds indicates that the respondents do not yet consider these requirements to be sufficiently fulfilled.

Other risks that were classified as significant are the lack of empathy of robots and the decline of the social environment at the workplace. In this context, it is clear that the idea of a workplace for the future is not sufficiently tangible for employees. Many have the image of a robot-heavy work environment in which humans play a secondary role.

4.4 Empirical Results on Human Resources

Challenges for human resources management are in particular the lack of skilled workers, demographic change and health aspects. As already described before, one solution is the use of robotics. This is also accompanied by changes in the educational system. In order to find out the attitude of the employees towards this approach, it was asked whether they could imagine working hand in hand with a robot. 44.3% answered that they could imagine this cooperation. The arguments reflect many of the advantages and opportunities already mentioned. These are the increase of effectiveness and efficiency, the facilitation of work and relief especially from monotonous and dangerous tasks, as well as support in physically demanding activities. In this way, man and robot complement each other positively in the long term. Workers are able to work longer due to the health relief, which is one way to deal with the challenge of demographic change. Another reason is the need to cover the lack of capacity, which also results from the shortage of skilled workers. Some of the interviewees also stated that they already work with robots and that they could imagine doing so in the future, if human contact is maintained.

In contrast, 55.7% cannot imagine working with a robot. Here, too, the many risks and disadvantages characterize the arguments of the respondents. In particular, the lack of interpersonal relationships and the lack of a social environment were elementary reasons for this. In addition, some of the employees carry out changing activities for which the use of a robot is still hardly conceivable. Often employees bear a lot of responsibility and have to make decisions, some of which are ethical and require experience. Since this requires empathy, among other things, the use of robots is currently not possible in many areas. Some also stated that they still lack the imagination to work with a robot.

These answers show schematically why robots have so far been used in such a small range in companies and only in specific areas. Looking at the sector of those who answered "yes" from this point of view, it is noticeable that they are mainly active in industry and respondents who answered "no" come primarily from the administrative, service and social sectors.

5 CONCLUSION

The fourth industrial revolution is changing the world. Robots, big data and artificial intelligence are the key technologies and the basis of important innovations for future development of economies and societies. Their broad utilisation might bring disruptive changes to economies and societies. A clear trend whether robotics will lead to job loss or job creation, still needs to be further analysed and might depend e.g. on complex circumstances such as level of uncertainty, state of economic development, education and training as well as the industry sector.

This study contributes to research on robotics and its possible impacts on human labour by integrating aspects of business ethics, mechatronics, production and human resource management. By executing an online survey among German employees from different sectors experiences with and attitudes towards robotics were collected in order to get an insight into crucial aspects to be considered when integrating robotics into working processes.

Even though, the findings cannot be generalized as the number of survey participants was limited, the results reflect discussions, fears and different stages of utilisation of robots in production processes that were to be found in studies from other countries [22, 24, 26]. Possible influences of robotics on human labour are depending on a multitude of factors and require an individual and situational case decision. In addition to the purely technical aspects of feasibility, social and ethical aspects are moving more into focus with the increasing utilisation of robotics. Besides technological decisions to be made by managers in order to adapt and improve their production processes to the use of robots, human resource managers should be integrated into these processes as well. Future research could focus on how to create learning opportunities for workers, but also be part of dealing with questions of how to develop the interface between humans and machines by acknowledging ethical and social standards.

Notice

The paper will be presented at MOTSP 2021 – 12th International Conference Management of Technology – Step to Sustainable Production, which will take place in Poreč/Porenzo, Istria (Croatia), on September 8–10, 2021. The paper will not be published anywhere else.

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Preliminary communication

Industry 4.0 and New Paradigms in the Field of Metal Forming

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Abstract: Over the last few year, the metalworking sector has been undergoing rapid and radical transformations driven by global competition and the revision of the production focus that is being moved from mass customization to mass individualization. A results of this is introduction of new manufacturing strategies such as Industry 4.0, a concept that combines cyber-physical systems and promote communication and connectivity. Therefore, this concept changes not only the face of the manufacturing systems but also causes transformation of existing business models and the society as a whole. This paper deals with the recent trends and paradigms in the field of metal forming, resulting from the concept of Industry 4.0 and the modern market challenges. The maim attention is paid on the flexibility of manufacturing systems and recent developments in design of smart forming tools.

Keywords: flexibility; Industry 4.0; metal forming; smart tools

1 INTRODUCTION

The Industry 4.0 (I4.0) represents the framework of a new industrial revolution that relies on digitalization and networking as well as the fusion of the cyber and physical worlds [1]. This concept is based on the intelligent connection of mechanical, electrical and software engineering, which contributes to the development of new technologies and business models, as well as new approaches to work and thinking. It was first presented at the Hanover Messe (2011) as a strategic project of the German government, companies and science with goal to help German manufacturers to become more competitive in global markets through better use of information technology and the Internet [1]. Shortly afterwards, the potential of I4.0 was recognized by others manufactures worldwide and it has quickly become a global phenomenon. I4.0 integrates dozens of technologies, some of which have evolved decades ago but new technologies are being developed on a daily basis and included in this concept. A results of this is a series of innovations that leap forward traditional factories to a fully connected and flexible manufacturing system. In essence, Industry 4.0 creates what has been called a smart factory.

Implementation of I4.0 is a complex process that causes significant costs, requires time and knowledge, and has its own operating costs. However, each company and technology sector must have its own view of implementation - there is no "exact level" of implementation that can be recommended. In this paper, some of the challenges that companies from metal forming industry are faced with in the implementation of the I4.0 concept as well as recent advances and future trends in metal forming sector are discussed.

2 BASIC TECHNOLOGIES OF INDUSTRY 4.0

As mentioned above, Industry 4.0 is a very complex concept that utilizes innovative, cutting edge technologies integrated into a highly sophisticated manufacturing system (Fig.1). There are several key technologies of I4.0 [3]: *Cyber-Physical Systems*, *Industrial Internet of Things, Cloud Manufacturing, Big Data, Machine-to-Machine communication (M2M)*, *Augmented & Virtual Reality, Digital Twins, Smart Maintenance, Energy Efficiency Monitoring, Reconfigurable, Connected & Smart Factory etc.*

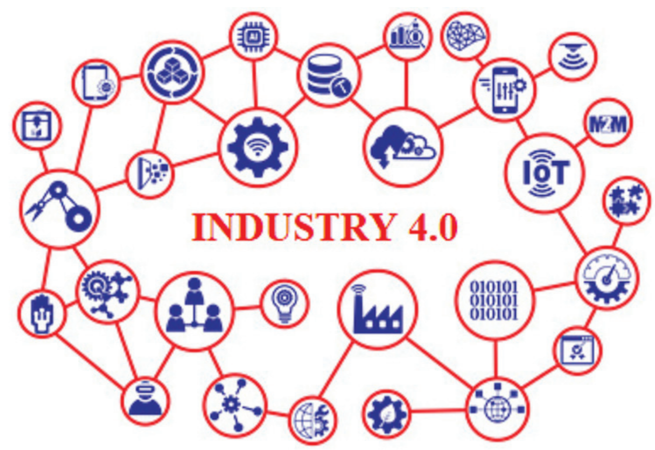

Figure 1 Key technologies of Industry 4.0 and their integration

In addition to integration, communication and information exchange are crucial issues for the implementation of I4.0 technologies [4]. Namely, by adding sensors, actuators and other types of intelligent components to physical objects and devices we create integrated systems, but only if enable network communication between such systems they will be upgraded to cyber-physical systems - intelligent, networked systems with built-in sensors, actuators and processors that interact with the physical world (including humans as users) and support real-time operations. They represent the integration of local "intelligence" and communication capacities, and thanks to the built-in microcontroller these systems are "smart enough" to be able to make independent decisions. However, although their decisions are autonomous and decentralized, they are still in line with the process plan defined at higher levels of decision-making.

When assign IP addresses to cyber-physical systems, we get the Internet of Things (IoT). In this way the devices are able to exchange data with applications, operators and / or other connected devices. IoT enables objects to be located and remotely controlled via the existing network infrastructure as well as to change and adapt the "intelligence" of the objects remotely. Industrial Internet of Things (IIoT) refers to interconnected sensors, instruments, as well as other industrial devices and objects networked together with industrial applications including power management systems.

Cloud technology is a set of networked computing resources that provide IT infrastructure and services, including operating systems, applications, internal and external data storage space. Appropriate services are accessed over networks without the need to install software on the user's computer. The provision and use of IT services is enabled through different types of interface, protocols and web browsers. By switching to cloud technology, significant savings are achieved in terms of hardware, labor and energy. In this way, companies can reduce annual operating IT costs by over 80%. Some of the well-known cloud solutions used in the industry are: Dashboards (FESTO), MindSphere (SIEMENS) and Factory Cloud (ROCKWELL).

In industrial plants and processes, real-time data of large volume and various formats are generated at high speed. Big data technology enables continuous collection of information from various sources with the capacity of search and analysis in order to optimize production processes and workflows. The data obtained from the sensors are analyzed using algorithms for the so-called data mining. These algorithms are based on intelligent mathematical and statistical models and machine learning methods. The goal is to find behavioral patterns by revealing hidden connections between collected data.

M2M communication refers automated data exchange between machines and devices. To enable this, the machines have to be networked and ready to exchange data. In addition, an adequate standard (protocol) for communication is required. This allows machines to gain information about current production processes and, if necessary, to make corrections/changes in a particular operation or production flow. In this way manufacturing systems become reconfigurable, which is one of the most important features of Industry 4.0. The goal is personalized of production where, within mass production, individual corrections are automatically made in accordance with customer requirements.

Augmented reality is a technology that allows superimposition of the visible (real) world and the digital content, which is achieved through the use of digital visual elements or other sensory stimuli items. This is an auxiliary system used in logistics, maintenance, assembly, etc. (Assisted Operator). A distinction should be made in relation to the concept of virtual reality, where the real world is completely replaced by virtual.

Digital twin is a digital clone of a process, product, or service. It is a virtual image (virtual prototype), ie a digital replica of a real product, physical object, process or system. The concept of digital twin is defined as a digital record of components' and system behavior during the real operations that help optimization i.e., improvement and enhancement of system performance. It is, therefore, a link between a real object and its digital display that continuously utilizes data from the sensors located in a physical object. Real object data are used to enhance digital copy in real time. The digital display is then used for visualization, modeling, analysis, simulation and additional planning, as well as for various corrections and interventions on a real object.

Smart maintenance is based on predictive maintenance that includes continuous or periodic sensory-based monitoring of physical changes of machine conditions and process state (Condition Monitoring), as well as analysis of data obtained using machine learning methods or artificial intelligence. Accordingly, production downtime is avoid or minimized in a timely manner. The basic monitoring techniques are: analysis and diagnostics of vibrations, acoustic emission, analysis of thermal behavior, infrared thermography, ultrasonic testing, analysis of energy consumption, analysis of abrasives and particles, analysis of coolants and lubricants, etc.

Energy efficiency monitoring includes real-time monitoring of energy consumption and comparison with periodic archived data. Energy efficiency aims to use less energy for the same task. Focus is also placed on the use of renewable energy sources.

The central objective of I4.0 is a smart factory that represents an intelligent production environment in which production resources and logistics systems are organized mainly without human assistance. Employees, who are responsible for supervising and controlling of production lines, can fulfill these tasks remotely. The control realized from remote consoles is extensive and includes many functions, from output-level control to repair and maintenance.

However, it should be said that such highly automated environments have certain limitations. Personalization in production is becoming more demanding and very common regarding sophisticated customer expectations in modern society. This is where the concept of Industry 5.0 is applied, as the next step in the evolution of production. Under this new paradigm humans have been reintroduced into the process increasing their collaboration with robots and intelligent machines within factory plants. The role of humans in I4.0 is based on decision making, monitoring and preventive maintenance, while in I5.0 there is an active collaboration between humans and robots. Human intuition, reasoning and, critical thinking are resources that robots do not possess yet. In another words, Industry 5.0 should provide the best of both worlds: the benefits of robotics combined with advanced human cognitive abilities. In such an environment, product lines can become even "smarter", with people being able to participate more in customizing products.

3 RECENT AND FUTURE TRENDS IN METAL FORMING

Metal forming is one of the oldest way of processing metal material, which, according to Groche et al [5], has played a significant role in both society and manufacturing development. Several features characterize today's metal forming industry. First one is high degree of diversity – there is a variety of manufacturing procedures, materials, products and, machine and tool systems. Heterogeneity is also present in organizational structures and company sizes [6]. Another characteristic feature of this industry is focus on mass production. It results from high manufacturing costs (energy consumption, tool and machine costs) and low flexibility level since in most forming processes geometry of die/punch is fixed i.e., exclusively depends on the geometry of workpiece. The process conditions, in general, are non-stationary. It includes a change in tribological conditions, material properties, elastic response of the tool-machine system etc., and thus, application of the adaptive process control is quite limited. Due to all this, the implementation of the Industry 4.0 concept in the field of metal forming is a very challenging issue that requires close cooperation between researchers, industry and customers.

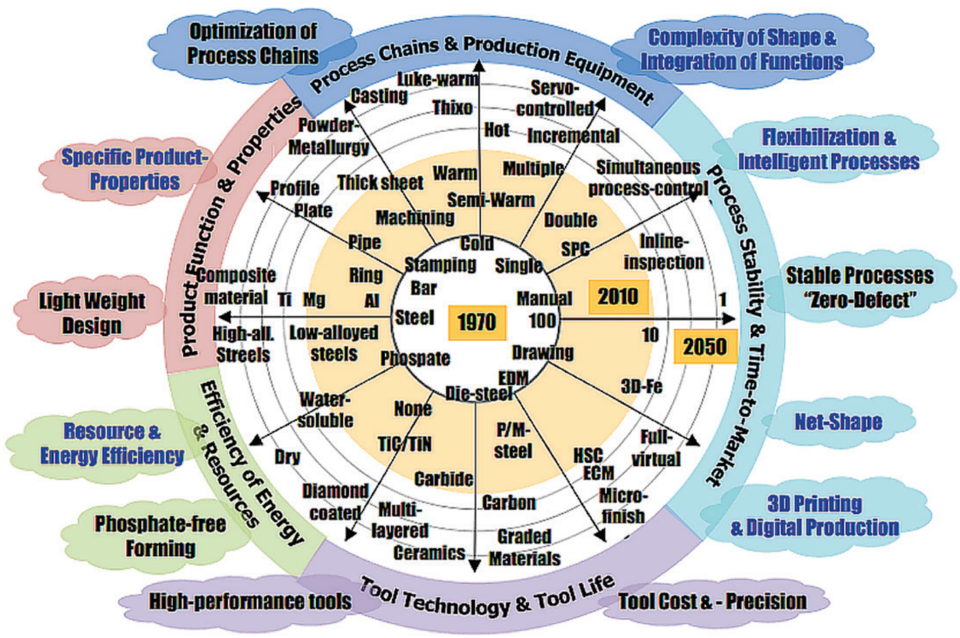

Figure 2 Recent and future trends in metal forming [7]

A summary of recent and future trends in the field of metal forming made by a group of experts within the International Cold Forging Group (ICFG) is given in Fig. 2. As can been seen, one of the major trend is aimed at increase of manufacturing flexibility and development of intelligent production systems. i.e., introduction of smart tools and machine, which is in harmony with the concept of I. 4.0.

4 FLEXIBILITY IN METAL FORMING

In recent years, the focus of industrial production has shifted from mass customization to mass individualization as result of increased competition in the global market as well as rapid changes in customers' habits and requirements [8]. In this respect, the development of highly flexible manufacturing procedures and systems is crucial.

As mentioned above, the flexibility of metal forming systems is generally poor, especially in case of conventional forming processes such as forging, extrusion, deep drawing, forming etc., which are carried out as a single-stroke process with specialized (dedicated) punch and die. To overcome this, several innovative forming processes based on incremental manner of deformation have been developed allowing for an easy modification of the product geometry. Using incremental forming approach a wide range of products can be obtained without any or with minimal modifications in the manufacturing system and thus, the economical output can be achieved even in case of individual and or small-batch production. Incremental forming is particularly convenient for manufacturing over-sized parts like shafts for power plants and large ships, space rocket bodies as well as highly personalized medical components. This technique also offers the possibility to produce complex shapes that were previously difficult to produce through conventional forming processes.

Incremental forming refers to processes that rely on a progression of localized deformation. It means that at any time only a small portion of the part is actually being formed while the desired shape is obtained by a series of small incremental deformations by applying localized pressure with a forming tool. Depending on the tool-machine system the zone of local plastic deformation is moving (over the entire volume) continuously or discontinuously.

In addition to economic advantages incremental forming also provides several technical benefits. A result of incremental manner of deformation is significant reduction of contact pressure and forming load compared to the conventional forming procedures. This enables use of small-sized machines of light bodies and low operating costs. Another benefit of low forming loads is a reduction of tool wear, which have a positive effect on both tool life and process stability. Further, due to gradual forming, this technique is suitable for processing materials of limited (low) formability such are high strength steels, titanium and titanium alloys, magnesium etc. Incremental forming processes are commonly performed at room temperature (cold forming) employing small, simple and cheap tool while the subsequent machining is reduced to a minimum since parts with a high degree of finalization are generally obtained (near-net shape and net shape parts).

Among the forthcoming flexible forming techniques, one that has attracted a lot of attention is Single Point Incremental Forming (SPIF) [9], which scheme is present in Fig. 3. It is also known as "dieless" technology since forming process is carried out using a universal tool - no dedicated die, which trajectory is programmed in advance and controlled by a CNC machine. In other words, all data regarding the geometry derive from the path of the forming tool. Therefore, it could be said that there is no limit in term of part geometry that can be obtained by the SPIF. Recently, multi-axis robots are increasingly used in the SPIF operations to further increase flexibility and productivity of the process. The SPIF was basically developed to serve the needs for prototyping and small-batch production in automotive and aerospace industry, but the application domain has been expanded over time [10].

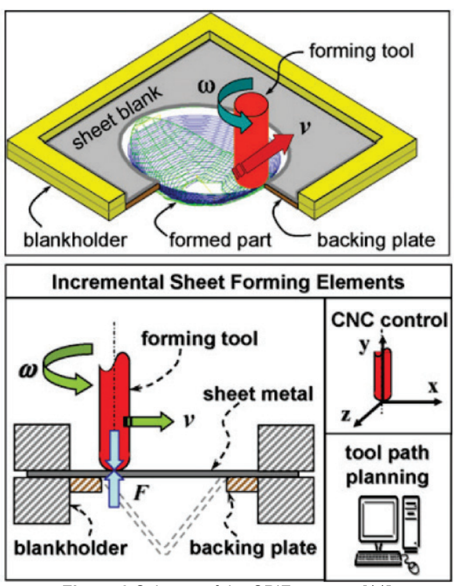

Figure 3 Scheme of the SPIF process [11]

The SPIF is often combined with conventional sheet forming methods (deep drawing, stretching) as well as Additive Manufacturing and Rapid Tooling (RT) technologies with goal to shorten the processing time, which is generally long in the SPIF. It is illustrated in Fig. 4 where deep drawing tooling produced by an AM/RT technique (Laminated Object Manufacturing – LOM) is employed to obtain a preform for the SPIF process. The main feature of this concept is the short time for design and manufacture of the punch and die. The processing time is also considerably reduces since the SPIF process (time consuming) is applied only in finishing stage to form the final shape of workpiece bottom.

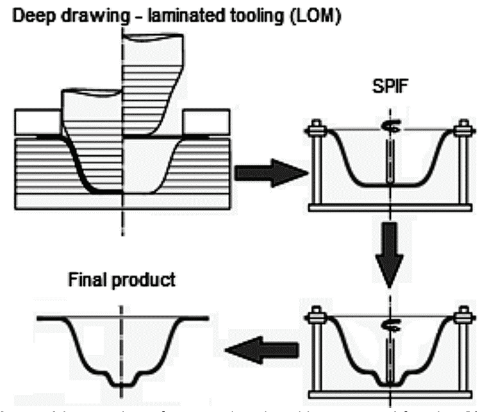

Figure 4 Integration of conventional and incremental forming [12]

The combination of stretch forming and Asymmetric Incremental Sheet Forming (AISF) is shown in Fig. 5. This hybrid process allows noticeable reduction of processing time and material thinning, which are main drawback of the AISF.

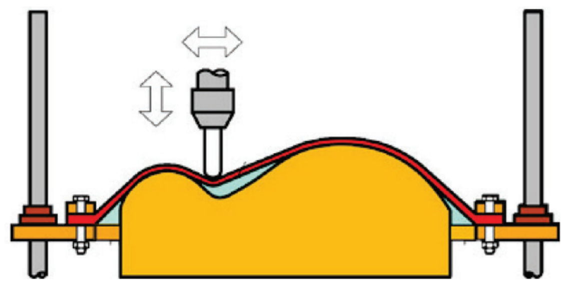

Figure 5 Scheme of stretch forming and AISF [13]

Digitized-die forming (DDF) is a new flexible manufacturing technology that employs specialized machines and tools to convert sheet metal plate into custom three-dimensional shapes. This technology known also as reconfigurable multipoint forming (RMF) is based on the concept of a die continuous surface discrete approximation. The core element of the DDF system is a cluster tool consisting of a pair of matrices of punches that are controlled by computer. The working surface of digitalized die is created by changing the height (vertical position) of each punch (Fig. 6). The DDF system allows for control of part geometry and compensation of the shape errors caused by material elastic springback and other process uncertainties, thus ensuring high accuracy of sheet part.

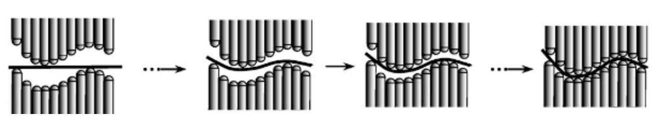

Figure 6 Principle of DDF process [14]

Another strategy to increase the flexibility level in sheet metal forming processes is based on substitution of the conventional die or punch with flexible media, such as elastomers (rubber forming processes), liquids (hydro-forming processes) or gases [21]. Metal forming with help of an incompressible fluid or hydroforming was first introduced in Japan in the early 1960s, but only with recent advances in the tool-machine systems it is now possible to use commercially this technology in the production of metal components. Hydroforming processes offer several technical and economic advances. This technique allows processing of hard to deform materials, reduction in the number of forming stages/operations (complex shapes can be made in one step), reduction of friction and material utilization, tool cost reduction, set-up time reduction. Other advantages are increase of the material formability, more uniform thickness distribution, lower level of residual stresses, and better surface quality compared to part obtained using traditional forming process. Finally, part produced by hydroforming exhibit optimal mass to strength ratio. The scheme of hydroforming process is given in Fig. 7.

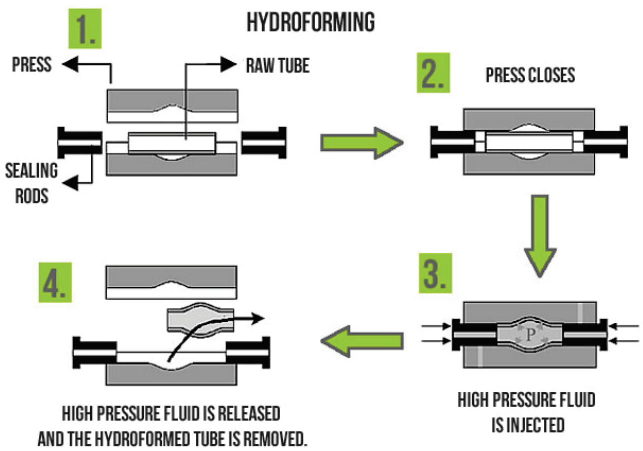

Figure 7 Tube hydroforming [22]

Hydroforming is predominately used in automotive industry (Fig. 8), but this technique is also suitable for prototyping and small-scale production of parts for the aerospace industry.

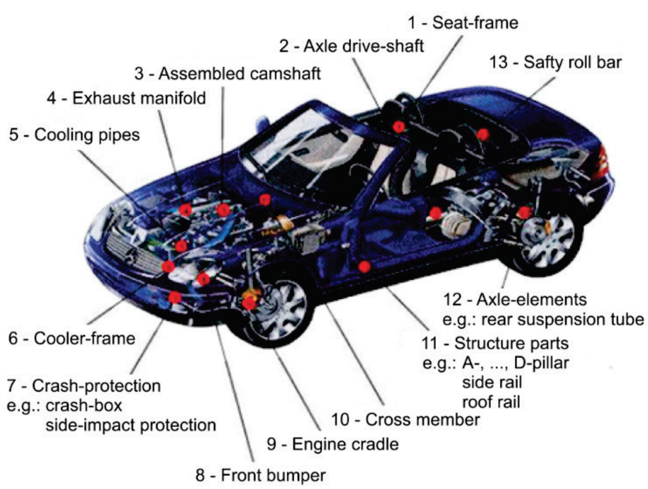

Figure 8 Examples of the automotive parts manufactured by tube hydroforming process [23]

5 SMART FORMING TOOLS

In a conventional metal forming process, the tool (punch and die) has a dominant influence on the part accuracy since it is a "negative" of the part to be manufactured (tool contain the contour of the desired part). Therefore, any deviation of the punch/die geometry from the desired due to design/manufacturing inaccuracies leads to the systematic errors (fixed, permanent) in workpiece geometry. In addition, the nominal dimensions of tools are continuously changing in exploitation due to tool elastic and plastic deformations, thermal expansion, wear occurrence etc., resulting in additional dimensional errors, which are permanent but not consistent in the amount. Further, the fluctuation in mechanical properties of input material or the load oscillations of crank press produce random errors. In this regards, it can be said that the final geometry of workpiece depends more of the above phenomena than on the nominal dimensions of tool. For this reason traditional passive metal forming tools are increasingly replaced by innovative/smart tools that are capable to collect valuable information for monitoring and control of metal forming processes [15]. This allows to take appropriate measures and corrective actions in a timely manner (active/dynamic compensation) so that errors and possible failures can be minimized or completely eliminated and the concept of zero defect manufacturing attained.

Today, with high levels of digitization and the possibility of almost unlimited digital networking, the future of tooling is smart one - data collection, exchange, analysis and adaptability are key features of tools in Industry 4.0 [16]. Classification of innovative, smart forming tool-structures/systems according criterion of tool "intelligence" level is shown in Fig. 9. All listed tool structures are advanced concepts but only intelligent tools with active, "in-process" control capability are suitable for integration in cyber-physical systems within Industry 4.0. To achieve this goal, these tools are equipped with intelligent components such as sensors, actuators and control systems to enable communication with other elements of the manufacturing system and to allow for the receiving and processing of measured/controlled data and information from of the manufacturing environment [16]. The structures of intelligent forming tools are depicted in Fig. 10.

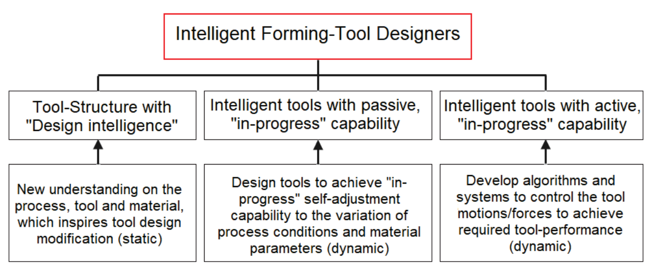

Figure 9 Classification of smart forming tools [17]

Smart forming tools include various types of sensors integrated into the tool at relevant location to convert process information into electrical signals, which are then amplified and processed/estimated by monitoring system - a set of data regarding the discrepancy between the actual and set values is obtained. Successful implementation of sensor strategies is based on successful detection and measurement of variables that correlate with the accuracy/quality of the part for a given forming process [15]. A large number of contact and non-contact sensors are used in metal forming for measuring displacement, surface properties, force, temperature, microstructure, defects, residual stresses and materials properties process [18]. For example, in forging processes information about the part and die temperature and its distribution is crucial issue not only for the part quality but also for heating strategy and die life. Thermocouples are mostly used to measure the forging die temperature. However, the thermocouple can usually only be installed with a minimum distance from the die surface and thus, the measured temperature is only an approximation of the real temperature. More accurate and consistent temperature measurement throughout forging process is achieved by employing optical pyrometers, infrared temperature sensors or thermal imaging cameras. Typically, optical pyrometers measure temperature to an accuracy of 1 to 2% of the full-scale range, which can reach 3300 °C [19].

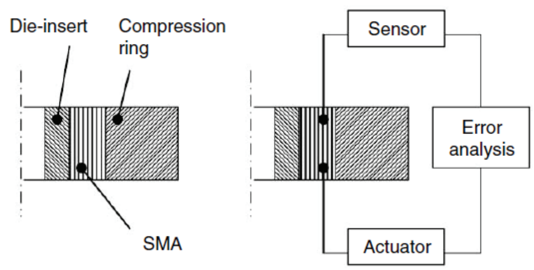

Figure 10 Structure of smart die structure with an SMA (smart memory alloy) for passive compensation (left) and die structure with an SMA for active control (right) [17]

Actuators are devices that converts electrical or physical signals/inputs into mechanical outputs, such as displacement, force, angle, or torque. Actuators used in forming processes enable the control/corrective actions to be carried out i.e., an update of the forming system in accordance with the deviation detected using sensors to obtain product with desired properties. Currently, in the field of metal forming, actuators are predominately employed to perform mechanical work (displacement and force) or to apply heat [18]. The requirements that actuators must meet in order to be efficiently employed in metal forming processes are high dynamic response, high force and high precision.

In metal forming processes, as with many other engineering systems, there are two control approaches applied: open loop and closed loop systems. Systems with closed loop control have the ability to control the system by monitoring the current output and correcting any deviations from the projected output values. This type of control requires an integrated measuring system. A typical closed loop control scheme of an advanced deep drawing tool with integrated process and product sensors is shown in Fig. 11. In most cases, deep drawing control strategies are being developed to enable a controlled flow of sheet blank by adjusting the blank holder force.

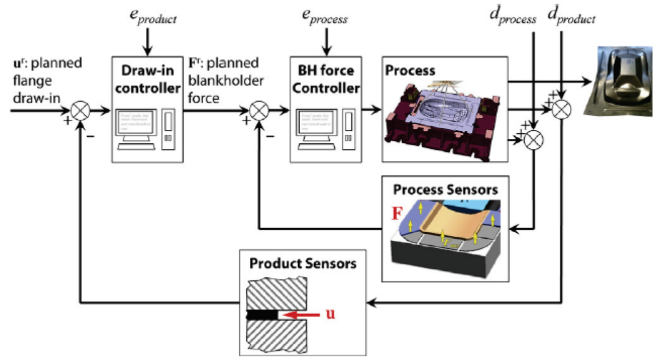

Figure 11 Closed loop control system in deep drawing [18]

Fig. 12 shows several measurement methods for control of bending angle and measuring material elastic springback, which can be integrated into a closed loop control system.

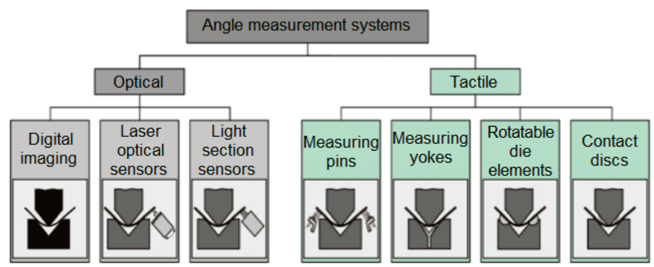

Figure 12 Different bending angle measurement methods [18]

One of the major goals in developing advanced metal forming processes is to reduce uncertainties caused by the variations in input material properties. In this objective, several material control systems based on different strategies were proposed such as the concept of data flow of material property control function intended for feed-forward control of sheet metal forming processes (Fig. 13) using on-line indentation test [20].

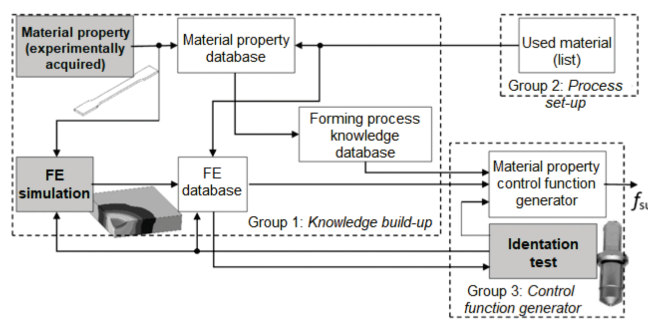

Figure 13 Data flow for material properties control in sheet metal forming [19]

6 CONCLUSION

Key strategy of Industry 4.0 is the creation of new innovation for smart systems such as smart forming tools, which is one of the most important components in metal forming production lines. An advanced smart forming tool is required to be equipped with sensors to measure and monitor various parameters of a forming process as well as actuators to fulfill control actions. In addition, such tool should be highly flexible in order to reduce production cost and increase process efficiency. It is expected that further development of information and communication technologies, non-conventional manufacturing technologies, computer technologies, measuring techniques etc. will significantly enhance the performance (flexibility, "intelligence", tool life, …) of metal forming tools in line with the Industry 4.0.

Notice

The paper will be presented at MOTSP 2021 – 12th International Conference Management of Technology – Step to Sustainable Production, which will take place in Poreč/Porenzo, Istria (Croatia), on September 8–10, 2021. The paper will not be published anywhere else.

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Preliminary communication

Optimisation of Mould Design for Injection Moulding – Numerical Approach

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Abstract: Computer simulation of injection moulding process is a powerful tool for optimisation of moulded part geometry, mould design and processing parameters. One of the most frequent faults of the injection moulded parts is their warpage, which is a result of uneven cooling conditions in the mould cavity as well as after part ejection from the mould and cooling down to the environmental temperature. With computer simulation of the injection moulding process it is possible to predict potential areas of moulded part warpage and to apply the remedies to compensate/minimize the value of the moulded part warpage. The paper presents application of simulation software Moldex 3D in the process of optimising mould design for injection moulding of thermoplastic casing.

Keywords: injection moulding; Moldex 3D; mould; numerical simulation; optimisation; warpage

1 INTRODUCTION

Injection moulding is one of the most important technologies for polymer processing. It allows high production rate of very complex geometrical shapes of moulded parts from wide range of polymer materials with high dimensional accuracy. Final quality, dimensional and shape accuracy (tolerances) of the moulded parts are the result not only of the applied polymer material and mould design, but also of injection moulding parameters. Injection moulding can be controlled through the number of parameters, with the final goal – production of high-quality moulded parts in the shortest possible injection moulding cycle time.

Modern trends in injection moulding, such as application of polymer materials with specific rheological and thermal properties, complex moulded part designs (e.g. thin walls), application of moulds with large number of mould cavities on one side, and requirements of higher quality of the moulded parts (e.g. dimensional and shape accuracy) on the other side, require comprehensive knowledge about polymer materials, mould design and influence of the most important processing parameters on the final moulded part quality. In the recent years numerical simulation of injection moulding became an essential part of the mould design process. It allows mould designers, as well as processors, to predict the occurrences in the mould cavity during all injection moulding phases. It also enables the prediction of the quality of the moulded part, and thus optimisation of the mould design in the early phase. One of the most frequent defects on injection moulded parts is the warpage after ejection from the mould cavity as a result of uneven shrinkage of the polymer melt during solidification. It occurs because of uneven wall thickness of the moulded part and/or uneven cooling of the polymer melt in the mould cavity. [1-4]

The paper presents application of simulation software Moldex 3D in the process of optimisation of the mould design for injection moulding of thermoplastic casing, in order to minimize the value of the moulded part warpage.

2 MOULDED PART WARPAGE

The quality of injection moulded plastic parts is the result of a complex combination of many factors which include used materials, processing parameters, and part and mould designs which can affect the shrinkage behaviour of the injection moulded part. Shrinkage is defined as the reduction in the size of the part as compared to the size of the mould. Material properties, part design, mould design, and processing conditions are influencing factors for non-uniform part shrinkage. Uneven shrinkage will cause moulded part deformation and change in shape, known as warpage. Warpage is a result of formation of stress in the moulded part structure, mainly due to two causes: thermal and pressure induced stresses [1]. In this paper thermal induced warpage will be analysed.

The residual thermal stresses arise when a piece of material is cooled inhomogeneously and when the cooling furthermore causes it to stiffen. When the surface cools, surface layer is free to contract and does not contribute to stress formation. In the following time steps, as the core layer contracts, the solidified surface layer hinders contraction of the core, which ultimately results in a parabolic stress profile with compressive stresses in the surface and tensile stresses in the core [2], as shown in Fig. 1.

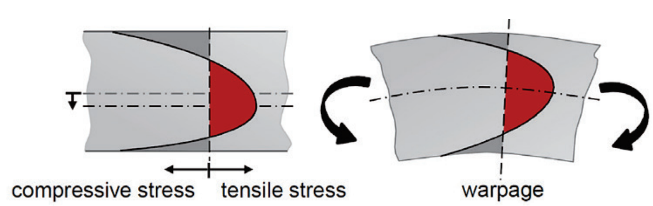

Figure 1 Thermal residual stress distribution across moulded part wall thickness [2]

Moulded part geometry (wall thickness, ribs, corners, etc.) in synergy with mould temperature regulation can have significant and complex influence on the moulded part shrinkage and the resulting warpage. One typical example is uneven shrinkage and warpage of the moulded part due to uneven cooling behaviour in the corners (Fig. 2). During the cooling process in injection moulding, heat fluxes in the mould are lower in inner corners and then the cooling becomes asymmetric (Fig. 2B).

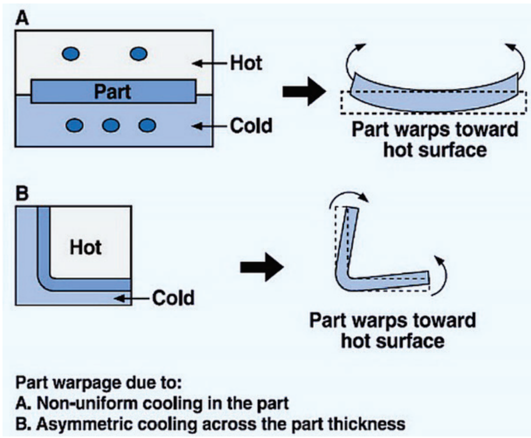

Figure 2 Moulded part warpage due to differential cooling [5]

Cooling channel placement within the mould also determines cooling efficiency and uniformity. Positioning the channels too close to the cavity surface can cause cold spots and uneven cooling. If they are too far away, cooling becomes more uniform but less efficient. As shown in Fig. 3, uneven distances to the cavity surface lead to an uneven heat exchange. [6]

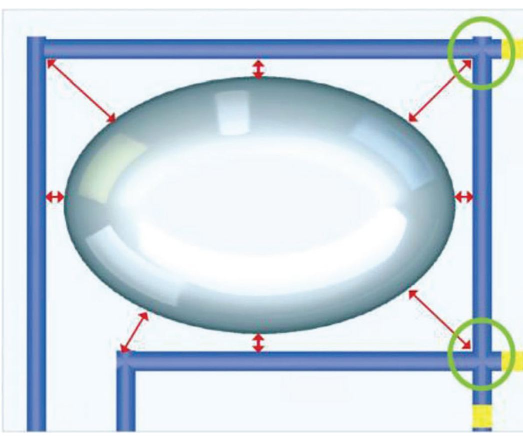

Figure 3 Conventional tooling mould temperature control [6]

For amorphous polymers, one of the most influencing factors in part shrinkage is the mould temperature. With lower mould temperatures, faster cooling rates are achieved which results in less time for macromolecular chain orientation, thus decreasing shrinkage. With mould temperature increase, cooling rate is decreased, which results in higher degree of macromolecular chain orientation, which consequently increases material shrinkage.

For semi-crystalline polymers, one of the most influencing factors in part shrinkage is achieved material crystallinity. With lower mould temperatures and high cooling rates, crystallization is hindered which results in lower part shrinkage. Likewise, with mould temperature increase, macromolecular chains have more time to crystallize which results in increased part shrinkage. [7]

In order to optimise injection moulding process and moulded part properties, many toolmakers apply new strategies in mould design and production. Most of them are focused on optimisation of heat exchange in the moulds in order to reduce injection moulding cycle time as well as to improve moulded part quality and to extend the mould lifetime. Additive manufacturing (AM) tooling with conformal cooling is the possible answer to those requirements. [8]

3 CONFORMAL COOLING

Cooling efficiency is particularly dependent on cooling channel characteristics such as proximity to the mould cavity, cross-sectional area, length, route and surface roughness. However, the design of conventional drilled cooling channels in injection moulds is limited by traditional manufacturing constraints such as the linear nature of the drilling process, which restricts the ability to conform the channel to the contour of the mould cavity (Fig. 4). Variation in the proximity of cooling channels to the mould cavity results in uneven heat dissipation, leading to: increased cycle time, part warping and sink marks, internal part stresses, and reduced tool life due to thermal stresses. [6, 8, 9]

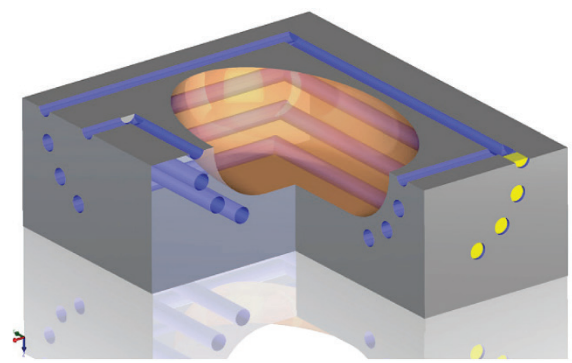

Figure 4 Conventional mould cooling channels [9]

AM mould inserts can be built with internal cooling channels that follow the contour of the cavity beneath the surface (Fig. 5).

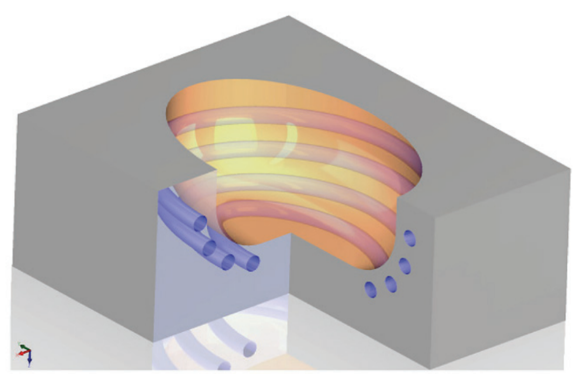

Figure 5 Conformal mould cooling channels [9]

Because the form of the channels follows the contour of the mould, the method is called conformal cooling. Due to the more intensive heat exchange, the productivity of a polymer injection mould can be increased significantly. Conformal cooling channels, applied with no numerical simulation will, generally, result in about a 10% cycle time improvement. On the other hand, conformal cooling channels, applied with numerical simulation and analysis will, generally, result in cycle time improvements from 20 to 40%. [6, 8, 9]

The use of conformal cooling channels also optimizes the moulding process by providing a constant temperature gradient and thus more even heat distribution throughout the mould. When plastic cools evenly, internal stress is minimized. This results in a higher quality part with less warping or sink marks. The more controlled cooling offered by conformal cooling channels allows you to precisely control how the plastic solidifies in the mould and, therefore, to minimize part distortion and shrinkage. [8]

The ultimate objective in optimisation of the injection moulding cycle time and moulded part quality is the creation of a mould temperature control system, which enables a constant and adapted temperature level for the polymer material, during the running injection moulding process on each point of the moulding surface. In order to achieve this result, when applying conformal cooling, appropriate coolant flow strategy and cooling channel shape have to be determined.

When designing conformal cooling channels, it's always recommended to use an injection moulding simulation software package (CAE) in order to identify different temperature zones within a mould so that the conformal cooling channels can be separated and optimised within each region. When designing conformal cooling channels, the first decision that needs to be made is which coolant flow strategy to use. There are three different strategies: zigzag pattern, parallel channel design and spiral channel design (Fig. 6). [8]

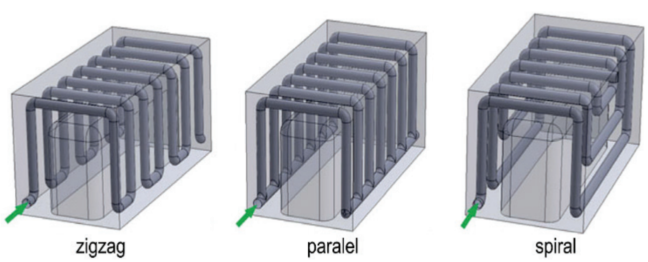

Figure 6 Types of conformal cooling strategies [8]

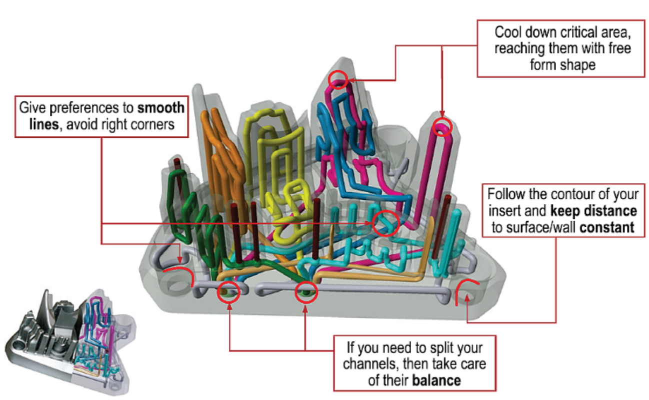

Figure 7 Conformal cooling of complex mould insert [10]

On complex tools, one can sometimes combine cooling strategies where, for example, part of the tool uses a zigzag type strategy, while the rest of the tool employs a parallel strategy. For very complex mould inserts specific rules have to be employed for optimal cooling (Fig. 7).

4 NUMERICAL INJECTION MOULDING SIMULATION

Software for numerical simulation of injection moulding have been developed to simulate the processing of the polymer from a melt phase at the start of injection to a solidified product at the time of ejection. The aim of these applications is to predict and understand the causes of shrinkage and warpage which might occur during production.

In the majority of applications for numerical simulation the injection moulding process is divided into 4 steps (Fig. 8). During the simulation of the cavity filling and melt compression phase, the flow of the thermoplastic melt through the runner system and mould cavity(ies) is analysed. During the phase of packing pressure, the occurrences in the mould cavity are analysed, which include additional material flow into the cavity in order to compensate potential part shrinkage. At the end of the packing phase, the cavity needs to be 100% filled. [11] The analysis of the moulded part solidification consists of determination of the moulded part cooling time and optimal parameters of the mould temperature regulation system. It is also possible to get insight into the temperature field of the mould which substantially determines the quality of the moulded part.

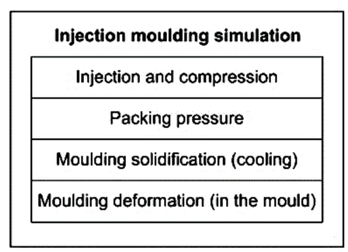

Figure 8 Injection moulding simulation steps [11]

During injection moulding simulation, it is important to decide whether the transient temperature effects are taken into consideration, since transient cooling simulations are more time consuming, but provide more insight in time dependent temperature distributions throughout multiple injection moulding cycles. Within certain amount of time, mould reaches its thermal steady-state, so no cycle temperature variations are present, and the temperature distributions are identical to the values calculated in steady-state cooling simulations.

5 NUMERICAL OPTIMISATION OF MOULD FOR CASING

In this chapter various mould configurations are observed with respect to overall part warpage and functional surfaces flatness measurement. Mould configurations are varied by changing the runner system type (cold runner system vs. hot runner system) and cooling system configuration (conventionally drilled cooling channels vs.

AM produced conformal cooling channels). In all simulations, selected material was widely available ABS Terluran 867M from BASF which is being processed at melt temperature of 250 °C and mould temperature of 80 °C. Polymer part being produced is a generic soap case with average thickness of 2 mm (Fig. 9)

Figure 9 Polymer part - casing

Prior to all actions regarding mould optimisation, overall part thickness needs to be evaluated. Potential part deformations can occur in areas with increased thickness, so these areas need to be carefully inspected during result assessment. Filleted features can lead to thinner part regions if fillet values are not identical on the inner and outer surfaces of part (Fig. 10). These areas lead to increased flow resistance which can lead to hindered pressure distribution during packing phase, which can ultimately lead to increased part warpage [12].

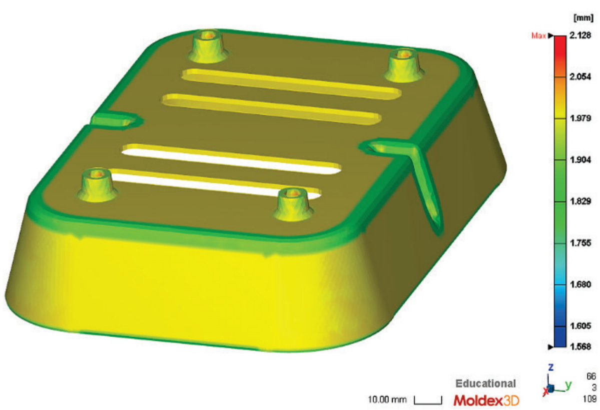

Figure 10 Moulded part thickness distribution

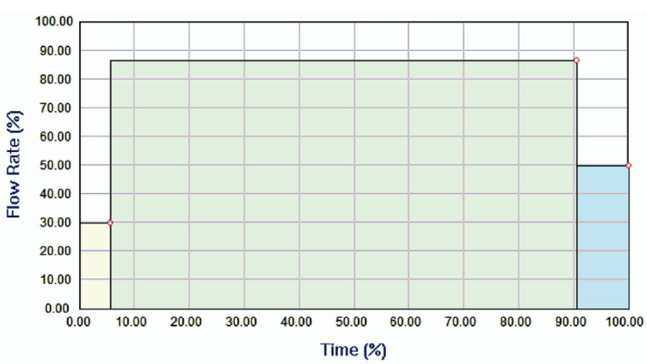

Figure 11 Flow rate profile

Since processing parameters can also influence the part warpage, in all numerical simulations initial processing parameters are defined identically. Maximum machine injection pressure is 155 MPa, while flow rate profiles and packing pressure profiles are defined as shown in Fig. 11 and Fig. 12.

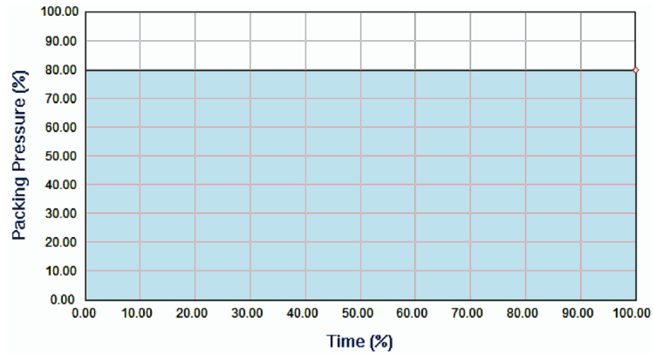

Figure 12 Packing pressure profile

5.1 Cold Runner System with Conventionally Drilled Cooling Channels

The least complex mould configuration consists of cold runner system which ends with cold edge gate, while cooling channels are conventionally drilled (Fig. 13).

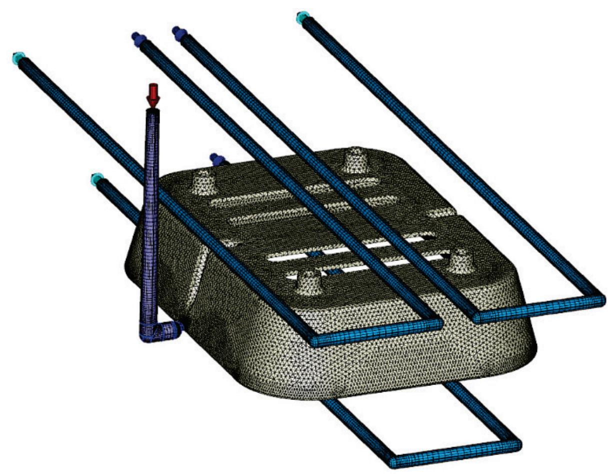

Figure 13 Simulation model with cold runner system and conventionally drilled cooling channels

Since in this mould configuration cavity is filled from one side of the cavity, due to uneven distances of cavity surfaces from cavity inlet point, uneven melt flow front is formed (Fig. 14).

By inspecting the packing pressure distribution (Fig. 15), potential warpage influence is observed. Areas which are farthest from the gate aren't subjected to packing pressure at all, which results in increased shrinkage in these areas. Packing pressure distribution is limited by gate dimensions and its freezing time, since after the gate is frozen, no pressure from injection moulding machine can influence the packing phenomena in areas which are farthest from the cavity gate. In order to improve packing pressure distribution, gate dimensions need to be increased so that the gate freeze occurs later, during the packing phase. This makes packing phase longer, and more influential on the total part warpage. Gate freeze time can also be postponed with melt temperature increase and mould temperature increase. [12]

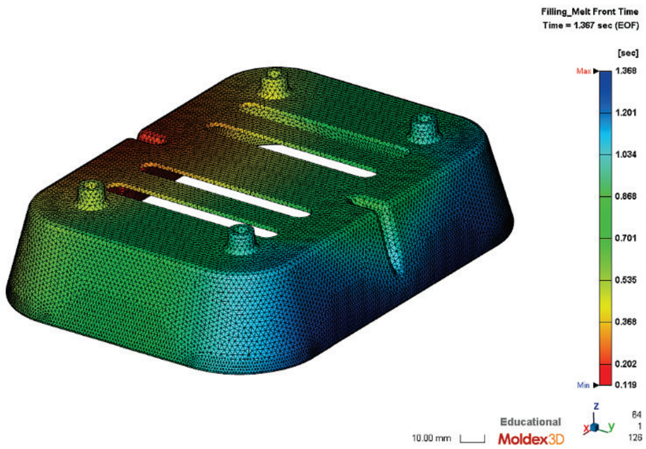

Figure 14 Cavity filling time

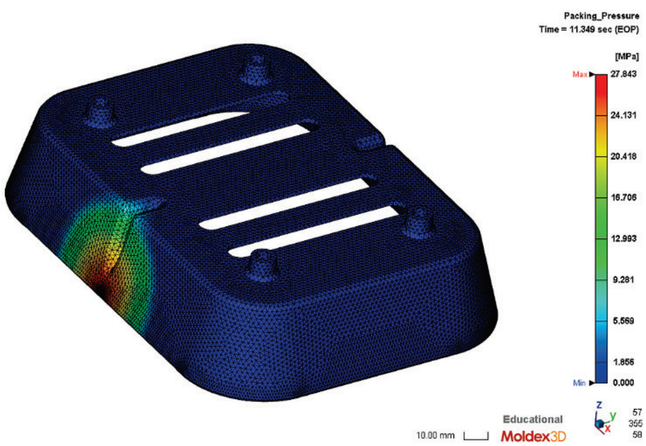

Figure 15 Packing pressure distribution

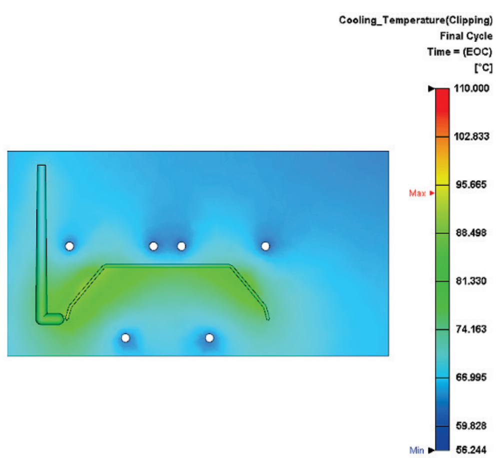

Figure 16 Mould temperature distribution (conventional cooling channels)

Since cooling channels are conventionally drilled, they can't be positioned in optimal locations inside the mould, therefore substantial temperature gradients are visible (Fig. 16) due to sub-optimal cooling efficiency (Fig. 17). In certain areas of the cavity, maximum core to cavity temperature difference is estimated as 20.8 °C (Fig. 16) which results in increased part warpage.

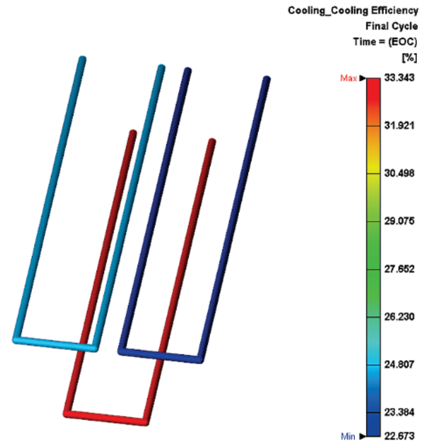

Figure 17 Cooling efficiency of conventionally drilled cooling channels

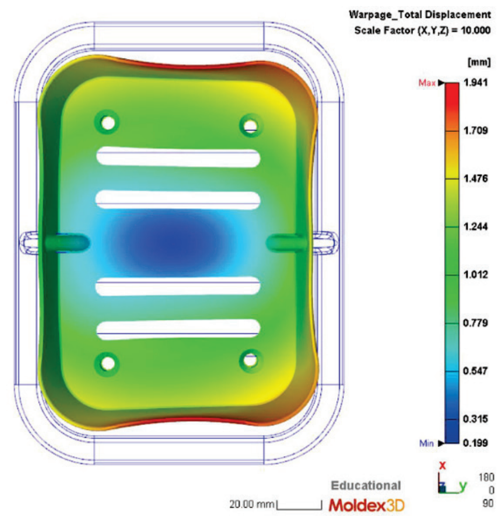

Figure 18 Warpage distribution with conventional cooling

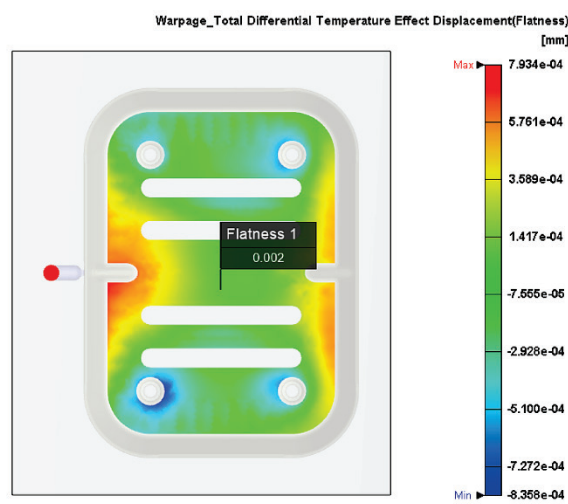

Figure 19 Top surface warpage due to differential temperature effect

By inspecting the final part warpage, it is visible that the areas which are farther away from the gate are more warped

(Fig. 18). It is important to emphasize that the warpage distribution is scaled by the factor of 10, which allows for better comprehension of warpage phenomenon.

Flatness of the top surface has been inspected (Fig. 19, Fig. 20) and the results show that the top surface is warped, but the most influential source of warpage comes from differential shrinkage.

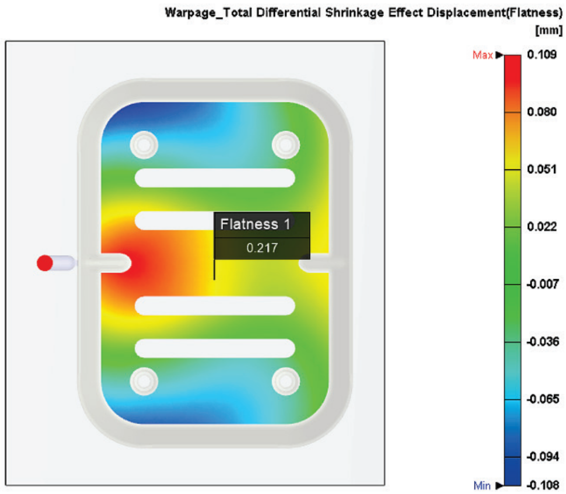

Figure 20 Top surface warpage due to differential shrinkage effect

5.2 Cold Runner System with Conformal Cooling Channels

By utilising the possibilities of AM, conformal cooling channels can be produced in order to improve thermal characteristics of the mould. In this mould configuration, both core and cavity are designed with inclusion of conformal cooling channels which are evenly spaced in the mould cavity (Fig. 21). It is important to state that the material characteristics of additively manufactured mould inserts are not identical to conventionally manufactured due to the nature of the additive manufacturing process (e.g. hindered thermal properties due to internal voids), but for this example identical material characteristics are considered.

In this configuration, heat can be more evenly extracted across all surfaces of the cavity, so better temperature distributions are achieved (Fig. 22).

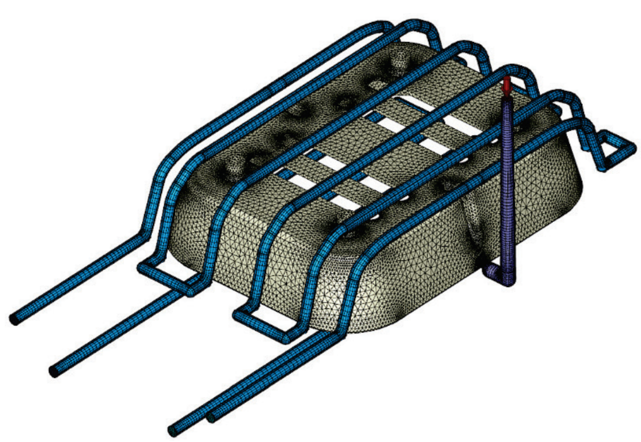

Figure 21 Simulation model with cold runner system and conformal cooling channels

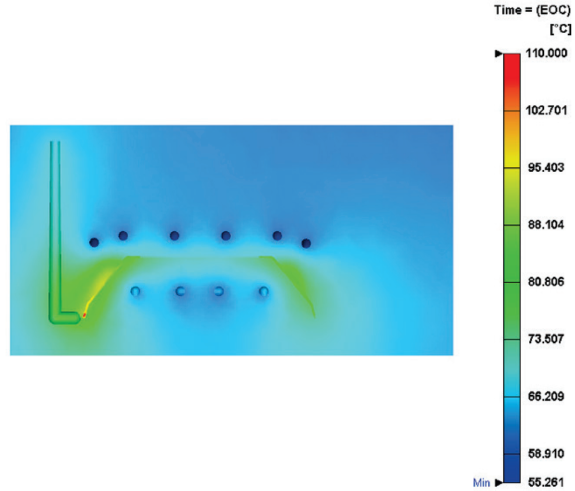

Figure 22 Temperature distribution of conformally cooled mould

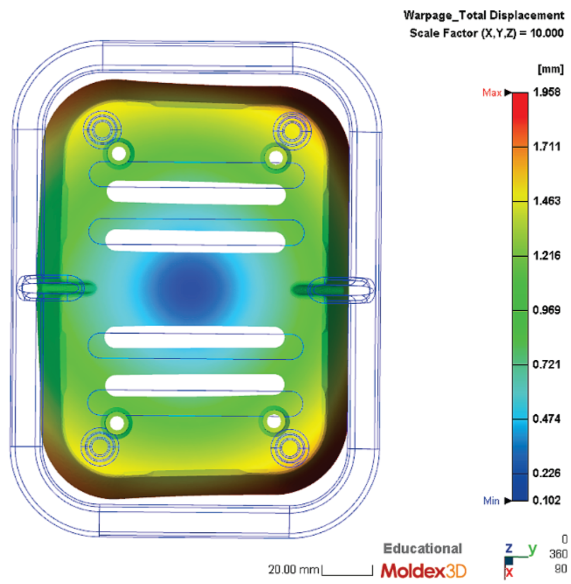

Figure 23 Warpage distribution with conformal cooling

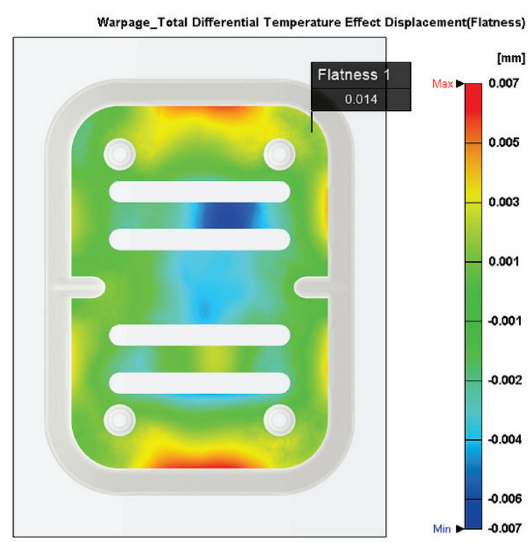

Figure 24 Top surface warpage due to differential temperature effect

Still, due to the runner system configuration, most of the warpage is related to differential shrinkage which leads to only slight improvement regarding total part warpage (Fig. 23).

Flatness measurement shows that the conformal cooling channels have improved the surface flatness regarding differential shrinkage effect. The warpage has worsened a bit due to differential temperature, but the temperature caused warpage value is 0,014 mm which is acceptable result (Fig. 24 and Fig. 25).

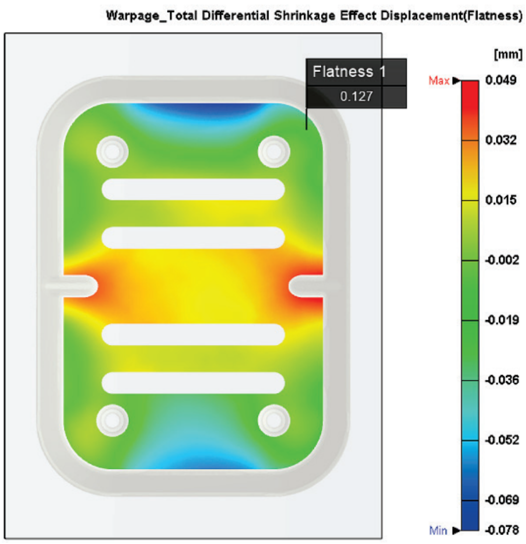

Figure 25 Top surface warpage due to differential shrinkage effect

5.3 Hot Runner System with Conformal Cooling Channels

In order to reduce the differential shrinkage problem, gate location should be relocated to the optimal position based on better melt flow distances inside the cavity. By placing the gate location in the middle of the top part surface (Fig. 26), during fill phase polymer melt travels the least through the cavity. Moreover, by utilising hot runner system, packing pressure distribution is more even which results in additional warpage reduction.

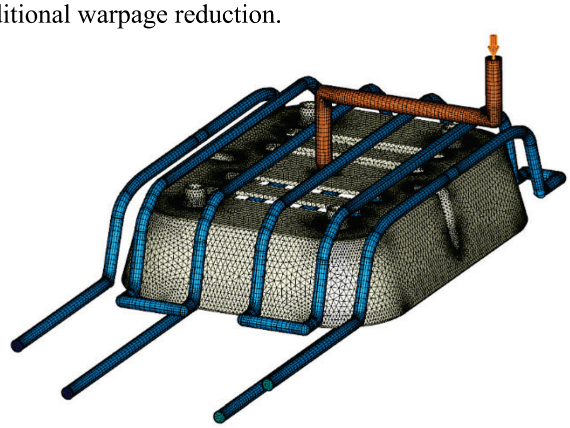

Figure 26 Simulation model with hot runner system and conformal cooling channels

Temperature distribution (Fig. 27) shows that there is no substantial temperature difference between core and cavity.

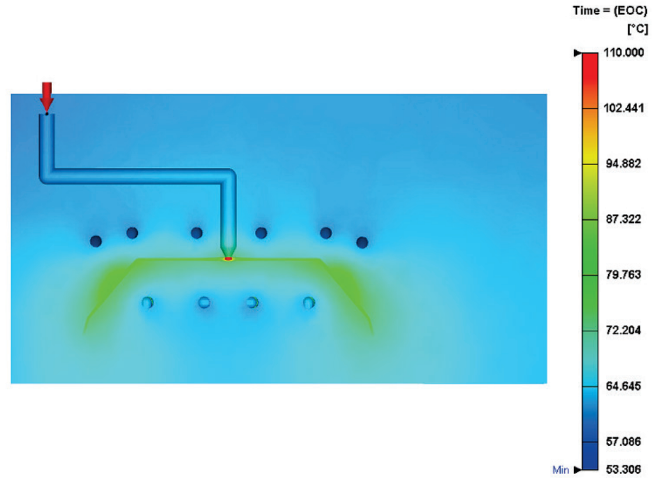

Figure 27 Temperature distribution of conformally cooled mould with optimal gate placement

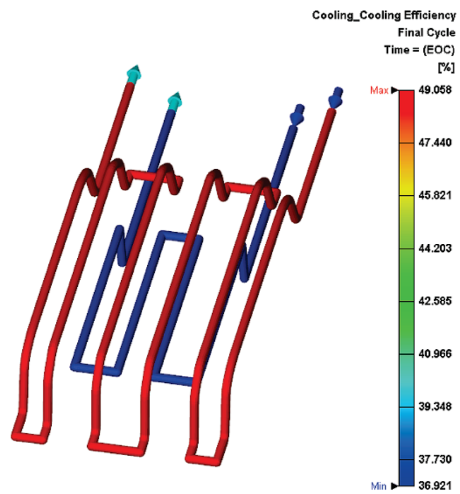

Figure 28 Conformal cooling channels efficiency

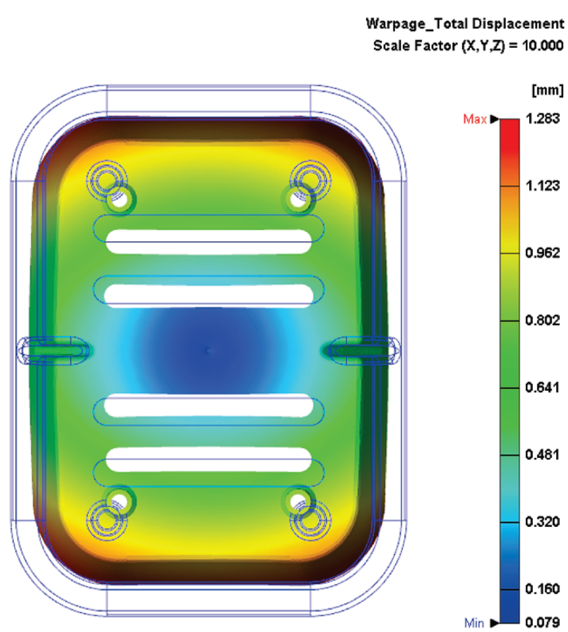

Figure 29 Warpage distribution with hot runners and conformal cooling

Conformal cooling channels have improved efficiency due to optimised placements related to mould cavity surface (Fig. 28).

By inspecting the warpage, it is visible that the warpage distribution is symmetrical, which can be compensated with anisotropic part scaling prior mould design and detailing (Fig. 29).

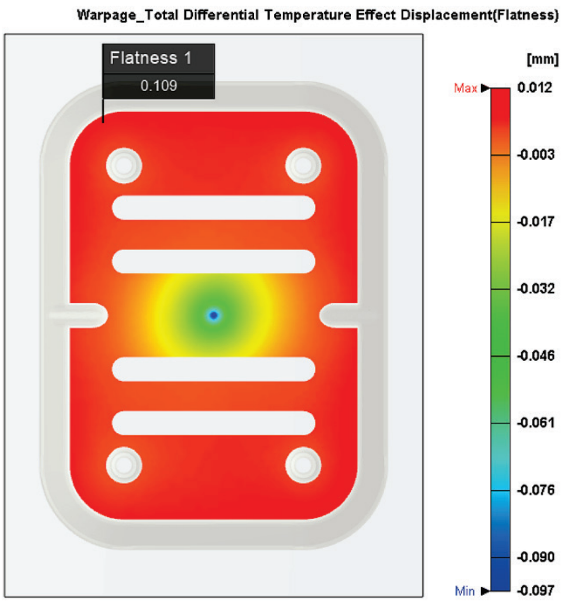

Figure 30 Top surface warpage due to differential temperature effect

Top surface flatness is still sub-optimal, so in order to improve it, further optimisation needs to be done from the processing parameters side. Also, due to increased heating from hot runner system, warpage due to differential temperature effect has substantially increased (Fig. 30, Fig. 31).

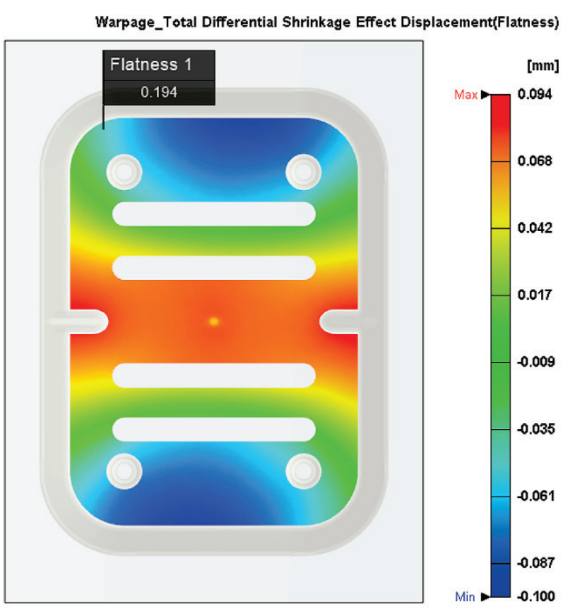

Figure 31 Top surface warpage due to differential temperature effect

5.4 Results Discussion

The best results regarding part warpage are achieved with cold runners and conformal cooling (Fig. 32). Top surface flatness which originates from differential temperature effect is the best in the case of cold runners and conventional cooling. Since flatness was measured on the top surface, by placing the hot runner gate at that plane, warpage due to differential temperature effect is the worst in the case of centrally placed hot runner gate and conformal cooling channels. Regarding the differential shrinkage effect, the best results are achieved with cold runners and conformal cooling channels.

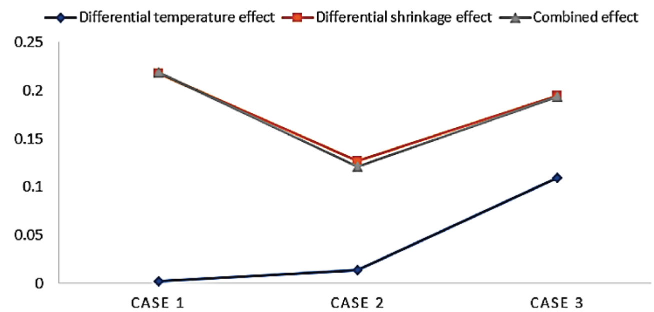

Figure 32 Top surface warpage overview

6 CONCLUSION

By utilising numerical simulation in mould optimisation, total part warpage was reduced by approximately 28% in the case of application of cold runner system and conformal cooling channels. Since all optimisation tasks were done using numerical simulations, additional tooling costs are avoided. In low to medium scale production, tooling costs have a substantial impact on total production cost, so appropriate mould configurations need to be taken into consideration. Moulds with cold runner systems and conventionally drilled cooling channels are the cheapest mould configurations, but due to sub-optimal gate location, packing conditions are not fulfilled through all regions of mould cavity. This leads to differential shrinkage, which results in substantial amount of part warpage. By utilising hot runner system and conformal cooling channels, tooling costs are higher, but total warpage is significantly reduced, and surface flatness improved. Some degree of warpage reduction is possible with further optimisation of processing parameters.

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Subject review

The Five Dimensions of Digital Technology Assessment with the Focus on Robotic Process Automation (RPA)

Bernhard Axmann*, Harmoko Harmoko

Abstract: In Technology Management, the assessment of new digital technologies is a challenging process. Most assessments are focusing on cost & benefit. These approaches often fail because main points are neglected. In this paper, the holistic approach of "The Five Dimensions of Digital Technology Assessment" will be described with the example of RPA (Robotic Process Automation). RPA is one of the most promising technologies to save data processing efforts in the office. The Five Dimensions of RPA Assessment is performed by assessing the benefits, technology readiness, usability, company readiness, and the costs that burden the company in the RPA implementation.

Keywords: assessment; benefit; company readiness; cost; RPA (Robotic Process Automation); technology readiness; usability

1 INTRODUCTION

Robotic Process Automation (RPA) is not a physical robot. It is software that mimics human behavior in the interaction with a computer. It performs rule-based tasks such as: sending an email, opening attachments, logging into the application, moving files or folders, filling the form, scarping data from a webpage, extracting data from pdf or images, and so on [1, 2].

In the next few years, the RPA's market share is estimated to increase by 20-30% per year or achieve US$ 2.46 billion in 2022 and US$ 3.97 billion in 2025 [3]. It is in line with the belief that RPA can increase productivity by 86%, quality by 90%, and cost reduction by 59% in the office [1]. Unfortunately, these benefits are not the only factors that consider RPA implementation in the companies. The lack of information about technology readiness, usability, and cost, is still an obstacle for the company to apply RPA immediately [4, 5].

This research will provide information as well as assesses RPA (Robotic Process Automation) with **The Five Dimensions (5D) Assessment** (benefit, technology readiness, usability, company readiness, and cost) which can be used as an initial reference before applying RPA. Using 5D aims to make the RPA assessment process is easier and comprehensive.

2 STATE OF KNOWLEDGE

2.1 Digital Technology Assessment

The implementation of RPA cannot separate from digitization because all automated processes use digital data. When the documents or data are not in a digital form, then OCR (Optical Character Recognition) and additional features need to be embedded. Similar to other digital technologies, the RPA must be assessed carefully. Hence, this research will conduct an objective and comprehensive RPA assessment using the Five Dimensions (5D) Digital Technology Assessment, which focuses on benefits, technology readiness, usability, company readiness, and costs (see Fig. 1).

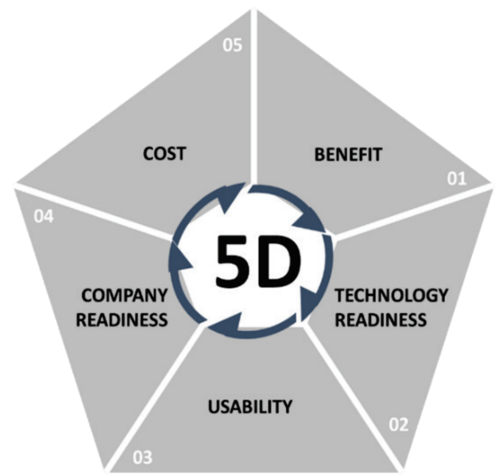


Figure 1 5D Digital Technology Assessment

- **Benefits** are the efficiency of working hours, the reduction of cost, customer satisfaction, and others.
- **Technology readiness** is the readiness of new technology is reflected by technology development and market expectation (Gartner Hype Cycle).
- **Usability** is the understandability, learnability, and attractiveness of new technologies, as measured with the need for internal and external experts.
- **Company readiness** is the efforts for preparing organization, people and data, before new technology implementation.
- **Cost** is the direct cost for investing, operating, and maintaining new technology such as software licenses, installation, custom development or additional feature, compatible hardware, electricity, employee salaries, maintenance, web hosting, server rental, and others.

2.2 Robotic Process Automation

The Industrial Revolution 4.0 is a combination of a physical and digital system that changes the way humans live. It is supported by various technologies such as; the

Internet of Things, Automation, Simulation, Big Data Analytics, Vertical & Horizontal Integration, Augmented Reality, Cloud Computing, Additive Manufacturing, and Cyber Security. I4.0 uses the principles of Interoperability, Modularity, Service Orientation, Real-Time Capability, Decentralization, and Virtualization [7].

In the context of automation, the area consists of automation in the offices and factories. The development of office automation is not as fast as automation in the factory. Since 1980, the factory's degree of automation has risen by 75%, while automation in the office just increased by 3 % [8]. Currently, there are several office automation technologies. One of the most promising is RPA, which has a growth rate is around 30% annually [9].

The RPA consists of three types, the attended robot, unattended robot, and the combination of them (hybrid robot). The attended robot works directly on the user's computer and acts as a personal assistant, thus requiring the user to trigger or start the process. In contrast, unattended robots work on the company's server and run without or less human interference. The hybrid robot is a combination of attended and unattended robots [2].

There are three major RPA providers currently on the market; UiPath, Automation Anywhere, and Blue Prism [10, 11, 12]. **UiPath**, or the previous name "DeskOver," was established in 2005 in Bucharest, Romania. It develops an efficient, robust and stable, robotic workforce controlled anytime and anywhere (cloud-based) [13, 14]. **Automation Anywhere (AA)**, or the previous name Tethys Solutions, LLC, was founded in 2003. It has operated more than 1.5 million bots (bots are the other name of RPA robot) in 20 countries [11]. The latest version of this software is Automation Anywhere Enterprise A2019, which uses a web or cloud-based platform and IQ bots as the artificial intelligence feature to recognize documents. **Blue Prism** was developed in 2001 in Warrington, United Kingdom. The initial goal of Blue Prism was to eliminate manual data entry processes with low returns and high risks. Blue Prism currently offers intelligent and responsive bots that handle various data types in the complete automation process [15, 16].

The advantages of RPA, such as increased efficiency, productivity, and accuracy, have been described in previous studies [1, 2, 4, 10]. Unfortunately, those have not immediately attracted the companies. One of the obstacle factors is a lack of knowledge about RPA and its future opportunities [5]. Therefore, this study will provide objective information about RPA and how to evaluate it.

3 RESEARCH METHODOLOGY

The research will use two methodologies, a literature study, and an expert interview, to answer the following research questions (see Fig. 2):

- What is 5D Digital Technology Assessment?
- What is Robotic Process Automation?
- How to evaluate RPA with 5D Digital Technology Assessment?

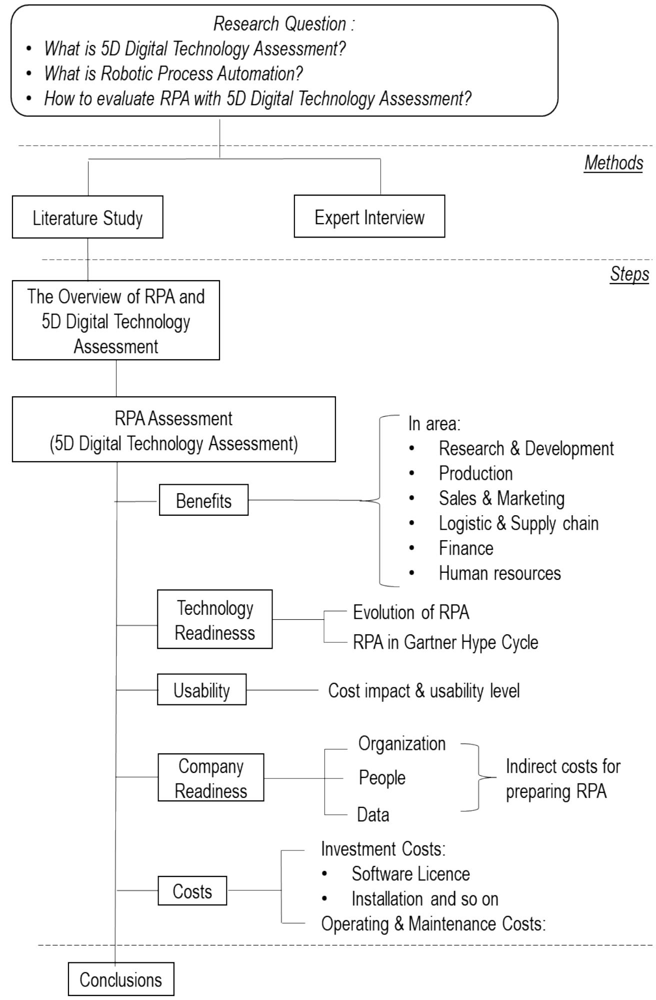


Figure 2 Research Methodology

The research begins with gathering information related to 5D Digital Technology Assessment and RPA, such as; how they look, their development over time, etc. The assessment process will be started by assessing the benefits of RPA, which aims to build company motivation and confidence in applying RPA. The Benefit assessment will capture all areas where RPA is potentially implemented, such as Research & Development, Purchasing, Production, Sales & Marketing, Logistic & Supply chain, Finance, and Human Resource Department. After that, the research will assess the technology readiness, which includes the development of RPA over time and its position in the Gartner hype cycle (GHC).

The usability assessment aims to see how much internal and external assistance is needed in the RPA implementation. The company readiness assessment is carried out by capturing the indirect costs to prepare: organization, people, and data before implementing the RPA. At the end of the RPA assessment, we will measure the cost dimension, which consists of direct investment costs, operational costs, and maintenance costs that arise when the RPA is implemented.

Table 1 The Benefits of Robotic Process Automation (in General)

The Benefits of Robotic Process Automation	
Area	Benefits
Research & Development	Tangible: • Optimize patent research & collect information about new technology that will be embedded in the developed product [19]
	Intangible: • Increase engineer or designer motivation & creativity by freeing them from routine tasks such as patent research.
Purchasing	Tangible: • Optimize invoicing process • Automate bidding & on-boarding process of new supplier [20]
	Intangible: • Increase supplier & prospective partner satisfaction by accelerating invoice, bidding, and on-boarding process.
Production	Tangible: • Manage BoM (Bill of Material) • Automate the planning or reporting process of production activities, material requirements, and so on [21]
	Intangible: • RPA was freeing employees from routine workloads such as writing production reports.
Sales & Marketing	Tangible: • Collect data on customer preferences and market trend • Automate recording process of customer data & improving customer relationship management [22]
	Intangible: • Increase customer satisfaction by 24/7 customer service • Increase & maintain company's image and reputation
Logistic & Supply chain	Tangible: • Manage inventory data • Automate recording process of delivery (incoming material and outgoing products) [23]
	Intangible: • Freeing employees from routine workloads such as entering data of inventory
Finance	Tangible: • Automate the reporting and updating process of the treasury, general ledger, and taxation. • Automate the employee payment process (payroll) [24]
	Intangible: • Avoid corruption through a transparent and accountable budgeting process.
Human Resource Department	Tangible: • Facilitate the on-boarding process of prospective employees [25]
	Intangible: • Avoid nepotism through a transparent and accountable recruitment process

4 5D - 1st STEP: BENEFIT

The benefits are cost savings, efficiency, and all the stakeholders' advantages due to the new technology implementation [17]. It can be tangible and intangible. The tangible benefit is a benefit that can be measured by a number, such as; increasing process time, reducing costs, smoothing cash flow, increasing income, improving quality & accuracy process, etc. While intangible benefit is a benefit that can be felt but difficult to measure by monetary outcomes, such as; increasing customer satisfaction, increasing employee motivation & creativity, growing market share, improving the reputation of a company brand, and so on [17, 18]. The implementation of RPA brings tangible & intangible benefits in many areas of the company (see Tab. 1).

Assessment: The decision to start RPA must be in line with the company's plans & strategy to reduce labour efforts in the office. The Table above informs companies about the potential benefits of RPA implementation. However, please keep in mind that the magnitude of benefit depends on selecting tasks /processes that will be automated. RPA is more significantly beneficial if the automated tasks/processes have high repetition and added value.

5 5D – 2nd STEP: TECHNOLOGY READINESS

In the initial phase of RPA (RPA 1.0), The Assisted Robot automates various tasks or processes on an individual desktop to reduce process times, save cost, and improve accuracy. Unfortunately, the assisted RPA still requires human intervention in real-time operation [26]. In the second phase, or RPA 2.0, robots are installed on multiple desktops, which run without or less human intervention. The robots will automatically log into the specific computer, start the operation, observe the progress, and stop the operation. Those steps are controlled in the dashboard, which provides several windows for assigning tasks, changing destinations & queues, and reacting to robot output (if necessary). The third phase, or RPA 3.0, is cognitive RPA that uses artificial intelligence, machine learning, computer vision, and natural language processing to carry out long and complex tasks through intelligent end-to-end processes (see Fig. 3)[26].

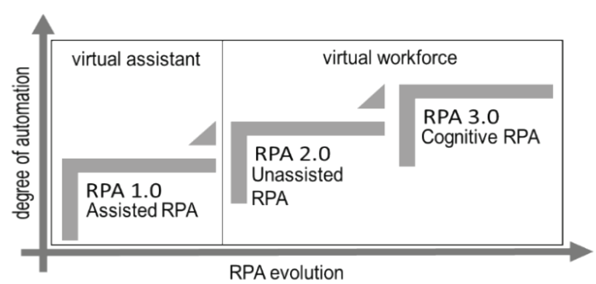


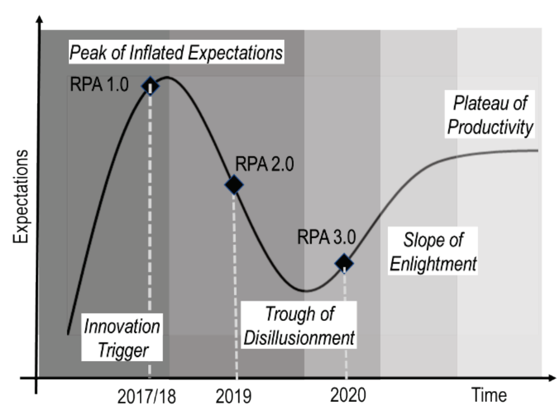
Figure 3 RPA Evolution [26]

Gartner Hype Cycle (GHC) is a brief overview of market expectation and perceived value of the new technology and innovation. It was introduced by Gartner Inc. in 1995 and updated every year as development technology and changing market expectation. Currently, 90 GHC has described various technology such as AI, digital marketing, advertising, and others [27]. Figure 4 shows a modification of GHC with five different areas from "1" to "5". The Intense grey color depends on the length of introduction time & the risk of failure. The darker grey means the longer introduction time and the higher risk to apply new technology.

At the beginning of the cycle, market reactions to new technology varied from less attractive to euphoric. An increasing market share usually follows euphoria. It happened at the first presence of RPA to the market, until 2018. At the time, RPA was "booming", and its position lies on the "Peak of Inflated Expectations" (see Fig. 4). People think of RPA as an office automation technology that promises full automation services with versatility and user-friendly. However, that is wrong, and the people were disappointed because RPA is not fully automated. Moreover, it is still unable to recognize physical documents such as hardcopy or handwritten documents. This disappointment has brought the "Trough of Disillusionment" in 2019 (see Fig. 4).

In 2020, Gartner plotted RPA on the way to the "Slope of Enlightenment" (GHC) because of the high expectation of cognitive RPA. The embedded cognitive capabilities such as; artificial intelligence, machine learning, and natural language processing make RPA recognize the physical documents and optimize processes (process mining). The cognitive capabilities are believed, can rise RPA to the "Productivity Plateau" (see Fig. 4).

The cognitive RPA has been adopted by UiPath and Automation Anywhere. The AI skill of UiPath, called AI Fabric, teaches a robot to read and understand different kinds of physical documents in different languages (document understanding feature). It allows robots to interact with screens (computer vision feature) and create dialogues to human-being (chatbot feature). Moreover, the robot is also taught to optimize processes using process mining & task mining features [28]. Like UiPath, The Automation Anywhere also has an artificial intelligence feature called IQ bots [29]. UiPath and Automation Anywhere make RPA ready to use for the fully automated end-to-end process with the AI skill.



Area	1	2	3	4	5
Introduction time	very long	long	middle	short	short
Risk to fail	very high	high	high	middle	small

Figure 4 The RPA Position in Gartner Hype Cycle[1]

Assessment: Implementing RPA when its technology in the area "3" is a wise choice and highly recommended because of the lower risk and shorter introduction time. However, if the company has core competencies and a large workload in office automation such as online-shop, banking, and insurance company, starting RPA as early as possible or when the technology is still in the area "1" will increase competitiveness although it is high risk and time-consuming.

Currently, the RPA has reached the "3" area. Hence, today is the right time for all companies to consider RPA as an office automation solution, although RPA's AI skills still need to be improved to reach the areas "4" and "5" (Plateau of Productivity).

6 5D – 3rd STEP: USABILITY

Usability is a broad term that refers to the state where the functions, features, and ways of using technology are easier to understand and learn by the users [30]. The New technology is easy to use when it does not require consultants' and external experts' assistance for installation, operation, and maintenance, thus saving costs (see Fig. 5).

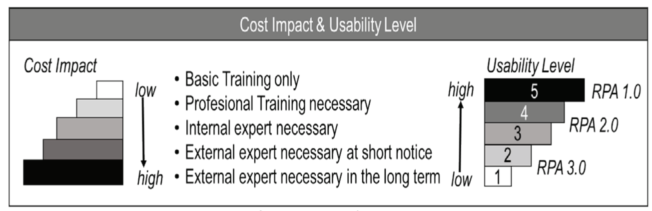


Figure 5 Cost Impact & Usability Level

In the context of RPA, the consultation service includes the advice to select the suitable software, the number of robots that will be deployed, and the potential process that will be automated. An external expert will be hired for programming software and maintenance of the robot's performance during the operation. However, for a company that does not have many robots, those kinds of service and external experts are unnecessary [31]. The consultation cost cannot be well determined because it depends on the specific service and the automated process's complexity. Nevertheless, as a primary reference, the RPA consultant salary in the job market is around US$ 50 - 100/ hour (college graduates in RPA consulting firms) [35, 36]. So, the actual consultation cost can be 300-400 % higher than that.

To make RPA more user-friendly, the RPA providers offer a self-learning module of basic RPA for free. They also provide free software access to community editions. UiPath collaborates with universities worldwide to provide free training for lecturers and students through the UiPath academic alliance scheme. Meanwhile, Automation Anywhere has a similar scheme, called Automation Anywhere University. The RPA tutorials using UiPath, Automation Anywhere, and Blue Prism are also easily found on the internet and YouTube channels. For small companies, UiPath has studio X, which accommodates SMEs' limited skill in applying RPA. Although it is not so powerful as UiPath studio, it is enough to encourage SMEs to use RPA. From the perspective of usability, UiPath is superior to other

[1] Figure 4 is author's illustration based on Gartner data 2017–20 [39, 40, 41]

providers. It is confirmed by a Gartner study about the leader company in the RPA software market [12].

Assessment: The usability rating depends on which RPA solution we want to introduce: RPA 1.0, RPA 2.0, or RPA 3.0. It starts at the lowest level "1" to "5" as the highest level (see Fig. 5). For **RPA 1.0**, the usability is rated with "5", which has the lowest cost impact. The implementation of RPA 1.0 is relatively easier than others. The users do not need to have a high skill of programming. In RPA 1.0, the companies do not need external experts. The users (employees) who do not have an IT background can learn it through tutorials on the internet and the RPA community (see Fig. 5). **RPA 2.0** is rated between levels 3&4 usability. Advanced training and internal expert assistance are needed because robots work on many computers connected to the servers and corporate networks (see Fig. 5). **RPA 3.0** is rated between 1&2. The company needs external expert assistance because cognitive RPA involves many advanced technologies and knowledge of artificial intelligence, machine learning, and natural language processing. The need for external expert assistance depends on the complexity of the automated process and the number of deployed robots. The RPA 3.0 requires higher costs than RPA 1.0 & 2.0. Nevertheless, it generates higher benefits than others (see Fig. 5).

7 5D – 4th STEP: COMPANY READINESS

In the context of implementing RPA, company readiness is defined as the ability to prepare the organization, people, and data before adopting RPA into business processes. The preparation is related to indirect costs that unwittingly burden. The cost of preparing organizations, people, and data in RPA implementation is relatively smaller than other automation technologies because RPA can be deployed and integrated into existing IT systems (without creating new systems) [2, 11]. However, it depends on which RPA solution we want to introduce: RPA 1.0, RPA 2.0. or RPA 3.0. The integration process of RPA 1.0 is easier than RPA 2.0 and 3.0 because it works specifically on the computer where the robot is installed. Whereas in RPA 2.0 and RPA 3.0, the robots work on several computers and form a network. The network must be controlled and coordinated by an orchestrator. Currently, the RPA orchestrator uses a cloud-based platform, so the robots can be remote-monitored in real-time and deployed across the world.

Table 2 Professional Training Cost [32]

RPA	RPA platform	Price	Duration
Cloud Foundation	Automation-Anywhere Blue Prism Pega RPA UiPath	0 – $160	25-26 hrs
Edureka	UiPath	$350	24 hrs
Multisoft Virtual Academy	Blue Prism	$390	30 hrs
Simplilearn	Automation-Anywhere UiPath	$799-999	36 hrs

RPA training courses play an essential role in educating people to build RPA and provide them with the requisite skills to fulfil RPA initiatives' need. There are a lot of basic tutorials available online for free. Nevertheless, for advanced RPA, there is professional training which costs as seen in Tab. 2.

Assessment: For the company readiness assessment, we made assumptions of costs for preparing organization, people, and data, which need to be verified in the future (see Tab. 3). To implement **RPA 1.0**, the companies do not need to change the organizational structure and process flow because the robot does not replace employee's functions in the organization, and it just acts as a personal assistant who helps individual employees to accelerate his / her tasks. RPA 1.0 does not require a high level of programming skill. One or two days of basic training is considered sufficient to run RPA 1.0, so the training cost and organization cost are estimated the lowest compared to RPA 2.0 and RPA 3.0. In RPA 1.0, the processed data must be structured and digitalized. Physical documents such as handwritten paper cannot be processed, by RPA 1.0, because it just automates data from one application to another, such as the excel file to the ERP system.

In **RPA 2.0**, the organization and process flow are slightly changed because employees' roles are no longer an executor but as administrator or robot supervisor. Therefore, additional training as an administrator is needed. In RPA 2.0, the processed data can be structured but may un-digitized. Physical documents such as paper must first be scanned or photographed before being processed by the robot.

In **RPA 3.0**, the organization and process flow are changed to include RPA experts. The implementation of RPA 3.0 provides excellent benefits for companies, but on the other hand, it also requires expertise to ensure the cognitive robot can run properly. Becoming a cognitive RPA expert requires additional training that is longer than basic and administrator training. The cognitive abilities in RPA 3.0 can process unstructured and undigitized data, such as handwritten documents. RPA 3.0 can also optimize the process by process & task mining features. Thus the organization and process flow can be improved over time.

Table 3 Preparation Cost Assumptions

Preparation	RPA 1.0	RPA 2.0	RPA 3.0
Organization	Organization no change & no cost	Organization need 10 -20 % administrators time	Organization need administrator + experts are hired 1 - 3 month
	$0 - 500 /year*	$5,000 – $10,000 /year*	$ 20,000 - 70,000 /year*
People	Training days: 1-2 days per person	Training days: 1-2 days per person, + 5-10 days administrator	Training days: 1-2 days per person, + 5-10 days administrator, experts 5-15 days
	$0 - 100* /day	$100 - 200* /day	$200 - 500* /day
Data	Only process: digitalized & structured data	Can process: undigitized & structured data	Can process: undigitized & unstructured & data

*author's assumptions

8 5D 5th STEP: COST

The meaning of costs in this chapter is the amount of money that a company spends related to the investment, operations, and maintenance of RPA. The number of costs depends on the RPA type and the process being automated. Logically, the more complicated processes, the higher costs will be incurred.

8.1 Investment Cost

The most prominent component in the investment cost of RPA is the software license. Generally, it is paid once and must be renewed every year. The following is a list of estimated RPA license prices (see Tab. 4).

Table 4 RPA License Price

Vendor	Estimated Pricing
UiPath	It starts at $3,990 per year, per user. There is a free version [33].
Automation Anywhere	For Small Business, starts at $ 750 per month or $ 9,000 /year [34]
Blue Prism	The standard licensing fees are around $100,000/ year for one customer [35]
Microsoft Power Automate	Monthly license cost between $12.60 – $421.50 [36]

8.2 Operating & Maintenance Cost

The Operating costs are considering elements when implementing RPA. Usually, the companies just focus on installation costs and get stuck on operational costs. The Operational costs are needed to scale the RPA in the long run. In 2019, the HFS research stated that only 13% of companies effectively scaled their office automation [37]. Most RPA providers quote an average total operating cost for one robot of around € 500 per month. With 50 robots, the cost goes up to € 300,000 per year [38].

Table 5 RPA Costs

Providers	RPA 1.0	RPA 2.0	RPA 3.0
UiPath	Studio X Attended Bot	Studio Pro Unattended Bot Orchestrator	Studio Pro Unattended Bot Orchestrator AI Fabric
	$2,000 – 4,000* /year	$20,000 – 30,000* /year	$30,000 – 70,000* /year
Automation Anywhere	AA2019 Attended bot	AA2019 Unattended bot Orchestrator	AA2019 Unattended Bot Orchestrator IQ Bot
	$2,000 – 9,000* /year	$20,000 – 30,000* /year	$30,000 – 70,000* /year

*author's assumptions

The RPA maintenance costs are highly dependent on the automation scale of the company. The more robots that are deployed, the higher the maintenance cost. In SMEs, the deployed robots are less than large companies so that the internal IT department can carry out the maintenance and supervision tasks. Meanwhile, in large companies, the maintenance and supervision of RPA can be sub-contracted to RPA service providers (outsourcing) because if it is done alone, the annual cost can be higher up to € 70,000 / officer who supervises 10 robots [31].

Assessment: In the cost assessment, each RPA solution has a different cost figure. To implement RPA 1.0, companies need a software license and an attended bot. As for RPA 2.0, companies need to add orchestrators and unattended bots, so the price is higher. For RPA 3.0, which AI embeds, the price is relatively the same as RPA 2.0 because the latest version or update RPA software (Studio Pro & AA2019), is including cognitive features (AI Fabric & IQ bots) free. The increasing costs of RPA 3.0 occur if the company requires unique and powerful AI features beyond the offered feature by RPA providers, such as Hypatos and others. The cost figure of RPA does not mention by a provider (UiPath or Automation Anywhere) openly on their website because it depends on the complexity of automated process and negotiation with a customer. The following table is an author's assumption which contains the range cost of RPA solution that needs to verify in the future (see Tab. 5).

9 FUTURE RESEARCH PLANS

After understanding RPA and the 5D concept in this paper, future research will lead to RPA's further assessment and further application of 5D Digital Technology Assessment. For the RPA assessment, the study will conduct surveys or interviews to explore the essential requirements of RPA implementation, such as human resources skills, organizational issues, and costs. The respondents will be the companies that have implemented RPA and consulting companies that handle RPA projects. With robust and actual data, the RPA assessment will be more accurate and accountable.

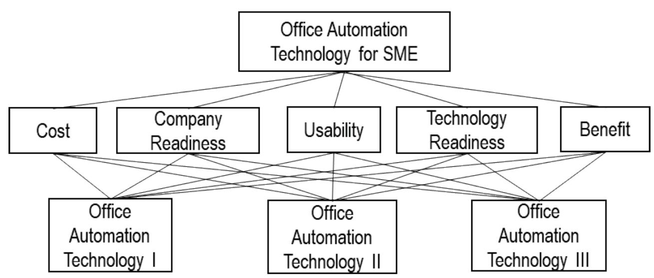


Figure 6 AHP hierarchy in selecting office automation technology for SMEs

For further application of 5D, the research will combine 5D with decision-making tools/methods such as Analytical Hierarchy Process AHP. The case study will focus on selecting office automation technology which appropriate and affordable for small-medium enterprises. The comparison criteria of each technology will refer to 5D (benefit, technology readiness, usability, company readiness, and cost), which defined in this preliminary study (see Fig. 6).

10 CONCLUSIONS

The Five Dimension (5D) Digital Technology Assessment Cycle is a new method that assesses digital technologies, which cover five aspects: benefits, technology readiness, usability, company readiness, and costs. It is a holistic approach with the target to be easy to use.

Robotic Process Automation is software robots that mimic human behavior in the interaction with computers. RPA is a promising office automation technology.

The target of this paper was to assess RPA with 5D. The assessment shows that RPA has significant potential, and its performance has improved over the last years. However, the introduction of RPA is still time-consuming and cost-intensive. Further research needs to be done to reassess the cost assumptions made in this paper for the 4th Step, "Company Readiness ", & the 5th Step, "Cost ".

Notice

The paper will be presented at MOTSP 2021 – 12th International Conference Management of Technology – Step to Sustainable Production, which will take place in Poreč/Porenzo, Istria (Croatia), on September 8–10, 2021. The paper will not be published anywhere else.

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Subject review

Lean Supply Chain: Take an Opportunity to do More with Less

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Abstract: The purpose of this paper is to demonstrate that the application of lean approach in supply chain can act and influence the improvement of performances of the overall supply chain, as well as of all its participants. Some of the benefits which can be achieved by applying lean tools, methods and techniques, with minimal required investment, in supply chain are: reduced wastes, reduced costs, improved quality, faster delivery, and consequently increased supply chain profitability. In this paper, the comparison of traditional and lean supply chain is done according to different derived characteristics. The identification of comparative characteristics is done by desk research in combination with conversational research. The paper can serve as a basis for transforming existing supply chain into a lean supply chain.

Keywords: lean supply chain; efficiency; lean approach; lean supply chain management; supply chain

1 INTRODUCTION

Application of lean approach provides improvement of the efficiency and effectiveness of participating companies in the supply chain (SC), as well as the overall supply chain. The lean approach is focused on eliminating wastes and better use of resources in performing business activities and processes. All unnecessary activities that do not contribute to the creation of value for products or services for customers need to be identified and eliminated. In practice, waste is often present in demand forecasting, procurement of materials and raw materials, inventory management, product manufacturing, product storage, preparation of deliveries, transportation, logistics services and return of products [1]. Therefore, it is necessary to eliminate wastes in all supply chain processes: plan, source, make, delivery and return of products [2]. Accordingly, it is important to educate, respect and involve all employees from operational workers in the production process to the highest levels of company and supply chain managers.

Manufacturing has evolved from the craft and mass non-lean production to more recent lean manufacturing. The field of supply chain management (SCM) has also evolved rapidly, along with these developments in manufacturing. Supply chain management can be defined as "the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole" [3]. One key characteristics of present-day business is the competition of supply chains. The success and failure of supply chains will be determined by the customers [4]. Today, the requirement for survival for most supply chains is providing the right product, in the right quantity and quality, at the right cost, at the right time to the right customer. Hence, to fulfil this requirement, some companies have transformed their supply chains by adopting and implementing concepts of lean supply chain (LSC).

This paper is organized into five sections. The next section elucidates the theoretical basis of lean approach. Section 3 provides a literature review regarding lean supply chain management (LSCM) and briefly discusses the tools, techniques, procedures and practices of lean supply chain. Section 4 provides comparison of traditional and lean supply chains based on derived characteristics. Section 5, gives conclusions and proposes directions for further research.

2 LEAN APPROACH

The history of the emergence of the lean system is closely related to Japan and the Toyota Company, thought to be the creator of the lean manufacturing, also called the Toyota Production System (TPS) [5]. In the early 1980s, the Japanese automotive industry, led by Toyota, has taken lead in the global automotive industry by translating traditional production organization into lean manufacturing. The goals of TPS were to eliminate wastes and realize the processes based on actual customer demand. This required the education and development of all employees, the prospect of a supply chain driven by real customer demand, the creation of a self-learning organization, and the introduction and implementation of standardized processes. Toyota has thus been able to produce products with fewer defects, in shorter production processes, with fewer suppliers, with lower inventory levels and with less investment.

The term "lean" dates back to 1988 when John Krafcik published "The Triumph of Lean Production System" in the Sloan Management Review. Womack and Jones (1996) determine lean approach as a systematic analysis and elimination of redundant activities in work processes as well as sources of losses, with the aim of influencing quality, cost and time [6]. According to them, lean approach enables organizations to operate better with less and less resources i.e. less human resources, less equipment, less space and time. NIST (2000) defines lean as a "systematic approach to identifying and eliminating wastes through continuous improvement, flowing the product at the pull of the customer in pursuit of perfection" [7]. Authors Shah and Ward (2007) explain lean as a management philosophy that is concerned with identification and elimination of wastes within and beyond organizations' product value chain [8]. Gupta, Sharma and Sunder (2016) determine lean as "an integrated multi-dimensional approach encompassing wide variety of management practices based on philosophy of eliminating wastes through continuous improvement" [9]. Basic characteristics of lean concept proposed in [5] are: elimination of wastes, minimizing wastes, maximizing the quality of products or services, continuity and balance of material flow, pull principle of material flow management, directionality to meeting customer requirements, continuous staff training, flexibility of the process, strong partnership with suppliers, efficiency of technical and technological equipment, standardization of work, a culture of continuous improvement of processes and operations, etc.

Some authors differentiate the terms of "hard" and "soft" lean [10]. According to them, "hard lean" deals with the manufacturing process and techniques, methods and tools of production, with a focus on improving efficiency. "Soft lean" refers to an organization's value system, adaptability, employee participation and a focus on value for the consumer.

Therefore, the essence of lean is to reduce wastes, produce quality products and services in the right quantity, and deliver them at the right time at the lowest cost [11]. The seven types of wastes that enterprises need to deal with are: transportation, inventory, motion, waiting, over-processing, over-production and defects. Except for the above, as the eighth type of waste is recognized the lack of involvement and use of human resources (e.g. [12, 5]). Lean's basic principles are to eliminate 3M: Muda, Mura and Muri, which are Japanese terminology for wastes, unevenness and overburden, and get continuous process improvement by increasing productivity, reducing cost or both (e.g. [13, 14]).

3 LEAN SUPPLY CHAIN

Supply chain can be defined as "a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer" [15]. Supply chain is a "global network used to deliver products and services from raw materials to end customers through an engineered flow of information, physical distribution and cash" [16]. Lean supply chain involves identifying all types of wastes in the overall supply chain and taking steps to eliminate them while minimizing delivery time [17, 18]. It should enable that flows and processes from the supplier, through the manufacturer, then the distributor, and to the end customers, proceed without waste [19, 20]. Participants in the lean supply chain must constantly make efforts to make various improvements and focus on eliminating wasteful or worthless activities along the chain [21] while meeting the real needs of customers. Successful implementation of lean approach in the supply chain requires the direct involvement and cooperation of focal company, and their key suppliers and key customers.

Lean principles and practices became popular in the 1990s, and their application in the context of the supply chain attracted more attention a few years later [22]. The implementation of the lean concept in the supply chain was initiated by Womack and Jones (1996) with the publication of the book "Lean Thinking" [6]. According to El-Tawy and Gallear (2011) when lean thinking is adopted by all the main participants in the supply chain, it is a new way of thinking that is referred to as lean supply chain [23]. In 1996, Lamming defines lean supply chain as "an arrangement (which) should provide a flow of goods, services and technology from supplier to customer (with associated flows of information and other communications in both directions) without wastes" [24]. Therefore, the lean concept can be applied in the overall supply chain, starting with ordering materials from suppliers, through the production of products, their distribution and delivery of products to end customers, and the eventual return of products ([25-27]). Vitasek et al. (2005) define lean supply chain as "a set of organizations directly linked by upstream and downstream flows of products, services, information and funds that collaboratively work to reduce cost and waste by efficiently pulling what is needed to meet the needs of individual customers" [28]. However, it is noted that lean supply chain concepts are not yet sufficiently developed [29], and that there is a lack of generalization of the lean supply chain management framework [30].

Based on past experience, it has been observed that the application of lean supply chain management leads to continuous improvement of supply chain performance, regardless of supply chain activity ([20, 31-33]). Lean supply chain management promises "enhancing competitiveness by improving efficiency and increasing flexibility at all stages of the supply chain" [34]. The application of lean supply chain management enables wastes elimination, quality improvement, costs reduction and increasement of supply chain flexibility ([35, 6]. However, it is difficult to implement LSCM because it requires the involvement and collaboration of multiple supply chain participants [36]. Vlachos (2015) emphasizes lack of top management involvement as one of the main obstacles to support LSCM implementation [37]. Jadhav et al. (2014) also said that the top of the supply chain should be managed by strong leaders in order to make a real lean change [38]. Accordingly, the actual engagement of top management plays major role in conducting and sustaining enhancement [39]. Otherwise, shortage of commitment can cause number of complications, such as limited resources, longer decision-making processes, and miscommunications [30]. Successful implementation of LSCM faces four significant challenges: (I) existing ways of commerce based on changing auction prices, (II) obstacles in establishing a shared value stream, (III) the involvement and concern of top managers, and (IV) the influence of external factors based on power [30]. Several authors have suggested the need for leadership restructuring and the establishment of supporting infrastructure ([40, 41]).

Lean supply chain management enables better results in the overall supply chain [30], reduce wastes in the supply chain, reduce inventory in SC, reduce business risk through joint ventures in R&D and technology, achieve the required product quality, increase knowledge through joint product design [42]. Authors Womack et al. (1990) noted that automotive manufacturers who have succeeded in collaborating with distributors based on lean philosophy have achieved greater profits over the product life cycle, increased customer loyalty, benefits from customer knowledge for product development and improved sales forecasts [35]. Lean supply chain management is enabled by information and communication technologies [40]. It is recommended to start with lean approach in supply chain, and then consider introducing new information systems and technologies to support the supply chain process [43].

Up to this point, several examples of successful lean supply chains in manufacturing and service industries have been presented: automotive industry (e.g. [40, 20]), food supply chain (e.g. [37]), electronics (e.g. [25]), toys supply chain ([39]), agribusiness ([26, 30]), fashion ([44]), healthcare (e.g. [45]), etc. Minor applications have been noted in areas such as computer science, construction, design, engineering, government and the military [46].

3.1 LSCM Principles and Practices

Each supply chain is unique and complex. The right choice of LSCM practice depends on the context of each company and its supply chain [47]. The strategy of transition from the traditional supply chain model to the LSCM cannot be indiscriminately generalized, as different contextual factors are decisive for such a decision [48]. Great number of studies is connecting LSCM practices with lean concept principles [26, 29, 37]. Anand and Kodali (2008) [29] that were later updated by Jasti and Kodali (2015a) [49], suggest 8 methods for the application of LSCM, consisting of 82 practices, which are: information technology management; management of suppliers; eliminating wastes; just in time (JIT) manufacturing; customer relationship management; logistics management; senior managers' commitment; and continuous improvement. Perez et al. (2010) suggests such a structure of LSCM practices that considers seven different aspects that belong to one of five lean principles: value specification; value stream identification; value stream formation; value specification based on the demand of customers; aim for perfection [30]. The seven proposed aspects are: demand management; value definition; processes and products standardization; value chain efficiency; key process indicators; establishment of good relations with chain members; and cultural change. Blos et al. (2015) suggested a structure constructed of eight SCM operational dimensions, whose function is to make the supply chain less vulnerable to both in-house and foreign risks: (I) customer service, (II) inventory management, (III) flexibility, (IV) time to market, (V) finance, (VI) ordering cycle time, (vii) quality, and (VIII) market [50]. Tortorella et al. (2017) have empirically validated 4 bundles of 22 interconnected and internally consistent LSCM practices: customer-supplier relationships management, logistics management, elimination of wastes and continuous improvement and top management commitment [51].

When it comes to individual LSCM practices, most commonly used are Kanban and close relationship between customer, supplier and relevant stakeholders (e.g. [24, 25]). Kanban is usually related with JIT deliveries [52, 53], by which the real material is delivered at the expected time, to the place and the quantity in which it was requested [54]. In addition, several studies point to the practice indicates a distribution centers that affects the cost of transportation and the realization of orders ([26, 55-57]). Further, the 5S is used as a tool of visual management based on the belief that the organization of work space is crucial to ensuring a smooth workflow. It is based on 5 Japanese words starting with the letter ‘s’ which were later translated to equivalent English words: Seiri (Sort), Seiton (Set in Order), Seiso (Shine), Seiketsu (Standardise) and Shitsuke (Sustain). After identifying value from the customer’s perspective, the next step is to identify the value stream for each product, by Value Stream Mapping (VSM) tool. There is a large number of other useful LSCM practices (e.g. Heijunka, Jidoka, six sigma, poka-yoke, work standardization, etc.).

4 COMPARISON OF TRADITIONAL AND LEAN SUPPLY CHAINS

Each supply chain consists of a large number of participant enterprises (e.g. suppliers, manufacturers, distributors, wholesale, retail). Supply chain participants are directly and indirectly involved in the processes and flows of products, services, information, money and knowledge, from end suppliers to end customers [58].

In a traditional supply chain, each participant seeks to maximize their own profit, regardless of the other supply chain participants. Thus, retail seeks to meet the demand of end customers and to maximize profits. Based on demand of end customers, procurement orders are sent to wholesale. Wholesale determines projected needs based on received orders from retailers, as well as forecasts of retail demand. Wholesale wants to maximize its own profits. It issues procurement orders to the manufacturer. The manufacturer is making a master production schedule based on received orders and demand forecasts. Furthermore, it additionally uses components and inventory data to plan production. He procures the necessary raw materials and supplies from the supplier. The manufacturer also wants to maximize its own profit. The supplier seeks to meet the needs of the manufacturer and to maximize profits. Therefore, in a traditional supply chain, each participant predicts demand based on received data from the immediate downstream participant. Thus, wholesale does not have insight into the demand of end customers, as well as other upstream participants in the supply chain. This behaviour of the participants in the supply chain usually results in an occurrence of bullwhip effect. This description of traditional supply chain was done based on [59].

Within the lean supply chain, all participants collaborate and strive to meet the real needs of end customers while maximizing the overall profitability of the supply chain. Supply chain profitability is the difference between the revenue generated from the sale of products to end customers and the total cost of the supply chain [60]. Participants in the lean supply chain pay special attention to eliminating all wastes in the chain and in that way reducing costs at the overall supply chain level.

The comparison of traditional and lean supply chain was done according to different characteristics (Tab. 1). The following characteristics are derived for purpose of this comparison: the aim of participants in SC; cooperation in SC; time horizon of relationships between participants in SC; processes in SC; customers in SC; demand forecasting; suppliers in SC; selection of suppliers in SC; frequency of product delivery; product quality control; human resources in SC; SC performance measurement; process improvements in SC; and participation in new product development. The results presented in a lot of works are used, such as [24, 61-64, 41, 65-68, 8, 59], etc.

Table 1 Comparison of traditional and lean supply chains

Characteristics	Traditional SC	Lean SC
The aim of participants in SC	Each SC participant strives to maximize own profit	All SC participants strive to maximize the profitability of the overall SC. Emphasis on eliminating all wastes in SC and reducing the cost of the overall supply chain.
Cooperation in SC	Communication of SC participants to achieve their own goals	Collaborative relationships between SC participants based on mutual trust, commitment and shared responsibility to achieve common goals.
Time horizon of relationships between participants in SC	Short term	Long term
Processes in SC	The processes aren't integrated nor standardized in SC. Key processes in SC are usually not determined.	Processes are built based on the actual customers' needs. The key SC processes are determined. The processes are standardized. Tendency is to apply fail-safe processes (jidoka). Visual control of the process in SC is used.
Customers in SC	Meeting the needs of immediate customers is being considered (first level customers).	Relationships with all customers are considered (all levels). Segmentation of customers is done. Higher forms of cooperation are achieved with key customers.
Demand forecasting	Each SC participant works to predict demand	End-customer demand is predicted and data is provided to all key participants in SC.
Suppliers in SC	Large number of suppliers. Mostly no supplier segmentation is done.	Small number of suppliers. Supplier segmentation is performed. Higher forms of cooperation are being pursued with key suppliers.
Selection of suppliers in SC	The criteria regarding the price of the product mostly are used	Multiple criteria are used (e.g. average delivery time, product quality, order quantity, ordering frequency, supplier's distance, level of willingness to cooperate, level of service, order status visibility, etc).
Frequency of product delivery	It is not a frequent product delivery	Very frequent product delivery
Product quality control	Mostly, it's not strict	Strict and standardized product quality control activities
Human resources in SC	Employees on low-level are not given sufficient attention	Continuous education, appreciation and involvement of all employees from operational workers in the production process to the highest levels of enterprise managers and supply chain.
SC performance measurement	Participating companies measure their own business performance	Performance measurement at SC level. Both financial and non-financial performance measures are used.
Process improvements in SC	SC participating companies improve owns processes	Creating a self-learning SC. Continuous improvement of the SC processes.
Participation in new product development	Only one SC participant participates in the development of a new product	More SC participants are participating in new product development

Within the lean supply chain, collaborative relationships are established between participants to maximize the profitability of the overall SC. Emphasis is on eliminating all wastes in SC and consequently on reducing the costs of the overall supply chain. The focal company considers all customers and all suppliers and performs segmentation to reveal key customers and key suppliers in lean supply chain. Further, the focal company tries to establish long-term higher forms of cooperation with key customers and key suppliers. Lean supply chain processes are designed based on customers' real demand, they are standardized, and key processes are identified that receive particular attention in terms of different advancements using lean management concepts, principles, methods, techniques and tools (e.g. Value Stream Mapping, Little's Law, Takt Time, 7 wastes, 3M, 5S, JIT (Just In Time), Poka-Yoke, jidoka, Single Minute Exchange of Die (SMED), Total Productive Maintenance (TPM), Overall Equipment Effectiveness (OEE)). Performance measurement is done at SC level by using Supply Chain Operations Reference (SCOR) model, Global Supply Chain Forum (GSCF) model, Balanced scorecard (BSC) model, or some other model. More interested participants of SC are involved in new product development. All employees participate in the continuous improvement of the processes in lean SC lead by company and supply chain managers.

5 CONCLUSION

Application of the lean approach in supply chain can efficiently improve the performance of the supply chain, as well as all its participants. Some of the potential benefits of applying lean in supply chain are reduced wastes, reduced costs, improved quality, faster delivery and flexibility, improved efficiency, reduced production lead-time, reduced work-in-progress inventories, etc. Thus, the lean concept provides answers to the need to make supply chain processes more effective, efficient and adaptable, using extremely applicable sets of tools, methods and techniques. With minimal investment, it enables supply chain participants to maximize utilize of their resources, and thus reduce costs and increase supply chain profitability. Participants in the lean supply chain should continually make various improvements with the focus on eliminating wasteful or worthless activities along the supply chain while meeting the real customer's requirements. Successful implementation of lean approach in the supply chain requires the direct involvement and cooperation of focal company, and their key suppliers and key customers.

In this paper, the comparison of traditional and lean supply chains is done according to different characteristics. The following characteristics derived and used: the aim of participants in SC; cooperation in SC; time horizon of relationships between participants in SC; processes in SC; customers in SC; demand forecasting; suppliers in SC; selection of suppliers in SC; frequency of product delivery; product quality control; human resources in supply chain; supply chain performance measurement; process improvements in supply chain; and participation in new product development. One of the main conclusions is that participants of lean supply chain collaborate on eliminating wastes and better use of resources in performing supply chain activities and processes while striving to meet the real needs of end customers.

Finally, the following scopes can be interesting for future research: (1) a comprehensive framework for implementation of lean approach in supply chain should be developed; (2) a practical guide for transforming existing supply chain into a lean supply chain can be suggested; (3) a more case studies of lean supply chain should be presented; etc.

Notice

The paper will be presented at MOTSP 2021 – 12th International Conference Management of Technology – Step to Sustainable Production, which will take place in Poreč/Porenzo, Istria (Croatia), on September 8–10, 2021. The paper will not be published anywhere else.

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Subject review

Trading Application Based on Blockchain Technology

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Abstract: Blockchain is a growing distributed list of records that are linked using cryptographic hashes. Its robustness, simplicity, immutability and trust are basis for development of interesting innovative business solutions. Considering some use-case scenarios within the financial sector, we developed a Blockchain based trading application placed on the Cosmos network. Cosmos is a decentralized network of independent, scalable, and interoperable Blockchains, creating the foundation for new economy. Our work describes the application functionalities for buying, selling and renting goods. It shows the easiness of trading, while eliminating the third parties and demonstrates the disruptive potential of the Blockchain technologies.

Keywords: application; blockchain; buying; renting; selling; Tendermint; trading

1 INTRODUCTION

The Blockchain technology is a distributed network technology, capable to achieve consensus over the data that circulates in the network. The new data structure implemented in the Blockchain technology offers **high level of redundancy, traceability and liveness of the records**. The Blockchain technology is not one solution to fit all the implementation scenarios, different types are defined to suite the different implementation scenarios. General division of the Blockchain technologies types is in **four groups**: **public permissionless, public permissioned, private permissionless, private permissioned**. The grouping is done depending on the openness of the data that is circulating in the system (public and private) and the procedures for access restriction and user authentication for access management (permissionless and permissioned). All four types of Blockchain technologies show different characteristics and performance metrics. Depending on the use-cases scenarios, suitable type of Blockchain has to be selected.

There are lot of Blockchain technology currently on the market. Most of them are focused on the financial aspect of the Blockchain technology and the digital currency introduced by the Blockchain technology. Generally the public type of Blockchain has gained the attention from the masses, especially by the introduction of the **Bitcoin** [1], **Litecoin** [2] and **Ethereum** [3]. These Blockchain technologies are covering the majority of the Blockchain market. The success of the Bitcoin and Ethereum attracted many researchers to broaden the use of the Blockchain technologies in other use case scenarios. The main focus of the Bitcoin and Ethereum is the financial aspect but the introduction of Smart contracts [3], made this system suitable to use of the Blockchain technology in many systems beside than financial sector. Some of the most prominent use-cases are logistics, real estate and healthcare.

In this paper we are presenting **novel trading application based on Tendermint Blockchain technology** that allows the users to buy, sell or rent goods, thus eliminate any requirement for third parties or notaries in the trading process. To the best of our knowledge, this is the first trading application based on Tendermint Blockchain technology that allows cheaper, faster and highly secure transactions on a public Blockchain technology.

2 RELATED WORK

Great number of trading applications based on Blockchain technology are present on the market, but most of them are focused on the process of selling or buying items, but not renting items. Initially the trading applications were developed with idea of exchanging digital assets or services. One of the greatest influence on the development of trading applications based on Blockchain technologies was the collectible game known as CryptoKitties [4, 5]. The CryptoKitties is game of collectible and breedable assets represented as virtual cats, developed on the Ethereum platform. This game created enormous rise of transactions on the Ethereum network and showed the capabilities of the Blockchain technology in the process of trading digital assets.

Another innovative approach, described in [6], is trading of **computational power in a decentralized fashion**, based on Ethereum platform. The proposed framework assumes that spare computational resources can be shared with entities and charged for the service. The agreement between the parties, the terms of use and the settings are managed by Smart contract.

In [7] the authors show the results from the developed proof-of-concept of a marketplace based on Ethereum Blockchain. The solutions offers functionalities of trading digital, but also physical goods. It implements mechanisms for group escrow arbitrage, integration with logistic entity and reputation system.

The importance of the development a marketplace based on a Blockchain technology is presented in [8], where the authors are showing the marketplace developed on the Ethereum Blockchain but also are giving price and taxes comparison for trading on some of the mainstream shopping platforms and the newly developed Blockchain based marketplaces.

Beside the general applications for decentralized marketplaces build on Blockchain technology, where the users can buy or sell assets, there are solutions for renting goods. In [9] the authors are proposing Blockchain based application for house renting, developed on Ethereum platform and integrated with IPFS [10] and Oraclize services [11]. A car leasing system is presented in [12], developed on a private Blockchain in order to make it more cheap for the users.

Most of the solutions presented in the literature are based on the **Ethereum Blockchain technology**, by implementation of Smart contract characteristics. The current version of Ethereum network struggles to cope with the increased number of transactions and makes the trading process expensive and very time consuming. The development of the **trading application based on Tendermint protocol** will significantly improve the speed of transaction finalization and keep the transaction fees very small.

3 TENDERMINT FRAMEWORK BASICS – THE PROTOCOL STRUCTURE AND THE CHARACTERISTICS

The Tendermint framework [13] and the Cosmos Hub [14] offer modular approach in the building of Blockchain applications. The high modularity is key factor for faster and broader adoption due to better adaptation to other technologies. Moreover the IBC (InterBlockchain) protocol developed by the Tendermint community offers flawless integration of different types of Blockchain technologies in one ecosystem. Additionally the Tendermint framework offers layers structure of the Tendermint Blockchain application and a key concept for separation of the consensus mechanisms and the higher layers of the application. This separation makes the application easily adaptable to other Blockchain frameworks.

3.1 Tendermint Framework Structure

According to the Tendermint framework an application is segmented in **three layers** (see Fig. 1): Networking, Tendermint Core (Consensus layer) and ABCI (Application BlockChain Interface) interface. On top of the ABCI interface is the application definition developed in a Cosmos SDK.

The Tendermint networking layer defines the **peer-to-peer gossiping procedures and network formation**. Compared to the traditional point-to-point networking approach, the gossiping procedure in Tendermint networking layer provides more optimal and less redundant message exchange procedures.

On top of the Tendermint network layer is the Tendermint consensus mechanism, which is **Practical Byzantine Fault Tolerant** [15] based consensus mechanisms with significant improvements by implementation of nil vote and vote locking mechanism for simpler consensus achievement. Tendermint consensus mechanisms provides fast consensus cycles and fast transaction validation with high throughput of transactions in a non-Byzantine environment. The Tendermint's State Machine Replication mechanisms can hold up an attack of up to 1/3 of adversary Byzantine nodes interfering the consensus mechanism.

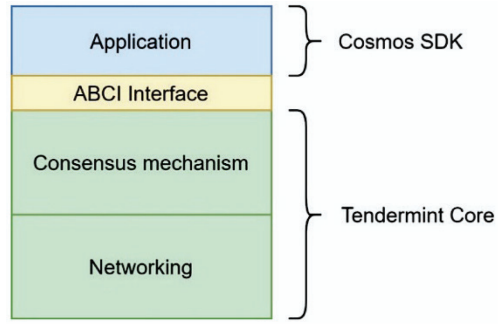

Figure 1 Tendermint layered structure

The ABCI interface is a layer that defines the connection functions between the consensus mechanism and application. It defines the methods handling procedures and translation of the parameters from the consensus mechanism to the appropriate parameters in the application and vice versa. This interface enables the fusion between the Tendermint consensus mechanisms and Ethereum environment defined by the Ethermint community, which results in the development of Ethermint solution. Beside this popular fusion, there is possibility to make any other adaptation of existing Blockchain technology to work on top of the Tendermint consensus mechanism.

3.2 Tendermint Characteristics

Tendermint is lightweight consensus protocol offering high transaction throughput, scalability, fast transaction finalization and implementation of Smart contracts, which makes the Tendermint as one of the most suitable protocols for development of trading application. Moreover is has highly energy efficient property compared to the Bitcoin and Ethereum consensus mechanisms, due to PBFT-based consensus mechanisms which does not require computationally intensive processes in order to conduct the consensus among the users.

In some cases of the trading practice, the transfer of the goods require legal transfer of ownership, approved by a notary or other middleman entities. This approach is additional financial burden to the requester of the service or the buyer. The openness and liveness of the data, the traceability and immutability of the records, and the redundancy provided by the Blockchain technology make the applications build on these platforms to be highly trustable. This characteristic and the implementation of Smart contracts will eliminate the requirement of third party or middleman in the trading processes.

4 BLOCKCHAIN-BASED TRADING APPLICATION

The application covers trading of miscellaneous items, but the most significant impact will be in the trade of vehicles, real estate and other items where the trade has to be covered with notarized contract. The main purpose of this application is to exploit the strength of the Blockchain technologies and eliminate the involvement of third parties (notaries) in the process of trading goods. The Blockchain technologies are capable of providing publically accessible, provable and traceable transactions, and the implementation of Smart contracts creates automated processes for ownership transfer and can be linked to any institution that requires to update the ownership status.

A Smart contract is self-executable code residing on the Blockchain, identified by an address, callable from other Smart contracts or directly by a user. The Smart contract is capable to swap the ownership of an item and transfer the funds for the item in a single call, and pay small fee for the execution of the Smart contract. That way the trading actions of buying and selling, by use of Smart contract, will be executed in a single call of the Smart contract by providing the buyer's address, seller's address and the amount of tokens required for transaction completion. In a case of insufficient funds, the transaction is halted and it will not proceed. The renting process is more complex than the selling and buying procedures, and requires additional functionalities due to temporal transfer of ownership of the items and the way of charging for item usage (per use or time interval).

4.1 Logical Structure

The application cover the trading activities of selling, buying and renting. The current version of the application assumes instant fund transfer for the buying and selling processes. The simple functionality of the transfer functions can be further expanded with fund-locking approach in a situations when this application will be linked to delivery services. The fund-locking approach will lock the money for bought or sold item until the delivery is not confirmed by delivery service (either by physical delivery or transfer the digital good through online services).

The renting use-case has more complex functionalities in order to cover the most cases that appear in a renting scenarios. Figure 2 shows the simplified diagram of interaction between the entities in the renting process.

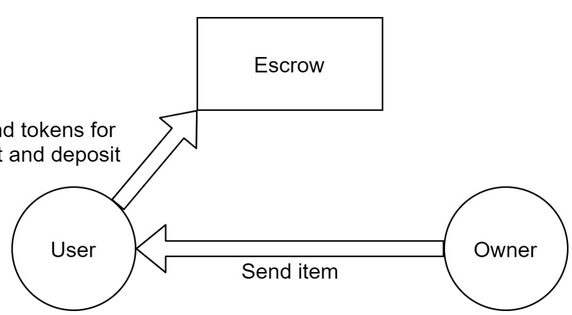

Figure 2 Rent item interaction

The renting process includes Escrow entity which locks the funds for renting until the item is hold by the renter. The renting process starts at the moment when the renter prepays the rent and deposits pre-agreed amount as damage or stilling deposit. The owner approves the start of the renting and rent period starts. The rent can be charged per time interval or per use, depending on the owner preference which is stated in the advertisement.

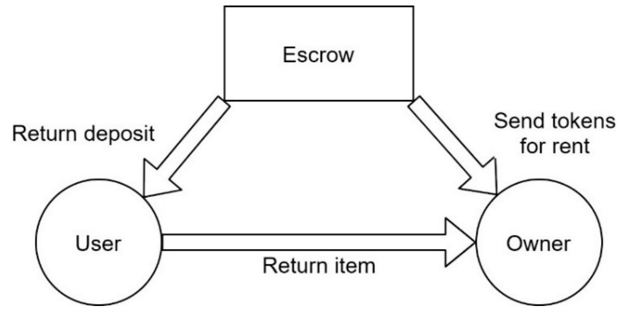

Figure 3 Item return procedure with no damage detected to the item

The rent finishes when the renter sends back the item or the prepaid rent fund is completely spent. Next step is when item owner receives the item and checks for damages. If there are no damages to the item, the damage deposit is sent back to the renter and the rent fund is transferred to the owner wallet (see Fig. 3). If any damage is registered, the rent fund and damage deposit is transferred to the owner wallet, and note for the damage is attached to the item (see Fig. 4). In case when the item is not returned on time, the item is marked as stolen, and rent fund and damage deposit is transferred to the owner (see Fig. 5).

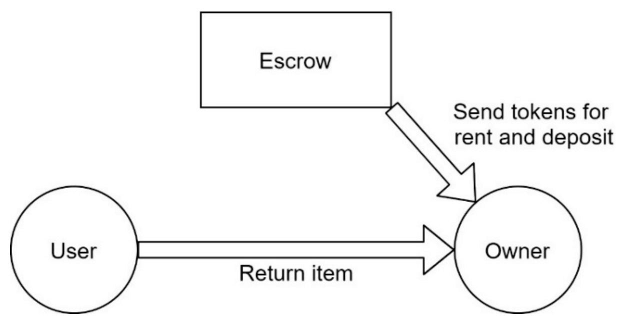

Figure 4 Item return procedure with damage detected to the item

For the time interval rents, there is possibility to charge the rent depending on the length of the rent, so at the moment of item return there will be unspent rent fund that will be returned to the renter, together with the damage deposit if there is not damage to the item.

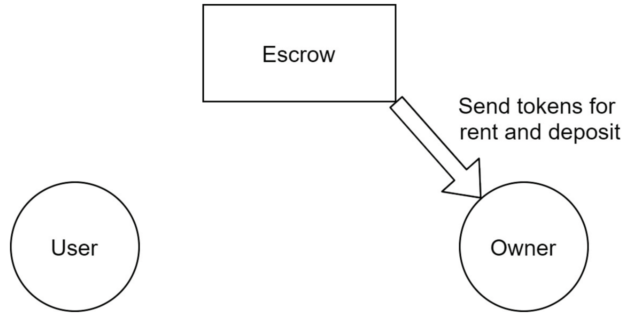

Figure 5 Item return procedure when the item is stolen

Figure 6 Index page of the application

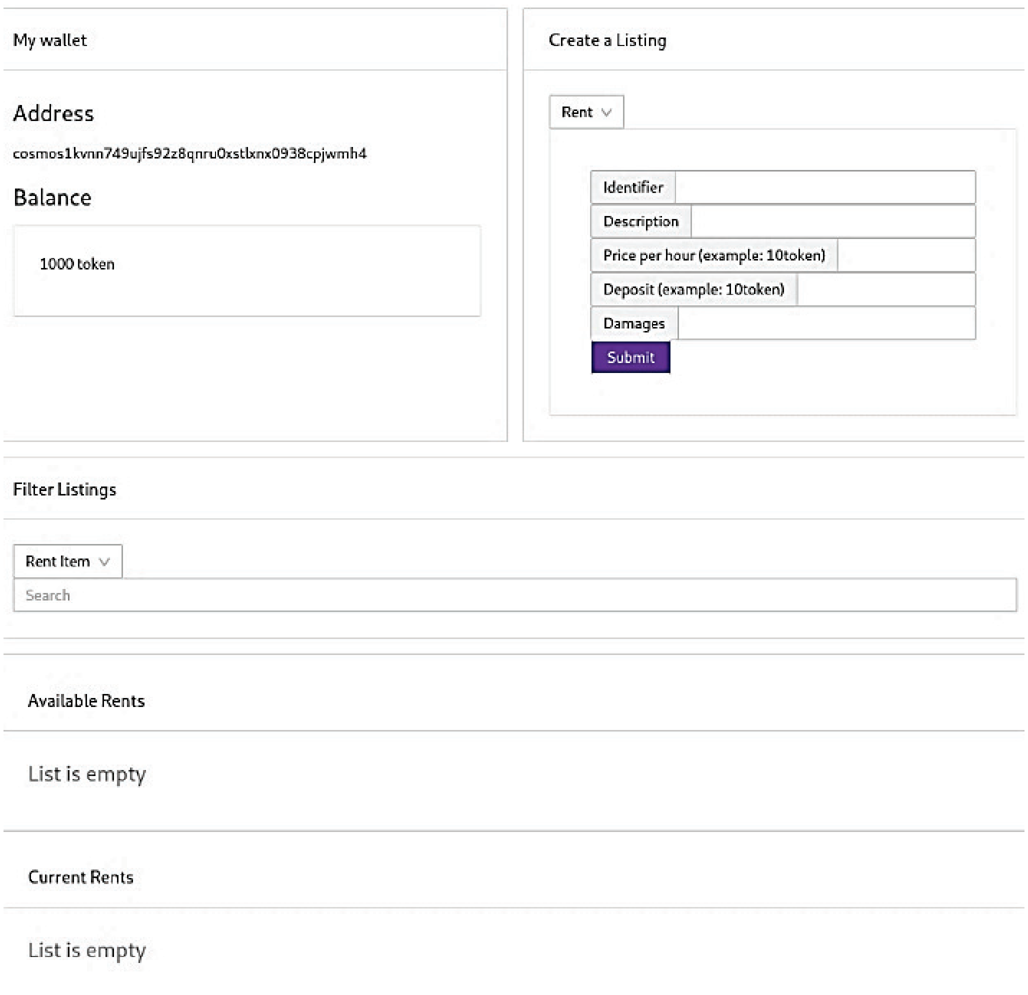

Figure 7 Trading page of the application

4.2 Interface Design

The application is divided in two pages where the initial page is the index page, and the second one is the trading page. The first page has two segments: login and sign in section. On the first page (see Fig. 6) the user can login into the application by use of previously created wallet, more precisely to enter into the wallet the user has to provide the mnemonic of the wallet. If the user has no account, in the sign in section it is possible to create wallet by providing the personal information and this way the user will be added to the system and create wallet to transfer the funds or manage the items for trading.

The second page, the trading page, has three sections (see Fig. 7). The first section is the user account information section where the user have better insight of the available fund and the wallet address. The second section is the advertisement creation section, where the user can add advertisement for renting, buying or selling an item. A listing creation process will require from the user to add identifier, description and price of the item. In the case of creation listing for a renting item, the owner has to provide damage deposit and any previous damages reported by the owner. The third section is the filtering or search section where the user can find advertisement for renting, buying or selling item. This section has subfields to show available items for trading and past transactions. Also in the case of renting item, there is subfield for current rents.

5 CONCLUSION

The Blockchain technologies will have immense impact on the trading processes in the future. The transparency of the interactions in the Blockchain network increases the trust in this technology. The cryptocurrency mass adoption and the integration of this type of currency with everyday trading processes is inevitable. The traceability and provability of the transactions are also important characteristics that make the Blockchain technology capable to act as notary. The implementation of the Smart contract may further automate the notarization process in the Blockchain system and eliminate the third parties in the trading process. This additionally impacts the decrease of the costs for trading and decrease of transaction fees. This application proves the ability of the Blockchain technology to make the trading processes transparent, secure and cheaper.

Notice

The paper will be presented at MOTSP 2021 – 12th International Conference Management of Technology – Step to Sustainable Production, which will take place in Poreč/Porenzo, Istria (Croatia), on September 8–10, 2021. The paper will not be published anywhere else.

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Transient Aspects of MRP Theory - Abridged

Robert W. Grubbström

Abstract: MRP theory concerns production-inventory systems, in which produced items are made up of sets of sub-items, either produced or purchased (imported into the system) and required to be available a lead-time before the product is completed. The hierarchical dependence of relations between items is captured by the use of input matrices from Input-Output Analysis, the necessary advanced timing by applying the methodology of Laplace transforms, and the production-economic consequences by the net present value (NPV). This theory has been developed for about 40 years, but little attention has been given to transient aspects, i.e. when there happens to be an initial available inventory of items usable in future production. In this paper, we attempt to highlight the theoretical consequences from having a positive initial available inventory.

Keywords: Laplace transform methodology; Input-Output Analysis; NPV; Production Economics; MRP Theory

1 INTRODUCTION

Material Requirements Planning (*MRP*) is a management information system providing a base for production decisions, when what is manufactured has a complex structure and when lead times are important features. MRP is a control system (mainly) dealing with the production of *assembled products*, made up of *items*, such as subassemblies, components, raw materials. Taking processing times into account, required raw materials and sub-components will be needed ahead of times at which the production of a particular item is completed. The MRP system calculates the amounts of produced and purchased items needed at different times and proposes a plan for when this production is to be carried out, taking these *lead times* into account.

MRP Theory is a theoretical body combing MRP and Input-Output Analysis with Laplace Transform methodology aiming at determining an optimal production schedule for a production-inventory system. In this paper we shall confine ourselves to *assembly systems* (convergent systems), in which end items (to be sold or delivered from the system), but MRP Theory has been developed and extended to other types of production such as extractive processes and transportation/distribution systems (divergent production systems), and also to recycling (reverse logistics) systems, including for instance disassembly processes. For overviews, cf. [1], [2] and for applications, e.g. [3], [4].

The first hard-cover book on Material Requirements Planning [5] was authored in 1975 by Joseph A. Orlycky, 1922-1986. In his foreword (p. ix) was stated that "subject of material requirements planning has been neglected in hard-cover literature and academic curricula ….one of the reasons for this situation is the subject's position outside the scope of quantitative analysis, and the view of it as being 'vocational' rather than 'scientific'." This rather gloomy comment was a challenge for many, and this current paper is yet another voice in this choir.

Two decades before that in the first issue of *Management Science*, Andrew Vazsonyi [6] had presented his result that the Bill-of-Materials (BOM) for an assembled product could well be written in mathematical form as a matrix the "Next Assembly Quantity Matrix", here denoted $\boldsymbol{H}$. When taking into consideration total requirements of all subassemblies, components, and materials, so on, that are needed for dispatching a batch of products (to be exported from the system), this was derived as the corresponding matrix $(\boldsymbol{I} - \boldsymbol{H})^{-1}$, describing the number of items needed for exporting one unit of an end product and coined by Vazsonyi as the "Total Factor Requirement" matrix.

These two matrices were also included in his book "Scientific Programming in Business and Industry" published three years later [7]. However, lead-times could not yet be captured in his treatment. And Nobel Laureate Tjalling C. Koopmans [8] (Koopmans 1951) and others before him recognised the commonality between Nobel Laureate Wassily W. Leontef's Input-Output Analysis [9], [10] with a macroeconomic and empirical touch, and the base for Vazonyi's s treatment, then for a time, named Activity Analysis. But with Input-Output Analysis, it became clear that $\boldsymbol{H}$ was the *input matrix*, and $(\boldsymbol{I} - \boldsymbol{H})^{-1}$ was the *Leontief inverse* of Input-Output Analysis.

In 1992 Grubbström and Ovrin published an article [11] using the z-transform (the discrete-time transform corresponding to the Laplace transform) to assembly processes. Since then, there have been many developments in what we now call "MRP Theory". By the help of, in particular, Professors Ludvik Bogataj and Marija Bogataj, this theory has been extended to transportation and recycling systems, having a quite different structure compared to assembly systems, cf. [12-13]. The optimal production plan $\boldsymbol{P}^*$ maximising NPV for any assembly system was stated and a solution method presented in [14].

We have organised the material in this paper as follows. The next section is devoted to the main parts of the Laplace transform method that are applied in MRP Theory. Section 3 develops our main results, which is followed by a section dealing with the economic value of having initial stocks. A numerical example follows in Section 5. This paper, as its title suggests, is an abridged version of this research. One important set of findings omitted below concerns initial backlogs, which comprise a parallel set of initial state variables compared to initial stocks, and which have not found space to be dwelled upon in this paper. Neither do we here allow for the possibility of initially outstanding orders, later to be fed into available inventory.

2 DIGRESSION ON THE LAPLACE TRANSFORM

The Laplace transform is named after the French mathematician, astronomer and physicist Pierre-Simon Laplace, 1749-1827. A forerunner in this methodology was the Swiss mathematician Leonard Euler, 1707-1783. The Laplace transform was originally used for solving differential equations and investigating stability properties of dynamic systems in electrical and mechanical engineering and astronomy, and in probability theory as a moment-generating function. More recent fields of application have been finance, production economics and risk preference theory, see [16-22].

Deakin [23-25] offers an overview of the historical development of its use. For its general theory and method, see e.g, [26-29]. One of the first applications to production-economic problems was made by Nobel Laureate Herbert A. Simon [30]. where he applied the transform method to controlling a simple production-inventory system with a time lag in production.

The Laplace transform translates a function of time $x(t)$ into its transform, being a different function $\tilde{x}(s)$ of a frequency s. In all standard applications, in which certain regularity conditions are valid for $x(t)$, there is a one-to-one relationship between these two functions, so given the time function, all of its properties are captured in its transform, and vice versa.

The (*unilateral*) transform considers functions only existing for non-negative values of t, and is defined by

$$£\left\{x(t)\right\} = \tilde{x}(s) = \int_{t=0}^{\infty} x(t)\mathrm{e}^{-st}\mathrm{d}t \quad (1)$$

showing two alternatives for the notation of the transform. For the *bilateral* transform, applied e.g. in probability theory, the integration covers the entire time axis $\int_{t=-\infty}^{\infty} x(t)\mathrm{e}^{-st}\mathrm{d}t$, and t is often interpreted with a different dimension than time, but in our applications in MRP Theory, only the unilateral transform is used. In general, the frequency s is a complex variable $s = \sigma + i\,\omega$, with σ being the real part of s, and $i\omega$ the imaginary part, where i is the imaginary unit $i = \sqrt{-1}$. Translating the transform from the frequency domain back into its time function may be written $x(t) = £^{-1}\left\{\tilde{x}(s)\right\}$, where the operation $£^{-1}\left\{\cdot\right\}$ defines the *inverse transform*. A method for finding $x(t)$ from a given $\tilde{x}(s)$, is given by the integral

$$x(t) = £^{-1}\{\tilde{x}(s)\} = \frac{1}{2\pi i}\int_{s=\beta-i\infty}^{\beta+i\infty} \mathrm{e}^{st}\tilde{x}(s)\mathrm{d}s\,, \quad (2)$$

where the integration takes place in the complex (σ, ω) – plane along a vertical line $\sigma = \beta$, where β is chosen such that the integral converges. To evaluate this integral, *Cauchy's Residue Theorem* may be used, Augustin Louis Cauchy, 1789-1857, being a disciple of Laplace.

In this article, in particular, we will make use of the following theorems of the Laplace transform.

Time differentiation

$$£\left\{\frac{\mathrm{d}x(t)}{\mathrm{d}t}\right\} = s\tilde{x}(s)\,. \quad (3)$$

There are alternative conventions concerning this notation, depending on whether or not the possible step at $t = 0$ is included, but we prefer the convention in (3), which includes this step in the derivative.

Time integration

$$£\left\{\int_0^t x(\tau)\mathrm{d}\tau\right\} = £\left\{\overline{x}(t)\right\} = \frac{\tilde{x}(s)}{s}\,. \quad (4)$$

The bar notation (middle member of (4)) for cumulate flows will be used throughout this paper.

Final value (assuming this limit exists)

$$\lim_{t\to\infty} x(t) = \lim_{s\to 0} s\tilde{x}(s)\,. \quad (5)$$

Time translation (moving the time function uniformly along the time axis)

$$£\left\{x(t-T)\right\} = \mathrm{e}^{-sT}\,\tilde{x}(s)\,, \quad (6)$$

which holds as long as $t \geq T$, so $x(t)$ must be zero for $t < T$. When a function $x(t)$ is moved forwards in time, we have $T > 0$, and this formula holds defining $x(t - T)$ to be zero for $t < T$. However, when we move backwards in time and $T < 0$, then the function might cross $t = 0$ and it then would become truncated. So the formula assumes always that $x(t - T)=0$ for $t < T$.

Important in MRP Theory is the *Dirac impulse* (the *impulse function*) written $\delta(t - T)$. It is a generalised function only existing at one point in time $t = T$, with $T \geq 0$, and defined by

$$\int_{t=a}^{b} \delta\left(t-T\right)\mathrm{d}t = \begin{cases} 1, \text{ if } a \leq T \leq b, \\ 0, \text{ if } T < a \text{ or } T > b. \end{cases} \quad (7)$$

This function can be looked upon as an infinitely narrow and infinitely tall impulse with a *unit* area. The Laplace transform of a Dirac function is obtained as the simple exponential function:

$$£\left\{\delta\left(t-T\right)\right\} = \int_{t=0}^{\infty} \delta\left(t-T\right)\mathrm{e}^{-st}\mathrm{d}t = \mathrm{e}^{-sT}\,, \quad (8)$$

provided that $T \geq 0$.

The NPV theorem

If $x(t)$ is a cash flow, possibly including discrete payments, then the Net Present Value (*NPV*) of this cash flow is

$$NPV = \tilde{x}(\rho)\,, \quad (9)$$

where ρ is the continuous discount rate, i.e. the Laplace transform of the cash flow, when the frequency s is interpreted as this interest rate ρ [18].

As far as the author knows, there have been no major theoretical developments concerning the Laplace transform of truncated functions, such as regarding a function of the type $f^+(t) = Max\left(0, f(t)\right)$, which often are present in production-economic problems. For explaining developments below, we therefore include the following relations between a *discrete monotonically non-decreasing* staircase function $f(t)$ of *discrete time* and its truncated version $f^+(t) = Max\left(0, f(t)\right)$ and their respective Laplace transforms.

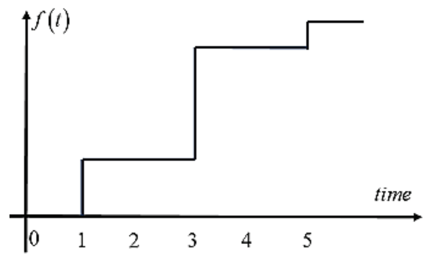

Figure 1 A typical staircase function in discrete time

If $f(t)$ is a staircase function of discrete time (Fig. 1), its time derivative may be written as a train of Dirac impulse functions

$$\frac{\mathrm{d}f(t)}{\mathrm{d}t} = f_0\delta(t) + (f_1 - f_2)\delta(t-1) + (f_2 - f_1)\delta(t-2),... \tag{10}$$

where f_i is the value of $f(t)$ for $i \le t < (i+1)$. The transform of $\mathrm{d}f/\mathrm{d}t$ is then by (3)

$$\begin{aligned} &£\left\{\frac{\mathrm{d}f(t)}{\mathrm{d}t}\right\} = f_0 + (f_1 - f_2)\mathrm{e}^{-s} + (f_2 - f_1)\mathrm{e}^{-2s} + ... = \\ &= (1-\mathrm{e}^{-s})\sum\nolimits_{i=0}^{\infty} f_i \mathrm{e}^{-is}, \end{aligned} \tag{11}$$

and the transform of $f(t)$ will be by (4)

$$\tilde{f}(s) = \frac{1}{s}£\left\{\frac{\mathrm{d}f(t)}{\mathrm{d}t}\right\} = \frac{(1-\mathrm{e}^{-s})\sum\nolimits_{i=0}^{\infty} f_i \mathrm{e}^{-is}}{s}. \tag{12}$$

If $f(t)$ is monotonically non-decreasing, the truncation $f^+(t) = Max\left(0, f(t)\right)$ will have the transform

$$\tilde{f}^+(s) = \frac{1}{s}£\left\{Max\left(0, f(t)\right)\right\} = \frac{(1-\mathrm{e}^{-s})\sum\nolimits_{i=T}^{\infty} f_i \mathrm{e}^{-is}}{s}, \tag{13}$$

where T is the first time that $f(t)$ becomes positive. The transform of the derivative of the truncated function $\mathrm{d}f^+(t)/\mathrm{d}t = \mathrm{d}Max\left(0, f(t)\right)/\mathrm{d}t$ will therefore be

$$s\tilde{f}^+(s) = £\left\{Max\left(0, f(t)\right)\right\} = (1-\mathrm{e}^{-s})\sum\nolimits_{i=T}^{\infty} f_i \mathrm{e}^{-is}. \tag{14}$$

Impulse trains

If we have a discrete time function $x(t)$, there is often a need for mathematically describing only the times, t_0, t_1, t_2,…, when this function has a non-zero value. If the transform of this transform is written $\tilde{x}(s) = \sum\nolimits_{i=0}^{\infty} x_i \mathrm{e}^{-ist_i}$, then its timing is obtained as a train of unit impulses, written

$$\tilde{x}(s) = \sum\nolimits_{i=0}^{\infty} x_i \mathrm{e}^{-ist_i}. \tag{15}$$

3 MRP THEORY WITH AN INITIAL STOCK

Throughout, we confine ourselves to assembly systems, for which the input matrix may be written as a triangular matrix.

We start with a system with no initial available inventory $\boldsymbol{R}(0) = \boldsymbol{0}$, where $\boldsymbol{R}(t)$ is the vector of available inventory of each item and $\boldsymbol{0}$ a column vector of zero-valued components. Disregarding lead times initially, with $\boldsymbol{H}$ as the input matrix describing the Bill-of-Materials (BOM) and $\boldsymbol{P}$ the column vector describing total production of all items, then $\boldsymbol{HP}$ will be the *dependent* (*internal*) *demand* (of sub-items) and $\boldsymbol{P} - \boldsymbol{HP} = (\boldsymbol{I} - \boldsymbol{H})\boldsymbol{P}$ will be *net production*, which is possible to export from the system. If $\boldsymbol{D}$ is a vector giving the externally demanded quantities of all items, then this demand will be exactly satisfied (neither surplus nor shortage), when $(\boldsymbol{I} - \boldsymbol{H})\boldsymbol{P} = \boldsymbol{D}$, i.e. when

$$\boldsymbol{P} = \left(\boldsymbol{I} - \boldsymbol{H}\right)^{-1}\boldsymbol{D}, \tag{16}$$

where $(\boldsymbol{I} - \boldsymbol{H})^{-1}$ is the Leontief inverse.

Making use of the time translation theorem of Laplace transforms (6), we introduce the diagonal lead-time matrix $\boldsymbol{\tau}(s)$, with $\mathrm{e}^{s\tau_i}$ in its ith diagonal position, where τ_i is the *lead time* for item i, i.e. the time ahead of the completion of item i that necessary sub-items for the assembly of this item need to be in place. If $\tilde{\boldsymbol{P}}(s)$ is the transform of (time-varying) production, then this production creates an internal (dependent) demand amounting to $\boldsymbol{H}\tilde{\boldsymbol{\tau}}(s)\tilde{\boldsymbol{P}}(s)$, this expression capturing both the size of the demand of different items and the times at which this demand occurs. Hence, the transform of net production will be $\left(\boldsymbol{I} - \boldsymbol{H}\tilde{\boldsymbol{\tau}}(s)\right)\tilde{\boldsymbol{P}}(s)$, so if external demand is to be exactly satisfied (both in size and timing), we must have $\left(\boldsymbol{I} - \boldsymbol{H}\tilde{\boldsymbol{\tau}}(s)\right)\tilde{\boldsymbol{P}}(s) = \tilde{\boldsymbol{D}}(s)$, or

$$\tilde{\boldsymbol{P}}(s) = \left(\boldsymbol{I} - \boldsymbol{H}\tilde{\boldsymbol{\tau}}(s)\right)^{-1}\tilde{\boldsymbol{D}}(s), \tag{17}$$

where $\tilde{\boldsymbol{D}}(s)$ is the transform of given (or estimated, forecasted) external demand.

Eq. (17) provides the *Lot-for-Lot solution* (L4L, "As Required") to all MRP problems, when there is no initial available inventory. Other standard ordering policies in MRP are primarily *Fixed Order Quantity* (FOQ) and *Fixed Period Requirements* (FPR), cf. [33].

The L4L policy $\tilde{\boldsymbol{P}}_{\mathrm{L4L}}(s)$ minimises available inventory throughout the process, so it must be optimal when the costs for holding inventory are very high or the ordering costs very low.

In contrast, the *All-at-Once policy* $(\forall @1)$ minimises the number of setups (when the production of each item is initialised). So each item is then produced in only one batch and this policy is optimal, when the costs for setups are very high (or the holding costs very low). Regarding total amounts, as before, we must have $(\boldsymbol{I}-\boldsymbol{H})\boldsymbol{P}_{\forall @1}=\boldsymbol{D}$, but the timing of production will be different. If the batch for item i is to be completed at time T_i, then

$$\tilde{\boldsymbol{P}}_{\forall @1}(s)=\begin{bmatrix} \mathrm{e}^{-sT_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \mathrm{e}^{-sT_n} \end{bmatrix}\boldsymbol{P}_{\forall @1}=\tilde{\boldsymbol{T}}(s)\boldsymbol{P}_{\forall @1}, \tag{18}$$

defining the diagonal matrix $\tilde{\boldsymbol{T}}(s)$, and internal demand will be $\boldsymbol{H}\tilde{\boldsymbol{\tau}}(s)\tilde{\boldsymbol{P}}_{\forall @1}(s)$. The times T_i are determined sequentially beginning at the top level (an end item having no internal demand) and proceeding downwards. On each level this batch completion time will be determined by the expression

$$T_i=\arg\min_t\left\{Max\left(0,\, \pounds^{-1}\left\{\left[\boldsymbol{H}\right]_{\text{row } i}\tilde{\boldsymbol{\tau}}(s)\tilde{\tilde{\boldsymbol{P}}}_{\forall @1}(s)+\tilde{\tilde{\boldsymbol{D}}}_i(s)\right\}\right)>0\right\}, \tag{19}$$

where $\tilde{\tilde{\boldsymbol{D}}}_i(s)=\tilde{\boldsymbol{D}}_i(s)/s$ denotes the transform of cumulative demand for item i, cf. (4), and which gives T_i as the earliest time that there is a positive internal or external demand for this item. The triangular nature of $\boldsymbol{H}$ ensures that for each batch, only times previously determined on higher levels enter when searching for the current earliest completion time.

Concerning economic consequences from choosing different production policies, we introduce three unit price and cost vectors (row vectors), namely $\boldsymbol{p}$ for sales prices and $\boldsymbol{c}$ for unit variable costs of the items, and K as the setup cost vector, capturing the fixed costs associated with producing/purchasing a batch of the respective items. Concerning $\boldsymbol{K}$, these costs are allocated to the completion time of the respective batches. Instead, if they were referring to the starting times of batches, we can exchange $\boldsymbol{K}$ for an adjusted setup cost vector $\boldsymbol{K}\tilde{\boldsymbol{\tau}}(s)$ moving the associated payments backwards in time by the respective lead times. Options for in-between timing are also easily taken care of.

With these basic payment parameters, we interpret $\boldsymbol{p}\tilde{\boldsymbol{D}}(s)$ to be the transform of revenues, $\boldsymbol{c}\tilde{\boldsymbol{P}}(s)$ the transform of variable production costs and $\boldsymbol{K}\tilde{\boldsymbol{P}}'(s)$ to be the transform of out-payments for setups, where $\tilde{\boldsymbol{P}}'(s)$ is the train of impulses for the completion times of batches, cf. (15). For the All-at-Once policy $\tilde{\boldsymbol{P}}'_{\forall @1}(s)$ will coincide with $\tilde{\boldsymbol{T}}_{\forall @1}(s)\boldsymbol{1}$, where $\boldsymbol{1}$ is a column vector of unit components. Applying the *NPV* theorem (9), the Net Present Value (*NPV*) collecting all modelled economic consequences into one financial measure is obtained as

$$NPV=\boldsymbol{p}\tilde{\boldsymbol{D}}(\rho)-\boldsymbol{c}\tilde{\boldsymbol{P}}(\rho)-\boldsymbol{K}\tilde{\boldsymbol{P}}'(\rho), \tag{20}$$

where the frequency s has been exchanged for the continuous discount rate ρ in the transforms. This equation presupposes that all inventory holding costs are capital costs, or modified capital costs (by raising the discount rate ρ appropriately in order to cover physical holding costs such as rent, manual holding, insurance, refrigeration, etc.). If out-of-pocket costs need to be taken care of more accurately, the equation needs to be modified accordingly, see [32].

Holding costs are usually referred to inventory. The coarser method of attaching holding costs to the physical level of inventory may here be interpreted as the difference between the undiscounted and discounted cash flow, to which the (undiscounted) setup costs are added, making up the *inventory-related costs*, i.e.

$$\begin{aligned} IRC &= \boldsymbol{p}\tilde{\boldsymbol{D}}(0)-\boldsymbol{c}\tilde{\boldsymbol{P}}(0)-\boldsymbol{K}\tilde{\boldsymbol{P}}'(0)- \\ &-\left(\boldsymbol{p}\tilde{\boldsymbol{D}}(\rho)-\boldsymbol{c}\tilde{\boldsymbol{P}}(\rho)-\boldsymbol{K}\tilde{\boldsymbol{P}}'(\rho)\right)+\boldsymbol{K}\tilde{\boldsymbol{P}}'(0)= \\ &=\boldsymbol{p}\left(\tilde{\boldsymbol{D}}(0)-\tilde{\boldsymbol{D}}(\rho)\right)-\boldsymbol{c}\left(\tilde{\boldsymbol{P}}(0)-\boldsymbol{c}\tilde{\boldsymbol{P}}(\rho)\right)+\boldsymbol{K}\tilde{\boldsymbol{P}}'(\rho), \end{aligned} \tag{21}$$

where *IRC* denotes the inventory-related costs, i.e. the sum of capital-holding costs and setup costs. Both measures must give the same result, since $NPV(\rho)+IRC(\rho)=$ $=\boldsymbol{p}\tilde{\boldsymbol{D}}(0)-\boldsymbol{c}\tilde{\boldsymbol{P}}(0)$, which is a constant (independent of discount rate and setup costs), also illustrated in Section 5.

We now turn to the main purpose of this paper, namely to study modifications to the above results, when there is a non-zero initial inventory of items $\boldsymbol{R}(0)$ available.

Irrespective of whichever production policy $\tilde{\boldsymbol{P}}(s)$ is chosen, available inventory $\boldsymbol{R}$ always follows

$$\tilde{\boldsymbol{R}}(s)=\frac{\boldsymbol{R}(0)+\left(\boldsymbol{I}-\boldsymbol{H}\tilde{\boldsymbol{\tau}}(s)\right)\tilde{\boldsymbol{P}}\left(s\right)-\tilde{\boldsymbol{D}}(s)}{s}, \tag{22}$$

in which the time integral theorem of the Laplace transform (4) has been used. When there still are items in stock, it is assumed that they in the first place cover external and internal demand. When these items are used up, in general, there will be a *remaining demand*, which we denote $\boldsymbol{d}(t)$. In the time domain, $\bar{\boldsymbol{d}}_i(t)$ is determined from

$$\begin{aligned} \bar{\boldsymbol{d}}_i(t) &= Max\left(0,\, \bar{\boldsymbol{D}}_i(t)+\pounds^{-1}\left\{\sum_j \boldsymbol{H}_{ij}\mathrm{e}^{s\tau_j}\tilde{\tilde{\boldsymbol{P}}}_j(s)\right\}-\boldsymbol{R}_i(0)\right)= \\ &= Max\left(0,\, \bar{\boldsymbol{D}}_i(t)+\sum_j \boldsymbol{H}_{ij}\bar{\boldsymbol{P}}_j\left(t+\tau_j\right)-\boldsymbol{R}_i(0)\right), \end{aligned} \tag{23}$$

i.e. where $\bar{\boldsymbol{d}}_i(t)$ is the remaining cumulative demand of item i. $\boldsymbol{R}(t)$ is a staircase function. $\bar{\boldsymbol{d}}_i(t)$, in general, will depend on the production of items j', for $j < i$. If a production plan $\tilde{\boldsymbol{P}}(s)$ is feasible, we must have $\boldsymbol{R}(t)\geq\boldsymbol{0}$, otherwise there will be shortages of components, making the plan impossible to follow.

The time at which initial inventory is used up, in general, will be different for different items, and is written T_i for the i^{th} item. It is the earliest time at which $\bar{\boldsymbol{d}}_i(t)$ is positive:

$$T_i = \arg\min_t \left\{ Max\left(0, \bar{\boldsymbol{d}}_i(t)\right) > 0 \right\}. \tag{24}$$

For the $\forall @1$ policy it will be completion time of the (only) batch of this item. Determining these T_i can take place in the same way as explained above beginning with the top level, where there is no internal demand and proceeding downwards, using the times calculated earlier for higher levels.

Once the remaining demand has been determined, the L4L and $\forall @1$ policies according to the equations for the initially empty system, will be valid. For the L4L and $\forall @1$ policies, we have

$$\begin{cases} \tilde{\boldsymbol{P}}_{\text{L4L}}(s) = \tilde{\boldsymbol{d}}(s), \\ \tilde{\boldsymbol{P}}_{\forall @1}(s) = \tilde{\boldsymbol{T}}(s)\tilde{\boldsymbol{d}}(0), \end{cases} \tag{25}$$

where $\tilde{\boldsymbol{d}}(0)$ contains the total remaining demand for each item, which can be seen from applying (4)-(5), $\bar{\boldsymbol{d}}(\infty) = \frac{\lim_{s\to 0} s\tilde{\boldsymbol{d}}(s)}{s} = \tilde{\boldsymbol{d}}(0)$.

Applying the final value theorem of Laplace transforms (5) to (22), we find for the final remaining inventory $\boldsymbol{R}(\infty)$ in the L4L case

$$\boldsymbol{R}(\infty) = \lim_{s\to 0} s\tilde{\boldsymbol{R}}(s) = \boldsymbol{R}(0) + (\boldsymbol{I} - \boldsymbol{H})\tilde{\boldsymbol{d}}(0) - \tilde{\boldsymbol{D}}(0), \tag{26}$$

and in the $\forall @1$ case, the (expected) same result holds, due to both $\tilde{\boldsymbol{\tau}}(s)$ and $\tilde{\boldsymbol{T}}(s)$ collapsing into the identity matrix $\boldsymbol{I}$ for $s = 0$. Eqs (26) may be interpreted as the remaining inventory $\boldsymbol{R}(\infty)$ is initial inventory $\boldsymbol{R}(0)$ subtracted by (i) sub-items used up in production $\boldsymbol{H}\tilde{\boldsymbol{d}}(0)$, and (ii), by $\left(\tilde{\boldsymbol{D}}(0) - \tilde{\boldsymbol{d}}(0)\right)$, which is total demand less total remaining demand (when initial inventory is used up). The case that there is a positive remaining inventory for some item, thus occurs when initial inventory is more than enough to cover external and internal demand for this item.

A simple numerical example explaining these relationships is given in Section 5 below.

4 ECONOMIC VALUE OF INITIAL STOCK

We investigate the economic consequences from having, or not having an initial available inventory $\boldsymbol{R}(0)$. Thus, we compare the Net Present Value obtained either we have this initial stock or not. The difference will depend on which production policy is followed.

Starting with an empty inventory, the *NPV* according to (9) following the L4L policy will be:

$$\begin{aligned} NPV_{\text{empty, L4L}} &= \boldsymbol{p}\tilde{\boldsymbol{D}}(\rho) - \boldsymbol{c}\tilde{\boldsymbol{P}}_{\text{L4L, empty}}(\rho) - \boldsymbol{K}\tilde{\boldsymbol{P}}'_{\text{L4L, empty}}(\rho) = \\ &= \left(\boldsymbol{p} - \boldsymbol{c}\left(\boldsymbol{I} - \boldsymbol{H}\tilde{\boldsymbol{\tau}}(\rho)\right)^{-1}\right)\tilde{\boldsymbol{D}}(\rho) - \boldsymbol{K}\tilde{\boldsymbol{P}}'_{\text{L4L, empty}}(\rho), \end{aligned} \tag{27}$$

where $\tilde{\boldsymbol{P}}'_{\text{L4L, empty}}$ the impulse train of production timing associated with $\left(\boldsymbol{I} - \boldsymbol{H}\tilde{\boldsymbol{\tau}}(\rho)\right)^{-1}\tilde{\boldsymbol{D}}(\rho)$ in this L4L case, cf. (15).

Instead, having an initial stock $\boldsymbol{R}(0)$ will give the *NPV*:

$$\begin{aligned} NPV_{\text{L4L}} &= \boldsymbol{p}\tilde{\boldsymbol{D}}(\rho) - \boldsymbol{c}\tilde{\boldsymbol{P}}_{\text{L4L}}(\rho) - \boldsymbol{K}\tilde{\boldsymbol{P}}'_{\text{L4L}}(\rho) = \\ &= \boldsymbol{p}\tilde{\boldsymbol{D}}(\rho) - \boldsymbol{c}\tilde{\boldsymbol{d}}(\rho) - \boldsymbol{K}\tilde{\boldsymbol{d}}'(\rho). \end{aligned} \tag{28}$$

So the value of the initial stock in the L4L case is

$$\begin{aligned} \Delta NPV_{\text{L4L}} &= NPV_{\text{L4L}} - NPV_{\text{empty, L4L}} = \\ &= \boldsymbol{c}\left(\left(\boldsymbol{I} - \boldsymbol{H}\tilde{\boldsymbol{\tau}}(\rho)\right)^{-1}\tilde{\boldsymbol{D}}(\rho) - \tilde{\boldsymbol{d}}(\rho)\right) + \boldsymbol{K}\left(\tilde{\boldsymbol{P}}'_{\text{L4L, empty}}(\rho) - \tilde{\boldsymbol{d}}'(\rho)\right). \end{aligned} \tag{29}$$

This expression presupposes that (i) that the given demand can be satisfied when $\boldsymbol{R}(0) = \boldsymbol{0}$, and (ii) that if there might be a remaining positive, available inventory $\boldsymbol{R}(\infty)$, the value of this inventory is worthless.

In the $\forall @1$ case, we instead obtain

$$\begin{aligned} NPV_{\text{empty, }\forall @1} &= \\ &= \boldsymbol{p}\tilde{\boldsymbol{D}}(\rho) - \boldsymbol{c}\tilde{\boldsymbol{P}}_{\forall @1\text{, empty}}(\rho) - \boldsymbol{K}\tilde{\boldsymbol{P}}'_{\forall @1\text{, empty}}(\rho) = \\ &= \boldsymbol{p}\tilde{\boldsymbol{D}}(\rho) - \boldsymbol{c}\tilde{\boldsymbol{T}}_{\text{empty}}(\rho)\tilde{\boldsymbol{D}}(0) - \boldsymbol{K}\tilde{\boldsymbol{T}}_{\text{empty}}(\rho)\boldsymbol{1}, \end{aligned} \tag{30}$$

where $\tilde{\boldsymbol{T}}_{\text{empty}}$ is the matrix containing diagonal elements e^{-sT_i} with T_i being the earliest time that item i is demanded internally or externally, and:

$$\begin{aligned} NPV_{\forall @1} &= \boldsymbol{p}\tilde{\boldsymbol{D}}(\rho) - \boldsymbol{c}\tilde{\boldsymbol{P}}_{\forall @1}(\rho) - \boldsymbol{K}\tilde{\boldsymbol{P}}'_{\forall @1}(\rho) = \\ &= \boldsymbol{p}\tilde{\boldsymbol{D}}(\rho) - \boldsymbol{c}\tilde{\boldsymbol{T}}(\rho)\tilde{\boldsymbol{d}}(0) - \boldsymbol{K}\tilde{\boldsymbol{T}}(\rho)\boldsymbol{1}. \end{aligned} \tag{31}$$

Therefore the value of initial inventory will be:

$$\begin{aligned} \Delta NPV_{\forall @1} &= NPV_{\forall @1} - NPV_{\text{empty, }\forall @1} = \\ &= \boldsymbol{c}\left(\tilde{\boldsymbol{T}}_{\text{empty}}(\rho)\tilde{\boldsymbol{D}}(0) - \tilde{\boldsymbol{T}}(\rho)\tilde{\boldsymbol{d}}(0)\right) + \boldsymbol{K}\left(\tilde{\boldsymbol{T}}_{\text{empty}}(\rho) - \tilde{\boldsymbol{T}}(\rho)\right)\boldsymbol{1}. \end{aligned} \tag{32}$$

The same qualification applies to this evaluation as in the L4L case.

It should be pointed out that the timing vector $\tilde{\boldsymbol{T}}_{\forall @1}(\rho)\boldsymbol{1}$ always coincides with the timing vector $\tilde{\boldsymbol{P}}'_{\forall @1}(\rho)$.

5 A NUMERICAL EXAMPLE

Let us consider a product A made up of sub-items as illustrated by the product structure tree in Fig. 2. For producing one item A, one sub-item B and two items C are required ahead of the completion of A by 1 time unit (the lead time of A). Item B, in its turn, is made from one unit of a fourth item D required two time units in advance of the completion of B. Numbering the items alphabetically, the Bill-of-Materials is thus given by the input matrix $\boldsymbol{H}$, and the lead times are captured in the lead time matrix $\tilde{\boldsymbol{\tau}}(s)$:

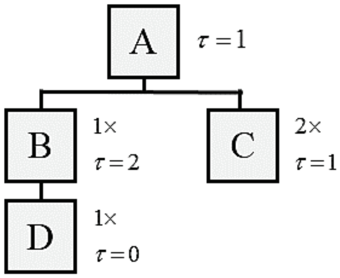

Figure 2 Product structure tree in example

$$\boldsymbol{H} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \ \tilde{\boldsymbol{\tau}}(s) = \begin{bmatrix} e^{s} & 0 & 0 & 0 \\ 0 & e^{2s} & 0 & 0 \\ 0 & 0 & e^{s} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \qquad (33)$$

So this enables us to determine the generalised Leontief inverse

$$\left(\boldsymbol{I} - \boldsymbol{H}\tilde{\boldsymbol{\tau}}(s)\right)^{-1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ e^{s} & 1 & 0 & 0 \\ 2e^{s} & 0 & 1 & 0 \\ e^{3s} & e^{2s} & 0 & 1 \end{bmatrix}, \boldsymbol{R}(0) = \begin{bmatrix} 5 \\ 1 \\ 2 \\ 2 \end{bmatrix}. \qquad (34)$$

Let us consider a time span of six time units (including a current period 0) and that external demand is present only for the end product A and is given by discrete period demand $\boldsymbol{D}_1(t)$ (using the notation $D_t = \boldsymbol{D}_1(t)$) according to

$$\boldsymbol{D}_1(t) = \left[D_0, D_1, D_2, D_3, D_4, D_5\right] = \left[0,\ 2,\ 1,\ 3,\ 1,\ 2\right]. \qquad (35)$$

Cumulative demand $\bar{\boldsymbol{D}}_1(t)$ will then be:

$$\bar{\boldsymbol{D}}_1(t) = \begin{bmatrix} D_0, D_0 + D_1, D_0 + D_1 + D_2, \\ D_0 + D_1 + D_2 + D_3, \\ D_0 + D_1 + D_2 + D_3 + D_4, \\ D_0 + D_1 + D_2 + D_3 + D_4 + D_5 \end{bmatrix} = \left[0,\ 2,\ 3,\ 6,\ 7,\ 9\right]. \qquad (36)$$

The Laplace transform of the (external) demand for this end item will be $\tilde{\boldsymbol{D}}_1(s) = 2e^{-s} + e^{-2s} + 3e^{-3s} + e^{-4s} + 2e^{-5s}$. The external demand and the cumulative external demand vectors are thus

$$\tilde{\boldsymbol{D}}(s) = \begin{bmatrix} 2e^{-s} + e^{-2s} + 3e^{-3s} + e^{-4s} + 2e^{-5s} \\ 0 \\ 0 \\ 0 \end{bmatrix},$$
$$\tilde{\bar{\boldsymbol{D}}}(s) = \frac{1}{s}\begin{bmatrix} 2e^{-s} + e^{-2s} + 3e^{-3s} + e^{-4s} + 2e^{-5s} \\ 0 \\ 0 \\ 0 \end{bmatrix}. \qquad (37)$$

Depending on production policy $\tilde{\boldsymbol{P}}(s)$, as stated by (21), available inventory will develop according to

$$\tilde{\boldsymbol{R}}(s) = \frac{1}{s}\begin{bmatrix} 5 \\ 1 \\ 2 \\ 2 \end{bmatrix} + \frac{1}{s}\left(\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ e^{s} & 0 & 0 & 0 \\ 2e^{s} & 0 & 0 & 0 \\ 0 & e^{2s} & 0 & 0 \end{bmatrix}\right)\begin{bmatrix} \tilde{\boldsymbol{P}}_1(s) \\ \tilde{\boldsymbol{P}}_2(s) \\ \tilde{\boldsymbol{P}}_3(s) \\ \tilde{\boldsymbol{P}}_4(s) \end{bmatrix} - \qquad (38)$$
$$-\frac{1}{s}\begin{bmatrix} 2e^{-s} + e^{-2s} + 3e^{-3s} + e^{-4s} + 2e^{-5s} \\ 0 \\ 0 \\ 0 \end{bmatrix},$$

the first term showing the assumed initial inventory $\boldsymbol{R}(0)/s$, cf. (22).

Starting with the top level, we now proceed to find the earliest time T_1 when there is a positive external or internal demand (above initial inventory). For A (item 1), we have $\tilde{\boldsymbol{R}}_1(s) = \tilde{\bar{\boldsymbol{P}}}_1(s) + \left(5 - \left(2e^{-s} + e^{-2s} + 3e^{-3s} + e^{-5s}\right)\right)$, which shows that initial inventory does not cover cumulative demand for more than periods 0-2, so for this item $T_1 = 3$, i.e. $\boldsymbol{P}_1(t)$ needs to be positive at $t = 3$ for either policy. Looking within the time domain, using (38) we have $\left(\bar{\boldsymbol{D}}_1\left(T_1\right) - 5\right)^{+} =$ $Max\left(0, \bar{\boldsymbol{D}}_1\left(T_1\right) - 5\right) = \left[0,\ 0,\ 0,\ 1,\ 1,\ 2\right]$, also showing that $T_1 = 3$ both for L4L and $\forall @1$.

On level 2 (choosing the B item) there is only internal demand. From (21) we read $\tilde{\boldsymbol{R}}_2(s) = \left(1 + \tilde{\boldsymbol{P}}_2(s) - e^{s}\tilde{\boldsymbol{P}}_1(s)\right)/s$, which shows that $\bar{\boldsymbol{P}}_2(t)$ must cover $\bar{\boldsymbol{P}}_1(t+1) - \tilde{\boldsymbol{R}}_2(0) =$ $\bar{\boldsymbol{P}}_1(t+1) - 1$, so the first time that $\bar{\boldsymbol{P}}_1(t+1) > 1$, requires $\boldsymbol{P}_2(t) > 0$ and $T_2 = t$.

For the third item we have $\tilde{\boldsymbol{R}}_3(s) =$ $\left(2 + \tilde{\boldsymbol{P}}_3(s) - 2e^{s}\tilde{\boldsymbol{P}}_1(s)\right)/s$, or $\boldsymbol{R}_3(t) = \left(2 + \bar{\boldsymbol{P}}_3(s) - 2\bar{\boldsymbol{P}}_1(t+1)\right)$, which similarly shows that if $\bar{\boldsymbol{P}}_1(t+1) > 1$, then $\boldsymbol{P}_3(t) > 0$ and $T_3 = t$. For our final item 4 (D), we have $\tilde{\boldsymbol{R}}_4(s) =$ $\left(3 + \tilde{\boldsymbol{P}}_4(s) - e^{2s}\tilde{\boldsymbol{P}}_2(s)\right)/s$, or $\boldsymbol{R}_4(t) = 3 + \bar{\boldsymbol{P}}_4(t) - \bar{\boldsymbol{P}}_2(t+2)$, so the first time that $\bar{\boldsymbol{P}}_2(t+2) > 3$ necessitates $\bar{\boldsymbol{P}}_4(t)$ to be positive, i.e. $T_4 = t - 2$. The time development for internal and external demand and production for the four items following the two policies are illustrated in Figs. 3-6.

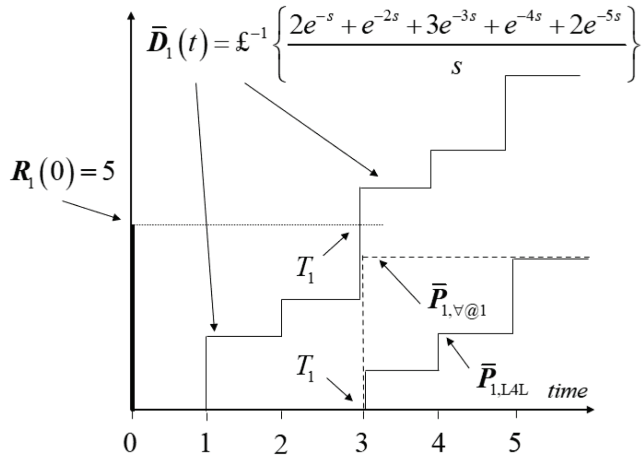

Figure 3 External demand of end item A as a staircase function and production satisfying this demand, L4L solid and $\forall@1$ dashed.

On the top level with no internal demand, we have $\bar{\boldsymbol{d}}_1(t) = Max\left(0, \bar{\boldsymbol{D}}_1(t) - \boldsymbol{R}_1(0)\right) = Max\left(0, \bar{\boldsymbol{D}}_1(T_1) - 5\right) =$ $\left[0, 0, 0, 1, 1, 2\right]$. So the transform of cumulate remaining demand becomes $\tilde{\bar{\boldsymbol{d}}}_1(s) = \left(e^{-3s} + e^{-4s} + 2e^{-5s}\right)/s$, and of remaining demand $\tilde{\boldsymbol{d}}_1(s) = \left(e^{-3s} + e^{-4s} + 2e^{-5s}\right)$. With the L4L policy $\tilde{\boldsymbol{P}}_{1,\mathrm{L4L}}(s) = \tilde{\boldsymbol{d}}_1(s)$, and with $\forall@1$, $\tilde{\boldsymbol{P}}_{1,\,\forall@1}(s) = e^{-3s}\tilde{\boldsymbol{d}}_1(0) = 4e^{-3s}$. Thus $T_1 = 3$. To summarise,

$$\begin{cases} \tilde{\boldsymbol{P}}_{1,\,\mathrm{L4L}}(s) = \left(e^{-3s} + e^{-4s} + 2e^{-5s}\right), \\ \tilde{\boldsymbol{P}}_{1,\,\forall@1}(s) = 4e^{-3s}, \\ T_{1,\,\mathrm{L4L}} = T_{1,\,\forall@1} = 3. \end{cases} \tag{39}$$

For item 2 (B), and the L4L policy, we have $\bar{\boldsymbol{d}}_2(t) = Max\left(0, \bar{\boldsymbol{P}}_{1,\,\mathrm{L4L}}(t+1) - \boldsymbol{R}_2(0)\right)$, or $\tilde{\bar{\boldsymbol{d}}}_2(s) =$ $= £\left\{Max\left(0,\, £^{-1}\left\{\left(e^{s}\tilde{\boldsymbol{P}}_{1,\,\mathrm{L4L}}(s) - \boldsymbol{R}_2(0)\right)/s\right\}\right)\right\} =$ $= £\left\{Max\left(0,\, £^{-1}\left\{\left(e^{s}\left(e^{-3s} + e^{-4s} + 2e^{-5s}\right) - 1\right)/s\right\}\right)\right\} =$ $= \left(e^{-3s} + 2e^{-4s}\right)/s$ and $\tilde{\boldsymbol{d}}_2(s) = \left(e^{-3s} + 2e^{-4s}\right)$, so $\tilde{\boldsymbol{P}}_{2,\,\mathrm{L4L}}(s) = \tilde{\boldsymbol{d}}_2(s) = \left(e^{-3s} + 2e^{-4s}\right)$ giving $T_2 = 3$. And for the $\forall@1$ policy, we obtain $\tilde{\boldsymbol{P}}_{2,\,\forall@1}(s) = e^{-T_2 s}\tilde{\boldsymbol{d}}_2(0) = 3e^{-2s}$.

Summarising, we have:

$$\begin{cases} \tilde{\boldsymbol{P}}_{2,\,\mathrm{L4L}}(s) = e^{-3s} + 2e^{-4s}, \\ T_{2,\,\mathrm{L4L}} = 3, \\ \tilde{\boldsymbol{P}}_{2,\,\forall@1}(s) = 3e^{-2s}, \\ T_{2,\,\forall@1} = 2. \end{cases} \tag{40}$$

Similarly, for Item C and L4L, we have $\bar{\boldsymbol{d}}_3(t) = Max\left(0, 2\bar{\boldsymbol{P}}_{1,\,\mathrm{L4L}}(t+1) - \boldsymbol{R}_3(0)\right)$, or $\tilde{\bar{\boldsymbol{d}}}_3(s) =$ $= £\left\{Max\left(0,\, £^{-1}\left\{\left(2e^{s}\tilde{\boldsymbol{P}}_{1,\,\mathrm{L4L}}(s) - \boldsymbol{R}_3(0)\right)/s\right\}\right)\right\} =$ $= £\left\{Max\left(0,\, £^{-1}\left\{2\left(e^{-2s} + e^{-3s} + 2e^{-4s} - 1\right)/s\right\}\right)\right\} =$ $= \left(2e^{-3s} + 4e^{-4s}\right)/s$. So $\tilde{\boldsymbol{P}}_{3,\,\mathrm{L4L}}(s) = \tilde{\boldsymbol{d}}_3(s) = \left(2e^{-3s} + 4e^{-4s}\right)$ and $T_3 = 3$. Instead for $\forall@1$, $T_3 = 2$ and we obtain $\tilde{\boldsymbol{P}}_{3,\,\forall@1}(s) = e^{-sT_3}\tilde{\boldsymbol{d}}_3(0) = 6e^{-2s}$. So, summarising:

$$\begin{cases} \tilde{\boldsymbol{P}}_{3,\mathrm{L4L}}(s) = \left(2e^{-3s} + 4e^{-4s}\right), \\ T_{3,\mathrm{L4L}} = 3, \\ \tilde{\boldsymbol{P}}_{3,\forall@1}(s) = 6e^{-2s}, \\ T_{3,\forall@1} = 2. \end{cases} \tag{41}$$

Finally for item 4 (D in Fig. 2), which has an initial available inventory of $\boldsymbol{R}_4(0) = 2$, we have $\bar{\boldsymbol{d}}_4(t) =$ $= £\left\{Max\left(0, £^{-1}\left\{\frac{\left(e^{2s}\left(e^{-3s} + 2e^{-4s}\right) - 2\right)}{s}\right\}\right)\right\}$, and therefore in the L4L case $\tilde{\bar{\boldsymbol{d}}}_4(s) =$ $= £\left\{Max\left(0,\, £^{-1}\left\{\left(e^{2s}\tilde{\boldsymbol{P}}_{2,\,\mathrm{L4L}}(s) - \boldsymbol{R}_4(0)\right)/s\right\}\right)\right\} =$ $= £\left\{Max\left(0,\, £^{-1}\left\{\left(\left(e^{-s} + 2e^{-2s}\right) - 2\right)/s\right\}\right)\right\} = e^{-2s}/s$, so $T_4 = 2$, and according to the $\forall@1$ policy $T_4 = 0$, so summing up

$$\begin{cases} \tilde{\boldsymbol{P}}_{4,\,\mathrm{L4L}}(s) = e^{-2s}, \\ T_{4,\,\mathrm{L4L}} = 2, \\ \tilde{\boldsymbol{P}}_{4,\,\forall@1}(s) = 1, \\ T_{4,\,\forall@1} = 0. \end{cases} \tag{42}$$

Assembling the components from (39)-(42), the production vectors and $\tilde{\boldsymbol{T}}(s)$ matrices will be:

$$\tilde{\boldsymbol{P}}_{\mathrm{L4L}}(s)=\begin{bmatrix}\mathrm{e}^{-3s}+\mathrm{e}^{-4s}+2\mathrm{e}^{-5s}\\ \mathrm{e}^{-3s}+2\mathrm{e}^{-4s}\\ 2\mathrm{e}^{-3s}+4\mathrm{e}^{-4s}\\ \mathrm{e}^{-2s}\end{bmatrix},\ \tilde{\boldsymbol{P}}_{\forall@1}(s)=\begin{bmatrix}4\mathrm{e}^{-3s}\\ 3\mathrm{e}^{-2s}\\ 6\mathrm{e}^{-2s}\\ 1\end{bmatrix},\qquad(43)$$

$$\tilde{\boldsymbol{T}}_{\mathrm{L4L}}(s)=\begin{bmatrix}\mathrm{e}^{-3s}&0&0&0\\ 0&\mathrm{e}^{-3s}&0&0\\ 0&0&\mathrm{e}^{-3s}&0\\ 0&0&0&\mathrm{e}^{-2s}\end{bmatrix},\ \tilde{\boldsymbol{T}}_{\forall@1}(s)=\begin{bmatrix}\mathrm{e}^{-3s}&0&0&0\\ 0&\mathrm{e}^{-2s}&0&0\\ 0&0&\mathrm{e}^{-2s}&0\\ 0&0&0&1\end{bmatrix}.\ (44)$$

In addition, from (43), we find the setup timing vectors of the two policies $\tilde{\boldsymbol{P}}'_{\mathrm{L4L}}(s), \tilde{\boldsymbol{P}}'_{\forall@1}(s)=\boldsymbol{T}_{\forall@1}(s)\boldsymbol{1}$ to be

$$\tilde{\boldsymbol{P}}'_{\mathrm{L4L}}(s)=\begin{bmatrix}\mathrm{e}^{-3s}+\mathrm{e}^{-4s}+\mathrm{e}^{-5s}\\ \mathrm{e}^{-3s}+\mathrm{e}^{-4s}\\ \mathrm{e}^{-3s}+\mathrm{e}^{-4s}\\ \mathrm{e}^{-2s}\end{bmatrix},\ \tilde{\boldsymbol{P}}'_{\forall@1}(s)=\begin{bmatrix}\mathrm{e}^{-3s}\\ \mathrm{e}^{-2s}\\ \mathrm{e}^{-2s}\\ 1\end{bmatrix}.\qquad(45)$$

The earliest completion time for item D is $T_4 = 0$ following $\forall@1$. Luckily, this item has no lead time and can be produced/purchased immediately. If this were not so, then the $\forall@1$ policy with one item D missing to start with, would require either an initial "express" replenishment, or the production plan needs to be modified making it a "hybrid" All-at-Once plan, with at least one additional setup. Since there is no external demand for D, this missing item cannot be backlogged, but on a higher level, in this example the top level, items A, may be backlogged.

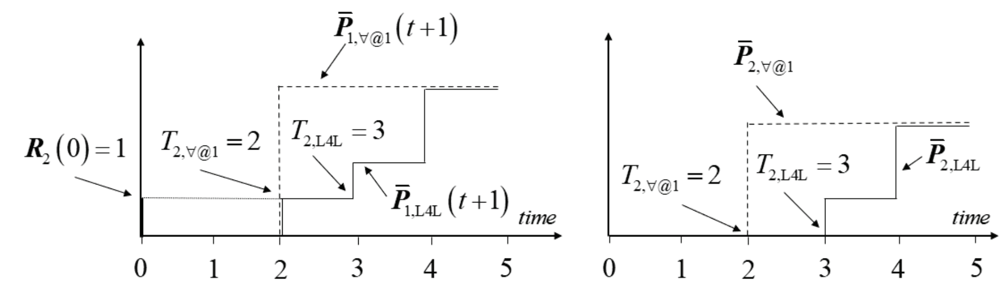

Figure 4 Item B developments, to the left internally generated demand (one time unit earlier), and to the right production satisfying this demand, L4L solid and $\forall@1$ dashed.

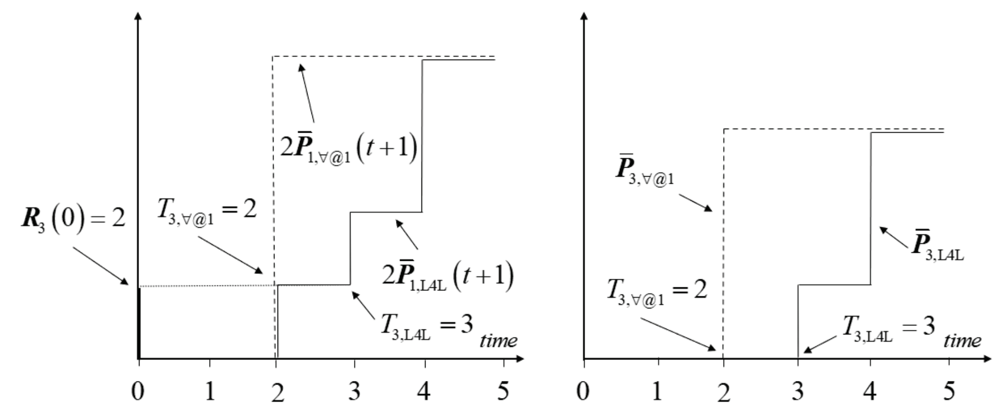

Figure 5 Item C developments, to the left internal demand, generated one time unit earlier, and to the right production, L4L solid and $\forall@1$ dashed.

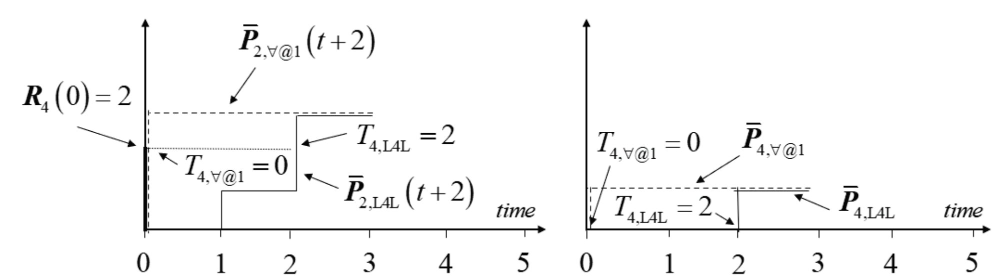

Figure 6 Item D developments, to the left internal demand, generated two time units earlier, and to the right production, L4L solid and $\forall@1$ dashed.

We now turn to economic consequences and assume the following parameter values

Table 1 Assumed economic parameter values

Name	Assumed parameter values	Comments
Sale price vector	$\boldsymbol{p}=[1000,\ 0,\ 0,\ 0]$	Only item 1 (A) is sold externally
Variable production cost vector	$\boldsymbol{c}=[200,\ 100,\ 300,\ 200]$	
Setup cost vector	$\boldsymbol{K}=[400,\ 250,\ 300,\ 250]$	
Continuous discount rate	$\rho=10\%-30\%$	Consequences are computed for different rates

With the parameter values given in Tab. 1, the following *NPV* is calculated for our two policies (both for ρ = 0.1):

$$\begin{cases} NPV_{\mathrm{L4L}} = \boldsymbol{p}\tilde{\boldsymbol{D}}(\rho)-\boldsymbol{c}\tilde{\boldsymbol{P}}_{\mathrm{L4L}}(\rho)-\boldsymbol{K}\tilde{\boldsymbol{P}}'_{\mathrm{L4L}}(\rho)=2425.34 \\ NPV_{\forall@1} = \boldsymbol{p}\tilde{\boldsymbol{D}}(\rho)-\boldsymbol{c}\tilde{\boldsymbol{P}}_{\forall@1}(\rho)-\boldsymbol{K}\tilde{\boldsymbol{P}}'_{\forall@1}(\rho)=2902.81 \end{cases} \tag{46}$$

So for ρ = 0.1, the $\forall@1$ policy gives a higher *NPV* than L4L and is to be preferred. However, for higher holding costs, represented by a higher value of ρ, one would expect the L4L policy to dominate, since L4L, among all possible policies, keeps available inventory to a very minimum. Varying ρ between 0.1 and 0.3 produces the *NPV* consequences displayed in Fig. 7.

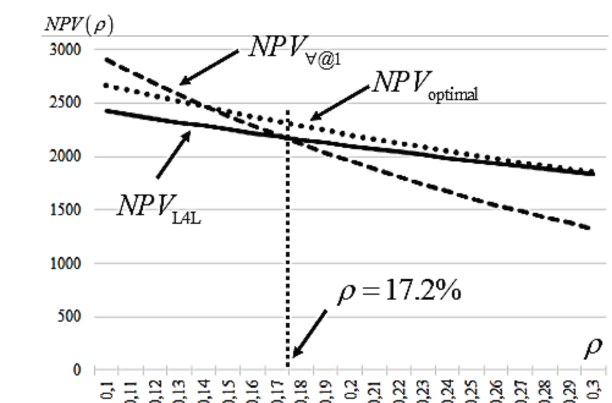

Figure 7 NPV as function of discount rate for policies L4L (solid), $\forall@1$ (dashed) and the optimal in-between policy (dotted).

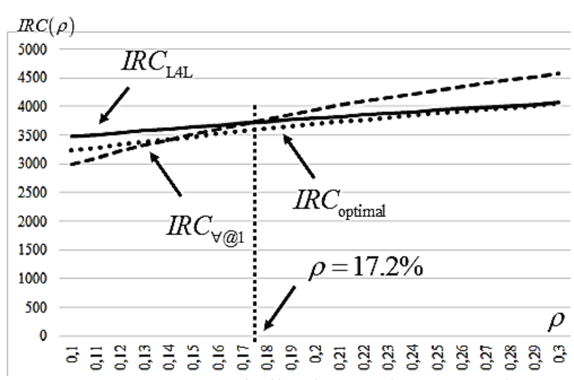

Figure 8 Inventory related costs (IRC) as function of discount rate for policies L4L (solid), $\forall@1$ (dashed) and the optimal in-between policy (dotted).

From Figs. 7-8, presenting the same conclusion, we see that for low values of ρ, $\forall@1$ (dashed curve) is to be preferred to L4L (solid curve) giving a higher *NPV*, and vice versa for values of ρ above 17.2%. At the intersection between the two curves, both policies are equally preferred, but the NPV can be improved further (inventory related costs lowered, see (21)) up (down) to the dotted curve.

There are only 128 different available production plans $\tilde{\boldsymbol{P}}(s)$ available in this example that meet the *inner corner requirement for optimality* (see e.g. [13] or [31]). For discount rates below 16%, the $\forall@1$ policy is optimal, for ρ between 16% and 26%, the plan

$$\tilde{\boldsymbol{P}}(s)=\begin{bmatrix} \mathrm{e}^{-3s}+\mathrm{e}^{-4s}+2\mathrm{e}^{-5s} \\ 3\mathrm{e}^{-3s} \\ 2\mathrm{e}^{-3s}+4\mathrm{e}^{-4s} \\ \mathrm{e}^{-s} \end{bmatrix}$$

is optimal, and above 26%, L4L is optimal, but the improvement here is so minute that it does not show in the diagrams.

To determine the value of having an initial inventory, we examine possible plans when $\boldsymbol{R}(0)=\boldsymbol{0}$. Starting with L4L using the Leontief inverse in (34), we find $\tilde{\boldsymbol{P}}_{\mathrm{L4L}}(s)$ to be

$$\tilde{\boldsymbol{P}}_{\mathrm{L4L}}(s)=\left(\boldsymbol{I}-\boldsymbol{H}\tilde{\boldsymbol{\tau}}(s)\right)^{-1}\tilde{\boldsymbol{D}}(s)=\begin{bmatrix} 1 & 0 & 0 & 0 \\ \mathrm{e}^{s} & 1 & 0 & 0 \\ 2\mathrm{e}^{s} & 0 & 1 & 0 \\ \mathrm{e}^{3s} & \mathrm{e}^{2s} & 0 & 1 \end{bmatrix}\tilde{\boldsymbol{D}}(s)=$$
$$=\begin{bmatrix} 2\mathrm{e}^{-s}+\mathrm{e}^{-2s}+3\mathrm{e}^{-3s}+\mathrm{e}^{-4s}+2\mathrm{e}^{-5s} \\ 2+\mathrm{e}^{-s}+3\mathrm{e}^{-2s}+\mathrm{e}^{-3s}+2\mathrm{e}^{-4s} \\ 4+2\mathrm{e}^{-s}+6\mathrm{e}^{-2s}+2\mathrm{e}^{-3s}+4\mathrm{e}^{-4s} \\ \left[2\mathrm{e}^{2s}+\mathrm{e}^{s}\right]+3+\mathrm{e}^{-s}+2\mathrm{e}^{-2s} \end{bmatrix}. \tag{47}$$

We see from the bottom left corner in the right-hand member that production must then take place in past time (market with brackets), so meeting this demand is impossible. Some external demand must be backlogged. The least possible change to remove this problem, is to backlog the first occurring three units of demand by changing external demand from $(2\mathrm{e}^{-s}+\mathrm{e}^{-2s}+3\mathrm{e}^{-3s}+\mathrm{e}^{-4s}+2\mathrm{e}^{-5s})$ to $(6\mathrm{e}^{-3s}+\mathrm{e}^{-4s}+2\mathrm{e}^{-5s})$. Therefore, the customers will have to wait two periods for two units and one period for one unit, which also postpones revenues. This gives the feasible production plan

$$\tilde{\boldsymbol{P}}_{\mathrm{L4L}}(s)=\begin{bmatrix} 6\mathrm{e}^{-3s}+\mathrm{e}^{-4s}+2\mathrm{e}^{-5s} \\ 6\mathrm{e}^{-2s}+\mathrm{e}^{-3s}+2\mathrm{e}^{-4s} \\ 12\mathrm{e}^{-2s}+2\mathrm{e}^{-3s}+4\mathrm{e}^{-4s} \\ 6+\mathrm{e}^{-s}+2\mathrm{e}^{-2s} \end{bmatrix}.$$

The economic consequences from not having an initial inventory are obtained from computing the NPV of revenues, production and setups. Choosing ρ = 20%, these amount to NPV_{revenues} = 4477.96, $NPV_{\text{production}}$ = 6356.04 and NPV_{setups} = 2834.40, i.e. totalling the negative value of NPV = –4712.48. This may be compared to the original L4L values (with an initial inventory), which are NPV_{revenues} = 5139.30, $NPV_{\text{production}}$ = 1494.07 and NPV_{setups} = 1546.75, totalling NPV = +2098.48. The number of setups has increased from eight to twelve. The postponement of revenues causes a loss of 661.35. The difference in *NPV* with and without the initial inventory amounts to ΔNPV = 6810.97, which we can compare with the sales value of the five units of the end item and nominal production cost (disregarding setup costs) for the other items in initial inventory, which amount to 6400.00.

6 CONCLUSIONS

In the foregoing, we have attempted to present consequences from having an initial available stock of items, compared with initially having an empty system. This presentation has been brief due to space requirements. Therefore, particularly aspects on consequences of having initial backlogs (negative inventories) have not been included in this report. Both initial inventories and initial backlogs may be distributed in time. There might be outstanding orders not yet haven been delivered into inventory.

Our main conclusion is that this type of theoretical extension to MRP Theory is achievable, but with the effect of added complications by needing to introduce new concepts, above all the new timing matrix $\tilde{\boldsymbol{T}}(s)$ and the concept of remaining demand $\tilde{\boldsymbol{d}}(s)$.

In future related work, emphasis will be on encompassing initial backlogs and outstanding orders.

Notice

The paper will be presented at MOTSP 2021 – 12th International Conference Management of Technology – Step to Sustainable Production, which will take place in Poreč/Porenzo, Istria (Croatia), on September 8–10, 2021. The paper will not be published anywhere else.

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Stability Analysis of Steel Welded Tubes Forming Process Using Numerical Simulations

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Abstract: In this paper, the research results of the stability of steel welded tubes forming process are presented. The aim of this research is to determine influence of geometrical and tribological parameters on stability of the process and to determine optimal values of influential process parameters. A research plan with variation of influential parameters was made, on the basis of which experimental and numerical experiments were performed. Tube forming was performed in one operation in a two-part tool made of hard metal by a combination of widening and narrowing. The geometrical factors observed during experiments are length, outer diameter and thicknesses of steel welded tube as a billet. Friction conditions in contact between tool and tubular workpiece are considered in two cases, the first one when standard machine oil is used as a lubricant and the second one when tube billet surface is phosphated. Based on results of experiments, influencing factors on stability of tube forming process were analysed and optimal production technology was recommended, including optimal values of influencing factors. Results obtained by experimental research were confirmed through numerical experiments based on finite element method.

Keywords: narrowing; numerical analysis; steel welded tubes; widening

1 INTRODUCTION

The production of tubular parts has a significant place in the automotive, defence, construction, process industry and energetics. In the past, such parts were made by cutting processes, but nowadays application of forming processes is dominant. The main advantages of producing tubular parts by forming processes are material savings, reduction of production time and production costs.

Tubular parts can be produced by hydro-forming or using widening and narrowing operations. The advantages of production tubular parts by narrowing and widening are lower costs of the necessary equipment and tools. There are several theoretical models which describe the process of tube forming processes by narrowing and widening.

Li et al. [1] proposed a theoretical model of widening metal tubes using a conical tool in the form of a mandrel, which was confirmed by the finite element method. In this model, tool with conical angle α acts along the axis of workpiece at velocity v_0. Formed tube was divided into five segments, and the largest strains occurred within two arcs. Based on the assumption of the forming mechanism, total work is spent on plastic bending along the central axis, plastic stretching in the direction of the diameter and on friction in contact zones. Energy consumption for all three processes is described in detail. Experiments have shown that the radius of a tube obtained by widening does not depend on the properties of materials but depends on geometry of tubes and tools.

Methodology for determining deformability limit in thin-walled tubes forming process is presented in paper [2]. Rigid tools are used in the experiment. The test is similar to the Nakajima test. Significance of the boundary deformability diagram is that it provides possibilities for optimizing the tube forming process.

In [3] a model of energy consumption in the forming process of thin-walled tubes is presented. Theoretical model is based on four assumptions. Theoretical analysis explains three deformation models that analyse the process of tube widening. Tube widening process is influenced by geometrical parameters: the ratio of the thickness of the tubular workpiece and the radius and tool inclination angle.

Research results of tube hydro forming process are presented in [4]. Effects of internal pressure, stroke and friction coefficient were analyzed. Taguchi's methods were used to optimize the process. Optimal height of the workpiece was determined based on the response of Taguchi's experiments.

Omar et al. [5] performed investigation of hydro-forming of welded tubes with variation of length and diameter ratio. Mechanical characteristics of the workpiece material and the welded tube seam were determined by tensile test and they are implemented in a numerical process simulation. Tubes are modelled as a system of two materials, the tube and the welded seam materials. Experiments were performed for different values of tube length and diameter. Results of the experiments and numerical simulations agree well and show that the L/D ratio (bulge ratio) has an impact on crack location. For value of ratio $L/D = 1$, a crack occurs in the base tube material near the welded seam zone, while for the values of the ratio $L/D = 2$ and $L/D = 3$ crack occurs on the side opposite to the welded seam zone.

This paper presents research of influence of geometrical factors and friction conditions on the forming process of welded tubes by concurrent combination of widening and narrowing. Geometrical factors of the tube that are considered during analysis are: length, diameter and thickness of the billet tube. Two cases of friction conditions were considered: first one when contact surfaces were lubricated with machine oil and second one when the tube billet surface was phosphated and SAP.G3 soap was used as lubricant. Experimental research was performed and confirmed by numerical simulations in accordance with research plan and combination of influential factors for each experiment.

2 THEORETICAL-EXPERIMENTAL RESEARCH OF TUBE FORMING

There are several methods to obtain products of simple or complex shape from tubular workpiece [6]. Most commonly used forming methods are: narrowing, widening, stretching, upsetting, twisting and combinations of these methods. In literature, there are several technologies of manufacturing the tubular products by forming the ends of tubular workpiece, where the solution to achieve higher strain ratios is found in the installation of holders on the inside or outside of the tube wall to ensure forced flow of material and to avoid forming defects.

Tube narrowing could be done by pulling or pushing material through narrowing ring, which has the final shape of tubular workpiece. Possibility of tube forming by narrowing depends on the narrowing coefficient, which affects the forming load value. Increasing of this load above the limit value leads to cracking or the formation of an annular fold in the non-contact cylindrical zone of the workipece. To make the process of narrowing stable it is necessary that the maximal value of circular stress satisfy the condition $\sigma_{\varphi\max} < \sigma_{\text{critical}}$ [6]. Value of the narrowing coefficient needs to be less than 0.8.

Tube widening occurs under the action of axial force. In the deformation zone, different forms of stress-strain state occur on different cross-sections. In addition to the tool shape, contact friction conditions also have an influence on forming load in tube widening process. The technological possibilities of tube widening are limited by the widening coefficient $k_{\text{wid}} = D_0/D_2$ [6]. When it is necessary to achieve higher strain ratios in tube widening process it is necessary to have more operations with annealing between those operations. Tubular parts are often produced by combination of narrowing and widening processes.

Hydro-forming of tubular parts is performed using internal pressure, which enables filling of the tool cavity. This method of tube forming is especially suitable for making asymmetrical tubular parts. Application of this technology is limited by the properties of the workpiece material, friction conditions and synchronization of the magnitude of the sealing force and internal pressure. Technological possibilities for application of this technology are quite wide due to the development of modern devices.

As mentioned, the subject of the research presented in the paper is the analysis of the influence of geometrical and friction parameters on the process of forming the tubular part shown in Fig. 1. The geometrical parameters of the tube billet that varied in the experiments are tube wall thickness (s_{0i}), tube diameter (D_{0i}) and tube length (h_{0i}). The selected values of these parameters for the analysis of the stability of the forming process are shown in Tab. 1.

Table 1 Tubular billet dimensions

	$i = 1$	$i = 2$	$i = 3$
Tube wall thickness (s_{0i})	2 mm	2.33 mm	2.5 mm
Tube diameter (D_{0i})	31 mm	32 mm	33 mm
Tube length (h_{0i})	68.5 mm	69 mm	69.5 mm

In order for the narrowing process at the ends of the tube billet to be successful, the narrowing force must overcome:

- resistance to narrowing of the non-contact and contact zone,
- bending resistance at the transition radius of the narrowing and
- resistance to narrowing in the conical part.

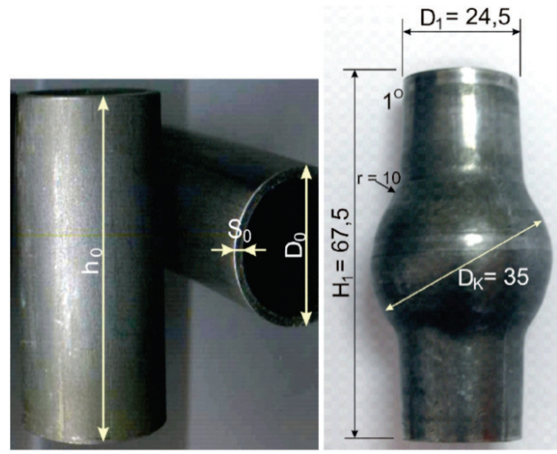


Figure 1 Geometrical characteristics of tubular billet and final workpiece [6, 7]

During the forming process, an uneven distributions of strain and stresses occur. According to [7], the stress state in the combined widening and narrowing forming process is considered in five different deformation zones. The deformation zones, shown in Fig. 2, in the phases of tube narrowing process are:

1) zone of free compression of the cylindrical part of the tube,
2) deformation zone without contact,
3) narrowing zone in the spherical part of the ring,
4) bending zone on radius and
5) narrowing zone in the conical part.

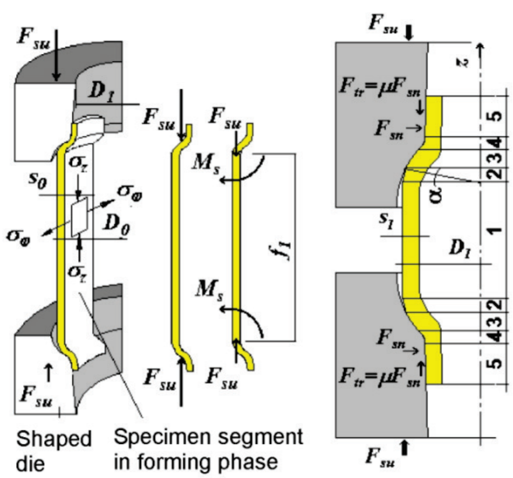


Figure 2 Action of forces and stress state during forming (left) and deformation zones during tube narrowing (right) [6, 7]

There are many design solutions for narrowing and widening tools. The concept of a two-part tool was chosen, which simultaneously narrows and expands the tubular workpiece to obtain the shape of a calotte in its central part. Tool consists of two shaping spherical parts made of hard metal, with PV20 quality (Fig. 3).

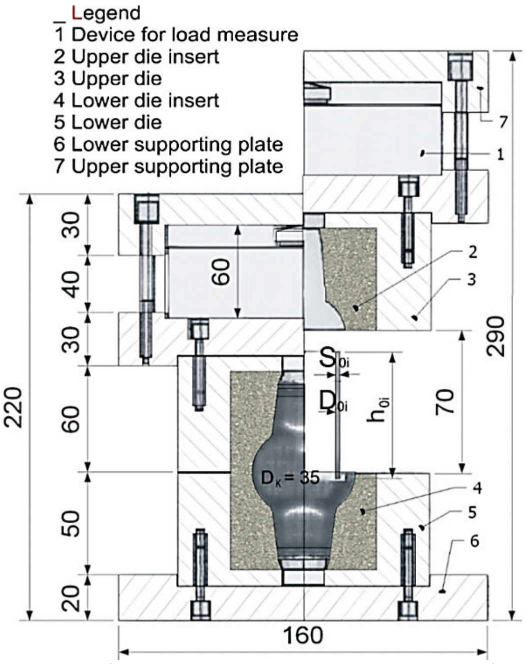


Figure 3 Central tool working parts and tubular workpiece [6]

Coefficient of narrowing and the coefficient of widening are important parameters in the process of the tube forming. Coefficient of narrowing is the ratio of diameter of the narrowed part and the initial tube billet diameter and in the case of the selected dimensions of workpiece, given in Tab. 1, the coefficient has following values:

$$k_{\text{nar}} = \frac{D_1}{D_{\text{oi}}} = (0.79,\ 0.76,\ 0.74). \tag{1}$$

Widening coefficient is the ratio of initial diameter of the tube and diameter of widened tube and for the selected combinations of geometrical parameters, corresponding coefficient values are:

$$k_{\text{wid}} = \frac{D_{\text{oi}}}{D_{\text{k}}} = (0.88,\ 0.91,\ 0.94). \tag{2}$$

Conducted experiments according to the research plan and by varying the influential geometrical parameters showed that the successful tube forming was achieved by combining the parameters of the tube billet $s_2 h_2 D_2$ that had a previous chemical preparation and lubricated by SAP.G3 soap, i.e. for the deformation coefficient:

$$k_{\text{def}} = k_{\text{nar}} \cdot k_{\text{wid}} = 0.76 \cdot 0.91 = 0.69. \tag{3}$$

3 EXPERIMENTAL AND NUMERICAL RESEARCH

Process of narrowing and widening were performed on a hydraulic press with a nominal force of 320 kN, at a deformation velocity of v = 0.023 m/s. After forming, the tube workpiece is additionally joined by welding with the side tube parts to obtain a T-connector. After considering all technical requirements, the material S235 JRG2 was selected for tube workpiece, as this material has good weldability. Since the workpiece is obtained by cutting to a certain length of welded tubes, it is necessary to consider the mechanical properties of the material after obtaining welded tubes from steel strips. During the forming of welded tubes, the deformability of the material is reduced by up to 18% in relation to the samples from the strip. Due to these facts, it is necessary to determine the characteristics of the base steel strip material and the material of the formed welded tubes.

For testing mechanical properties of workpiece material it was used uniaxial tensile test. Two types of samples were prepared, a standard sample punched from steel strip before bending of tube and a sample punched from formed and welded tube. Experimentally obtained flow curves are shown in Fig. 4, and they can be approximated in analytical form. Flow curve obtained by testing samples from steel strips can be represented by the analytical model:

$$K = C \cdot \varphi^n = 677 \cdot \varphi^{0.168}. \tag{4}$$

Flow curve obtained by testing samples from steel welded tubes has the form:

$$K = C \cdot \varphi^n = 616 \cdot \varphi^{0.064}. \tag{5}$$

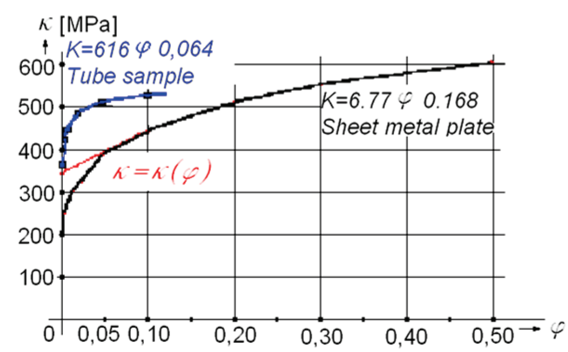


Figure 4 Flow curves obtained by material testing before and after forming of the steel welded tube [6]

Coefficients (factors) of friction were determined by a ring compression test [6]. In the case when machine oil is used as a lubricant, value of the friction coefficient/factor μ = 0.13 (m = 0.225) was obtained, and in case of chemically treated workpiece surfaces, respective values are μ = 0.095 (m = 0.164).

Considering influence of geometrical factors and influence of friction conditions on the stability of the forming process, a plan of experiments was made. Combinations of geometric parameters of the tube billet, shown in Tab. 1, were obtained by factor analysis. By varying these three geometrical parameters, it is possible to determine influence of their mutual interaction on the stability of forming process. In addition to the three geometrical factors, two cases of lubrication were considered:

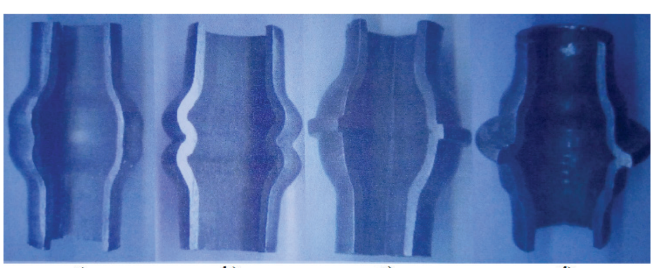
- lubrication with machine oil and
- chemically treated surface (phosphated) with SAP.G3 soap.

While forming tubular workpiece, it is necessary that the surface of the workpiece be chemically prepared - by phosphating. However, one part of the experiments was performed without chemical surface preparation in order to analyze the influence of friction conditions on appearance of defects during forming, so lubrication was performed using only machine oil. Plan of experiments when machine oil is used for lubrication is shown in the Tab. 2.

Table 2 Experiment plan (lubricant: machine oil)

No.	Experiment code	Combination of geometrical parameters
1	$s_1h_1D_1$	s_1 = 2 mm; h_1 = 68.5 mm; D_1 = 31 mm
2	$s_1h_1D_3$	s_1 = 2 mm; h_1 = 68.5 mm; D_3 = 33 mm
3	$s_3h_1D_3$	s_3 = 2.5 mm; h_1 = 68.5 mm; D_3 = 33 mm
4	$s_3h_1D_1$	s_3 = 2.5 mm; h_1 = 68.5 mm; D_1 =31 mm
5	$s_1h_3D_1$	s_1 = 2 mm; h_3 = 69.5 mm; D_1 = 31 mm
6	$s_2h_2D_1$	s_2 = 2.33 mm; h_2 = 69 mm; D_1 = 31 mm
7	$s_2h_2D_2$	s_2 = 2.33 mm; h_2 = 69 mm; D_2 = 32 mm
8	$s_3h_2D_1$	s_3 = 2.5 mm; h_2 = 69 mm; D_1 = 31 mm
9	$s_3h_3D_1$	s_3 = 2.5 mm; h_3 = 69.5 mm; D_1 = 31 mm
10	$s_3h_3D_1$	s_3 = 2.5 mm; h_3 = 69.5 mm; D_1 = 31 mm
11	$s_3h_3D_3$	s_3 = 2.5 mm; h_3 = 69.5 mm; D_3 = 33 mm

Advantages of forming without chemical surface preparation are lower cost and shorter production time. However, numerous defects occurred during the forming of the tube without chemical surface preparation, such as the appearance of a double bulge and overfilling or insufficient filling of the calotte, as shown in Fig. 5. On the tubular workpieces that are irregularly formed, it has been observed that the appearance of process instability occurs in different stages of forming process. On the workpieces shown in Figs. 4a and 4b, forming instability occurred at the very beginning of the process, so double folds and depressions were formed. In the other two workpieces, in the same figure, the instability of the process occurred at the end, with the appearance of excess material and its flow in the calotte zone.



a) b) c) d)

Figure 5 Defects occurred in forming tubular workpieces without chemical surface preparation

Since the experiments in which machine oil was used for lubrication showed poor results, a second set of experiments was made in which the surfaces of the workpieces were chemically treated. Chemical surface preparation includes degreasing and pickling of the tube billet surface in H_2SO_4 solution, then rinsing it with water, and then immersion in protectan 27. After the phosphating procedure, a quality SAP.G3 soap lubricant was applied. The goal is to improve the friction conditions and to enable the proper flow of material in the tool, without the appearance of defects. Plan of the experiments is shown in the Tab. 3.

Table 3 Experiment plan (lubricant: Zn phosphat + SAP.G3)

No.	Experiment code	Combination of geometrical parameters
1	$s_1h_1D_1$	s_1 = 2 mm; h_1 = 68.5 mm; D_1 = 31 mm
2	$s_1h_3D_1$	s_1 = 2 mm; h_3 = 69.5 mm; D_1 = 31 mm
3	$s_2h_2D_2$	s_2 = 2.33 mm; h_2 = 69 mm; D_2 = 32 mm
4	$s_3h_1D_3$	s_3 = 2.5 mm; h_1 = 68.5 mm; D_3 = 33 mm
5	$s_3h_2D_1$	s_3 = 2.5 mm; h_2 = 69 mm; D_1 = 31 mm
6	$s_3h_3D_3$	s_3 = 2.5 mm; h_3 = 69.5 mm; D_3 = 33 mm
7	$s_2h_1D_2$	s_2 = 2.33 mm; h_1 = 68.5 mm; D_2 = 32 mm
8	$s_2h_3D_2$	s_2 = 2.5 mm; h_3 = 69.5 mm; D_2 = 32 mm
9	$s_2h_2D_1$	s_2 = 2.33 mm; h_2 = 69.5 mm; D_1 = 31 mm
10	$s_2h_2D_3$	s_2 = 2.33 mm; h_2 = 69 mm; D_3 = 33 mm

For all experiments that were realized in accordance with the described plans, numerical simulations were realized using the finite element method and *Simufact forming* software. Simufact forming software uses MSC Marc solver for finite element calculations, based on the deformation method [8].

Due to the symmetry of the tubular workpiece, a 2D analysis was performed, which significantly reduced the time required for the simulation. The input data for numerical process simulations are shown in Tab. 4.

Table 4 Input data for numerical simulations

Simulation type	2D
Mesher type	Advancing front quad
Element type	Quads (10)
Element size	0.3 mm
Number of elements	1610
Friction conditions	Combined (μ = 0.095; m = 0.164) - chemically prepared surface (μ = 0.13; m = 0.225) - lubrication with machine oil
Flow curve	$K = 677\varphi^{0.168}$
Stroke	70 mm

4 ANALYSIS OF THE RESULTS OF EXPERIMENTAL AND NUMERICAL PROCESS MODELLING

The results of the experiments showed that in the case of lubrication with machine oil, the calotte is poorly filled or wrinkles and folds appear, which is completely confirmed by numerical simulations. A comparative representation of the defects that occur during the forming of the workpiece with the geometrical parameters $s_3h_3D_3$ is shown in Fig. 6.

Experiments in which the workpieces were immersed in a solution of SAP.G3 after phosphating showed better process stability, but it was still conditioned by combinations of geometrical parameters. Under such contact conditions, in case of workpiece with a diameter of D_3, calotte was overfilled and defects appear, while in the case of workpiece with a diameter of D_1, calotte was incompletely filled.

Figure 6 Comparison of the results of physical and numerical experiments $s_3h_3D_3$ when machine oil is used as a lubricant [6, 7]

Influence of workpiece geometrical parameters for appearance of defects and instability of the forming process was additionally analyzed by numerical experiments. Results of some of them are shown in Fig. 7. If we observe the influence of the diameter of the tube billet on the appearance of defects and the stability of the process, the left part of the Fig. 7 shows a virtual workpiece with an unfilled callote and tool for the applied billet of diameter D_1. Good process stability was confirmed for the tube billet of diameter D_2 (in the middle) and the effect of overfilling of tool and folding defect in the part of the calotte is evident in forming the tube billet of diameter D_3 (right part of the picture).

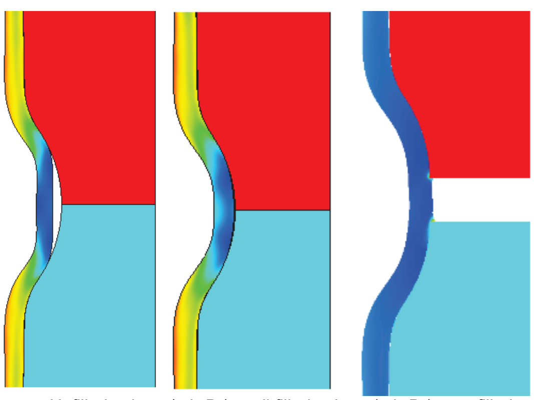


Figure 7 Unfilled calotte ($s_1h_1D_1$), well filled calotte ($s_2h_2D_2$), overfilled calotte ($s_3h_3D_3$) of tubular workpiece

Best forming results and thus the precision of the tube product were achieved with the tube billet dimensions of the $s_2h_2D_2$. A comparative representation of a properly formed workpiece is shown in Fig. 8.

Numerical experiments confirmed that the process in the case of chemically prepared workpiece surface and lubrication with SAP.G3 solution is stable and that the filling of the calotte is adequate. The material flow during the forming of the tubular workpiece $s_2h_2D_2$ obtained by numerical simulation of the process is shown in Fig. 9.

Figure 8 Properly deformed part obtained experimentally (left) and by numerical simulation (right)

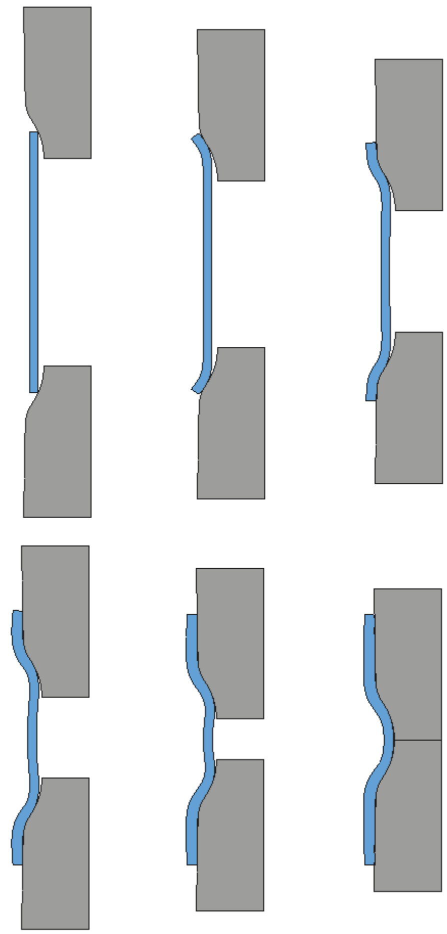


Figure 9 Numerical simulation of material flow during forming process (phosphated workpiece surface + SAP.G3 – $s_2h_2D_2$)

Distributions of the effective stress and the effective plastic strain in the tubular workpiece for the combination of geometrical parameters $s_2h_2D_2$ with the chemically prepared tube billet surfaces are shown in Fig. 10. In Fig. 10 is shown that highest values of plastic strain and effective stress are in narrowed part. The minimum values of effective plastic strain (Fig. 10b) are in the area of the calotte where the smallest wall thickening occurred.

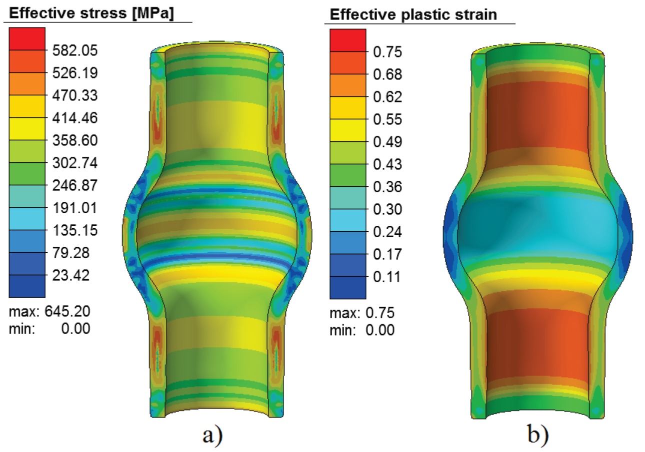


Figure 10 Distributions of effective stress (a) and effective plastic strain b) obtained by numerical simulation of forming tubular workpiece $s_2h_2D_2$

Maximum values of the forming loads registered experimentally and calculated by numerical simulations are shown in the Tab. 5.

Table 5 Maximum forming load values - obtained experimentally and numerically

Experiment code	Forming load – experiment (kN)	Forming load - numerical (kN)
$s_2h_1D_2$	85	98
$s_2h_2D_2$	102	99
$s_2h_3D_2$	102	101,9
$s_2h_2D_1$	101	92,1
$s_2h_2D_3$	113	117,9

It is noticeable that at constant values of workpiece diameter and the wall thickness, and with increasing the workpiece length, there is an increase of the maximum forming load value. When the wall thickness and the workpiece length are constant and the workpiece diameter increases, there is also an increase of the forming load.

Comparison of forming load diagrams obtained experimentally and numerically for optimal geometrical parameters and lubrication conditions in the $s_2h_2D_2$ experiment is shown in Fig. 11. Figs. 12 and 13 show a comparison of the forming load diagrams obtained experimentally and numerically for the case when tube billet diameters are D_1 and D_3. As the diameter of the tube billet increases, the required shaping force increases. Increasing the diameter increases required forming load. The comparative diagrams and values shown in Tab. 5 show a satisfactory agreement of the experimental and numerical results of the tube forming process analysis.

Based on the analysis of all results, it can be concluded that the forming of the steel welded tubes using machine oil as lubricant is not satisfactory. When experiments were performed with tube billets whose surfaces were chemically treated, the optimal combination of geometrical parameters of the billet with the values $s_2h_2D_2$ (s_2 = 2.33 mm; h_2 = 69 mm; D_2 = 32 mm) was determined. It is interesting to note that even in the case of lubrication with machine oil, this combination of parameters gives better results, but the diameter of the calotte and the dimensional accuracy of the tube final part are not achieved.

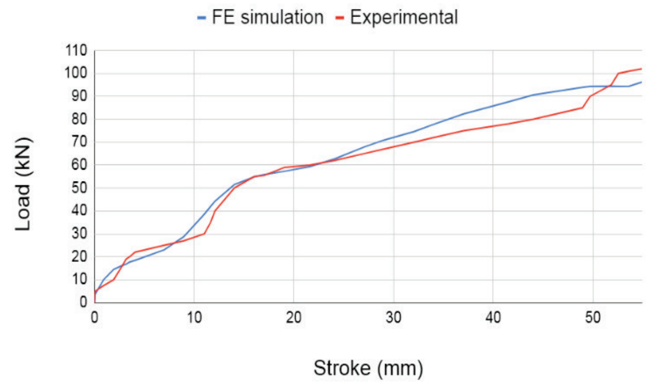


Figure 11 Forming load diagrams obtained experimentally and numerically ($s_2h_2D_2$)

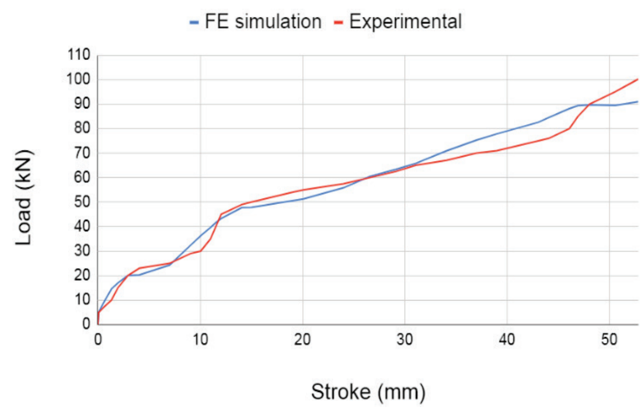


Figure 12 Forming load diagrams obtained experimentally and numerically ($s_2h_2D_1$)

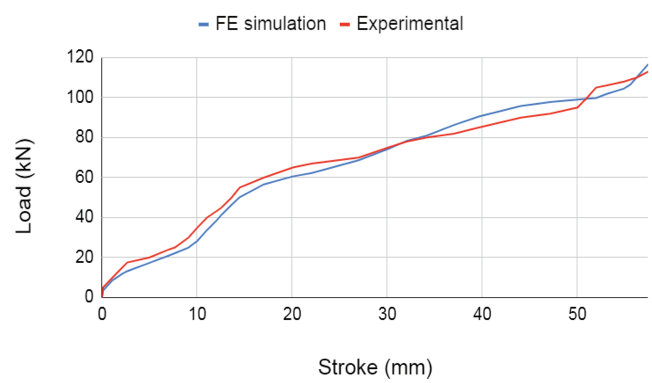


Figure 13 Forming load diagrams obtained experimentally and numerically ($s_2h_2D_3$)

5 CONCLUSION

Forming of tubular parts in tools on presses with a combination of narrowing and widening is possible to produce parts of complex geometry and good dimensional accuracy with low production cost.

For successful production, it is necessary to correctly determine the values of the geometrical parameters of the tube billet. Best forming results in experiments and numerical simulations were achieved for the tubular billet geometrical parameters $s_2h_2D_2$ (s_2 = 2.33 mm, h_2 = 69 mm, D_2 = 32 mm), i.e. for values of narrowing coefficient k_{nar} = 0.76 and the widening coefficient k_{wid} = 0.91. From results of the experiments for this example, it can be concluded that the forming process is stable for the ratio of the geometrical dimensions of workpieces $s_0/D_0 \cong 0.07$, $D_0/h_0 \cong 0.46$ and $k_{su}/k_{pr} \cong 0.84$. When the values of the coefficients of narrowing and widening change at the same dimensions of the tube billet, unsatisfactory filling of the calotte or its overfilling occur. When designing this forming technology for similar tubular parts it should be planned that the ratio of the coefficient of narrowing and widening should be in the range from 0.78 to 0.89. Moreover, one should also take into account the fact that increasing tube billet diameter, wall thickness or length increases the forming load.

Results of the experiments and numerical simulations confirm that the friction conditions, i.e. lubrication has a great influence on the stability of forming process of welded tubes by narrowing and widening. Thus, the selection of an appropriate lubricant and chemical preparation of the tubular billet are an essential for obtaining quality parts in the sable forming process. In experiments where workpiece surface was not chemically treated, but only machine oil was used for lubrication, the forming process proved to be unstable. Unfavorable friction conditions in the first set of experiments, where tube billet surfaces were not chemically treated, led to an increase in the narrowing force and difficult flow of the material, which resulted in the appearance of process instability and defects on the workpiece. It was concluded that it is necessary to reduce effect of contact friction through chemical preparation (phosphating) of tubular billet surfaces and application of SAP.G3 soap as a lubricant.

The matching of the results obtained experimentally and numerically shows the advantages of complementary application of the finite element method and numerical simulations of the forming processes in the analysis of influential process parameters on its stability, technology optimization and elimination of forming defects.

Acknowledgments

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Notice

The paper will be presented at MOTSP 2021 – 12th International Conference Management of Technology – Step to Sustainable Production, which will take place in Poreč/Porenzo, Istria (Croatia), on September 8–10, 2021. The paper will not be published anywhere else.

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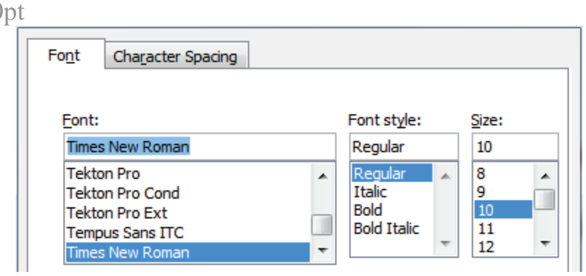

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$$\cos\,\alpha + \cos\,\beta = 2\cos\frac{\alpha+\beta}{2}\cdot\cos\frac{\alpha\text{-}\beta}{2}, \tag{2}$$

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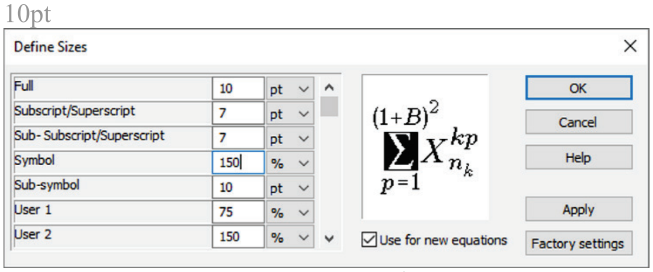

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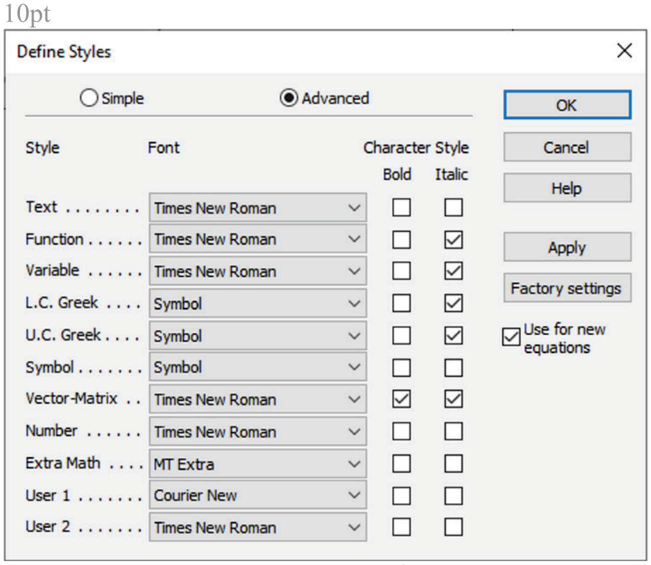

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