Sebahattin Tiryaki[1], Aytaç Aydın[2]

Multivariate Hotelling T^2 Control Chart for Monitoring Some Quality Characteristics in Medium Density Fiberboard Manufacturing Process

Multivarijatni kontrolni dijagram *Hotelling* T^2 za praćenje nekih svojstava kvalitete u proizvodnji ploča vlaknatica srednje gustoće

ORIGINAL SCIENTIFIC PAPER
Izvorni znanstveni rad
Received – prispjelo: 24. 11. 2020.
Accepted – prihvaćeno: 13. 12. 2021.
UDK: 674.817
https://doi.org/10.5552/drvind.2022.2046

ABSTRACT • *Statistical process control tools are of great importance in terms of controlling manufacturing processes and improving product quality. In this study, the manufacturing process of medium density fiberboards manufactured in a company operating in the forest products industry was monitored by using multivariate Hotelling T^2 statistical process control chart in terms of some quality characteristics. The T^2 values of the signals detected by the Hotelling T^2 control chart were also decomposed. By the decomposition of T^2 values, it was determined which quality characteristics contributed more to each signal. It was seen that the process was not in control for Hotelling T^2 control chart, which reveals the shift level in the mean of quality characteristics. As a result, the application of Hotelling T^2 allowed fast detection of possible abnormalities in the process. The decomposition of T^2 values successfully revealed which quality characteristics contributed significantly to the signals. Besides, it was concluded that, for monitoring, the Hotelling T^2 chart was able to employ simultaneously different quality characteristics of medium density fiberboard. The current application study also contributed to the emergence of the root causes of the large shifts in the process. In conclusion, the findings of the study enabled the company to ensure the process stability and to facilitate decision-making on actions to be taken for quality improvement.*

KEYWORDS: *wood based panel industry; Hotelling T^2; quality improvement; process control*

SAŽETAK • *Statistički alati za praćenje procesa vrlo su važni za kontrolu proizvodnih procesa i poboljšanje kvalitete proizvoda. U ovom su istraživanju praćena neka obilježja kvalitete procesa proizvodnje ploča vlaknatica srednje gustoće primjenom multivarijatnoga kontrolnog dijagrama Hotelling T^2. Napravljena je dekompozicija T^2 vrijednosti signala detektiranih kontrolnim dijagramom Hotelling T^2. Dekompozicijom T^2 vrijednosti utvrđeno je koja obilježja kvalitete više pridonose pojedinom signalu. Iz kontrolnog dijagrama Hotelling T^2 vidjelo se da proces nije pod kontrolom, što dovodi do pomaka srednjih vrijednosti karakteristika kvalitete. Kao rezultat toga, primjena kontrolnog dijagrama Hotelling T^2 omogućila je brzo otkrivanje eventualnih abnormalnosti u procesu proizvodnje. Dekompozicijom vrijednosti T^2 uspješno je otkriveno koja su svojstva kvalitete značajno pridonijela*

[1] Author is lecturer at Karadeniz Technical University, Arsin Vocational School, Trabzon, Turkey.
[2] Author is associate professor at Karadeniz Technical University, Department of Forest Industry Engineering, Trabzon, Turkey.

signalima. Osim toga, zaključeno je da se kontrolni dijagram Hotelling T^2 može primijeniti za istodobno praćenje različitih obilježja kvalitete ploča vlaknatica srednje gustoće. Trenutačna primjena studije također je pridonijela otkrivanju temeljnih uzroka velikih pomaka u procesu. Zaključno, nalazi studije omogućili su promatranoj tvrtki da stabilizira proces proizvodnje i olakša donošenje odluka o postupcima za poboljšanje kvalitete ploča vlaknatica.

KLJUČNE RIJEČI: *industrija drvnih ploča; Hotelling T^2; poboljšanje kvalitete; kontrola procesa*

1 INTRODUCTION
1. UVOD

Manufacturers continuously strive to improve the quality of product and production processes by reducing the variability in their processes. However, the fact is that there is no such a manufacturing process capable of repeatedly producing the same products with all features. In other words, there are always sources of variability that can cause differences between the final characteristics of the products manufactured in almost every manufacturing process. The main reason of the differences between the characteristics of the products coming from the same process is natural or chance and special or assignable causes (Rogalewicz, 2012). The natural variability is cumulative effect of lots of small and inevitable causes. A process that operates only with the effect of natural causes of variation is statistically accepted under control. In other words, these causes are considered as an inherent part of the process. Besides, another kind of variability, called assignable causes, may occur occasionally in the output of a process. This variation in key quality characteristics is generally larger than natural variation and often represents an unacceptable degree of process performance. That is, if a manufacturing process operates in the presence of the assignable causes of variation, it is considered to be an out of control process (Montgomery, 2012). It is clear that the assignable causes of variation that can be present in the process remarkably affect product quality. Hence, it is vital to separate the variation sources from each other to keep the process in a state of control by eliminating assignable causes and manufacture high quality products (Öberg and Åstrand, 2017). One of the most widely used methodologies for this goal is to monitor constantly the process together with statistical process control applications, which are of great importance in terms of the final product quality and customer satisfaction (Kurt and Karayılmazlar, 2019).

Statistical process control, a tool of quality control, uses various statistical approaches to monitor and control any process (Sivasubramanian *et al*., 2015). Thanks to statistical process control, the occurrence of assignable causes of shifts in the process can be quickly identified. Thus, it is possible to investigate the process and carry out necessary corrective actions before a great number of nonconforming products are manufactured (Montgomery, 2009). One of the most popular procedures for achieving the statistical control of any process is control charts, originally developed by Walter Shewhart in the early 1920s (Darestani and Aminpour, 2014). However, Shewhart control charts were univariate charts with some serious limitations. They allow monitoring only one quality characteristic on the chart at the same time. In addition, the overall probability of a false alarm may be inflated since any correlation between the quality characteristics of the product is ignored as the univariate charts are used (Waterhouse *et al*., 2010) Further, in many manufacturing processes, it is necessary to consider a great number of different quality characteristics or process parameters in making a decision on the quality of a product or making an assessment of the process. In such cases, practitioners should control and monitor all of them to keep the process stable and ensure its high quality (Rogalewicz, 2012). However, as stated above, it is not possible to control or monitor more than one quality characteristic or parameter related to the process simultaneously with univariate charts. To deal with the limitations of traditional univariate charts, multivariate statistical process control charts were recommended (Djekic *et al*., 2015; Hossain and Masud, 2016). The rapid rise of demands and requirements of consumers from a product increased the interest in multivariate methods and made these methods popular (Hajlaoui, 2011).

Hotelling T^2 chart is the most familiar multivariate statistical process control procedure. This chart is often employed to monitor the process mean of multiple quality characteristics simultaneously (Hossain and Masud, 2016). It is worth mentioning that the Hotelling T^2 chart only uses the information from the most recent sample. As a result, it is possible to say that it is a very effective tool for capturing large shifts in the process mean vector (Ghute and Shirke, 2008). On the other hand, the multivariate statistical process control procedures like Hotelling T^2, as used alone, can create a serious drawback in terms of interpretation. As the T^2 statistic shows that a process is out of control, it does not give precise information about which quality characteristic, or characteristics, is out of control (Gonzalez-de la Parra and Rodriguez-Loaiza, 2003). Some methods were developed to solve this drawback, that is to detect which quality characteristic, or a set of quality characteristics, contributes to the out of control signal (Bersimis *et al*., 2005).

A comprehensive literature review showed that Hotelling T^2 chart has been widely used to detect the shifts in quality characteristics or to control the process in various manufacturing processes out of wood based panel industry. However, although Hotelling T^2 chart is one of the best known multivariate statistical process control tools for monitoring the process mean vector in multivariate processes, it has been rarely employed in wood based panel industry. In a previous study, Young *et al*. (1999) tried the T^2 statistic for monitoring the vertical density profile in the manufacturing of medium density fiberboard (MDF) and oriented strand board (OSB). To the authors' knowledge, there is no application study that involves the analysis of the MDF manufacturing process in terms of quality characteristics considered in the current study using both Hotelling T^2 and decomposition of T^2 methods. It is clear that increasing the number of such studies for improving the quality of the products and processes is of great importance.

With this application study, it was aimed to use multivariate Hotelling T^2 chart in order to determine the shift level in the process mean vector of quality characteristics considered in the MDF manufacturing process of a forest products company. Another goal of the study was to detect the contribution of each quality characteristic to the signals encountered in Hotelling T^2 chart by decomposing the T^2 values. Thus, with the current study, an exhaustive statistical process control application has been performed in a forest products company and an important contribution has been made to the literature.

2 HOTELLING T² CHART
2. ANALIZA *HOTELLING T²*

The first original application in multivariate statistical process control was done by Hotelling (1947). This method, developed to monitor processes with two or more quality characteristics, is based on the T^2 statistic and is known as the Hotelling T^2 control chart (Mason and Young, 2002). The chart is one of the most well-known multivariate process control methods and is commonly employed in a wide variety of industries because of its ease of implementation and simplicity (Yeong *et al*., 2016). Hotelling T^2 is sometimes adopted as a multivariate version of the univariate Shewhart chart (Jamaluddin *et al*., 2018). The Hotelling T^2 chart can be applied to processes by following two different procedures. In other words, the chart can be employed either for subgroup data or for individual data. The Hotelling T^2 statistic for subgrouped data is as in Eq. 1 (Montgomery, 2009).

$$T^2 = n\left(\bar{x}-\bar{\bar{x}}\right)' S^{-1}\left(\bar{x}-\bar{\bar{x}}\right) \tag{1}$$

There are two phases, generally phase 1 and phase II, in creating control charts. In phase I, historical data are employed to detect whether a process is in control and to estimate process parameters in control as well as control limits. In phase II, control limits are used to check the data taken from the process (Alfaro and Ortega, 2008). The goal of phase I is to reach a data set in control, which is vital for detecting control limits for phase II. The phase I limits for the T^2 chart are as formulated in Eq. 2 and 3 (Montgomery, 2012).

$$UCL = \frac{p(m-1)(n-1)}{mn-m-p+1} F_{\alpha,\mathrm{p},\mathrm{mn-m-p+1}} \tag{2}$$

$$LCL = 0 \tag{3}$$

Where *UCL* is upper control limit, *LCL* is lower control limit, *p* is the number of quality characteristics, *m* is the number of samples, *n* is the sample size, and $F_{\alpha,p,mn\text{-}m\text{-}p+1}$ means a *F*-distribution with a degree of freedom for *p* numerator and *mn-m-p+1* denominator (Aparisi *et al*., 2004). The chart created in phase II is used to monitor future production. The *UCL* for phase II is calculated by Eq. 4 (Mitra, 2016). The *LCL* is taken as zero as in the phase I (Montgomery, 2012).

$$UCL = \frac{p(m+1)(n-1)}{mn-m-p+1} F_{\alpha,\mathrm{p},\mathrm{mn-m-p+1}} \tag{4}$$

$$LCL = 0 \tag{5}$$

The analysis of the equations shows that the *UCL* used for phase II in equation (4) is multiplied by (m+1)/(m-1) of *UCL* used for phase I in equation (2) (Montgomery, 2012).

3 MATERIALS AND METHODS
3. MATERIJALI I METODE

3.1 Materials
3.2. Materijali

In this study, a medium-sized company operating in the forest products industry in Turkey was selected as application domain. The panels with 2440 mm × 2800 mm × 18mm dimensions were used as experimental material. The manufacturing process of these panels was investigated in terms of some quality characteristics. Pine is mostly used in the MDF manufacturing process, followed by beech and eucalyptus species. These wood species are generally employed in certain proportions in the manufacturing process. The fibers obtained from the wood species for the manufacture of MDFs are subjected to drying in order to remove their moisture and they are dried to about 8-12 %. The dried fibers are mechanically laid to form the panels. The formed panel mats are compressed by using very high pressure to convert them into panels of the required thickness. Urea formaldehyde adhesive, which has a solids content of 45 % and is frequently employed in the manufacture of wood based panels, is used for the manufacture of panels. The panels manufactured were then kept under suitable conditions. The targeted density of MDFs is 720 kg/m³.

3.2 Methods
3.2. Metode

3.2.1 Quality characteristics
3.2.1. Obilježja kvalitete

It is of great importance to decide which quality characteristics of the product are to be examined prior to the plot of control charts. The quality characteristics considered in the scope of the current study were the mechanical or strength properties of MDF. For this purpose, the tests related to the modulus of rupture (*MOR*) (N/mm^2), modulus of elasticity (*MOE*) (N/mm^2), surface screw holding capability (*SSHC*) (N) and edge screw holding capability (*ESHC*) (N) characteristics, quite important in making a decision on the quality of MDF, were performed in the quality control laboratory of the relevant company.

3.2.2 Data acquisition process
3.2.2. Proces prikupljanja podataka

In this study, the MDF panels were taken from the manufacturing process randomly. In order to obtain reliable information about the manufacturing process, the number of samples or data should be accurately determined in the creation of the control charts. Montgomery (2012) reported that choosing the data number of 20-25 is accepted as a widely referenced approach and it is desirable to reach this number in the calculation of trial control limits. In Vardeman and Jobe (2016), it was mentioned that taking 20-25 samples is generally sufficient. Çetin and Birgören (2007) recommended increasing this number in case of using multivariate charts. Considering this situation, the number of samples was kept above the recommended limits. As a result, 137 data groups for three shifts of day were obtained with 5 measurement values for each quality characteristics considered for the evaluation of the process in the 4-month period between 1 February 2017 and 31 May 2017. In other words, each data group or sample consisted of five measurements.

3.2.3 Tests for quality characteristics
3.2.3. Ispitivanje obilježja kvalitete

In order to plot control charts, the data of previously detected quality characteristics should be obtained. For this purpose, the panels were taken from endless band during the manufacture in each shift, and test samples were prepared from the panels for each quality characteristics. Five samples were prepared for each characteristics from each panel in order to perform the tests of the quality characteristics. All these experimental activities were carried out by the IMAL IB 600 test machine with a capacity of 10 tons in the quality control laboratory of the company.

The *MOR* and *MOE* tests were carried out in accordance with the TS-EN 310:1999 standard. The sizes of the samples were taken as 20k + 50mm. In order to perform the tests, 5 samples were prepared from each experimental panel. In the tests, the force was applied at a constant speed throughout the experiment and the speed of the loading head was adjusted to reach the maximum force in (60±30) seconds. The tests for the *SSHC* and *ESHC* were also conducted, and then the results were recorded. The detection of screw holding capability of the samples was performed in accordance with the TS EN 320 (1999) standard. The samples with 50 mm × 50 mm dimensions were employed to obtain the *SSHC* and *ESHC* values. In the detection of SSHC and *ESHC* values, the samples were drilled with (2.7±0.1) mm crochet and screw holding apparatus with 4.2 mm × 38 mm screw was fixed to the samples with the help of a drill. Afterwards, the apparatus was attached to the test device and the screw was pulled out at a speed of (10±1) mm/min until it was completely removed from the test sample.

3.2.4 Chart design
3.2.4. Dizajn dijagrama

After selecting the control chart to be used for the investigation of the MDF manufacturing process, the charting operation was started using the data obtained from the process. Yeong *et al.* (2016) reported that the choice of design parameters has a great impact on the performance of the chart. Hence, special attention was paid to the design phase. As mentioned earlier, the charting of the T^2 statistic is considered in two stages: phase I and phase II (Yang and Trewn, 2004; Montgomery, 2009). Accordingly, in the current study, a total of 137 data obtained as a result of the data acquisition process were divided into two groups, 50 for phase I and 87 for phase II, respectively. In phase I, a set of data in control, often referred to as historical data set (HDS), was created. The main goal in this phase is to provide a basis for detecting initial control limits and to estimate the unknown parameters, in other words, to determine the design parameters of the chart to be drawn for phase II (Mason *et al.*, 2003; Yang and Trewn, 2004). In addition, it is important to emphasize that at this phase all data points with T^2 values greater than the *UCL* are regarded as outliers and therefore they are removed from the data set (Talib *et al.,* 2014). As a consequence, the unknown parameters were estimated for phase II using the HDS brought into a state of statistical control in phase I. Phase II involves chart creation for T^2 statistic. In this phase, the Hotelling T^2 chart was generated with 87 new measurements taken from the MDF manufacturing process and the actual state of the process was observed. The control limits for phase II were calculated by using the HDS obtained with the Hotelling T^2 chart. Further, in the calculation of the limits for both phase I and phase II, α was taken into account as 0.0027.

3.2.5 Chart interpretation
3.2.5. Interpretacija dijagrama

Since univariate statistical process control charts are considered a single quality characteristic, the relationship between quality characteristics is neglected. Hence, the interpretation of out of control data is easy. Unlike univariate control charts, in multivariate control charts, it is not straightforward to decide which quality characteristic, or a set of quality characteristics, causes the problem since the chart generated is associated with more than one quality characteristic and the correlations between these quality characteristics are taken into account (Bersimis *et al*., 2005). Therefore, as a multivariate chart, a major problem encountered in the use of the Hotelling T^2 chart is that it is difficult to interpret a signal that occurs in the process (Mason *et al*., 1997). In such a case, the standard practice is to plot univariate $\overline{x}$ control chart on quality characteristics individually. However, it was notified that this approach may not be successful because of the loss of information about quality characteristics. On the other hand, a useful practice is to decompose the T^2 values into components that reflect the contribution of quality characteristics individually (Montgomery, 2012). In the present study, in order to contribute to the solution of the problem related to the interpretation of the out of control signals in the T^2 chart, the T^2 values were decomposed. In this way, the degree of the contribution of all quality characteristics to the out of control signals on the chart was successfully determined, together with their significance levels. All charting application and the decomposing of the T^2 values were carried out by using Minitab software.

3.2.6 Assumptions
3.2.6. Pretpostavke

It is useful to examine some assumptions in the application of control charts. The assumptions were applied to the HDS reached as a result of phase I and without any out of control data point. For this goal, it was investigated whether the data was normally distributed as well as the correlation analysis revealing the relationship between the data. Kolmogorov-Smirnov test was employed to determine whether the data showed normal distribution. On the other hand, the compatibility of data to multivariate normal distribution was also tested by an analytical method based on Mahalanobis distance. It was notified that the first step for this method is to calculate squared Mahalanobis distance of each data. In addition, it was mentioned that if the population is normal and sample size is large enough ($n \geq 25$), the distances fit the chi-square distribution. This property can be used to obtain a chi-square plot. Finally, the ordered squared Mahalanobis distance and chi-square values are plotted. The fact that the plot demonstrates a linear structure is considered as a sign that the multivariate normality assumption is provided (Sharma, 1996). The Kolmogorov-Smirnov test and correlation analysis were carried out by using the SPSS (Statistical Package for the Social Science).

4 RESULTS AND DISCUSSION
4. REZULTATI I RASPRAVA

4.1 Evaluation of phase I results
4.1. Evaluacija rezultata I. faze

In this study, phase I was applied to test retrospectively whether the MDF manufacturing process was in control as the subgroups were being drawn. In other words, the Hotelling T^2 chart in this phase was used to bring the process into a state where it is statistically in control. In order to analyze the process with this chart, a data set with sample size 5 ($n = 5$), quality characteristic number 4 ($p = 4$) and sample repeat number 137 ($m = 137$) was obtained, and it was divided into two groups for phase I and phase II. The first 50 data were employed in order to achieve a process in control by the Hotelling T^2 chart in phase I, while the remaining 87 data were used to view the future status of the manufacturing process in phase II.

Before proceeding to the plotting application for phase I, the statistical summary of the data to be used in this phase was calculated as presented in Table 1.

As stated above, trial control limits were calculated to achieve a process or data set in control in the implementation of phase I using the Hotelling T^2 chart. This application was repeated until there was no data point beyond control, in other words, above the *UCL*. As the process was completely in control, phase I was finished, and thus a data set in control was obtained.

Table 1 Statistical summary of phase I dataset
Tablica 1. Statistički sažetak skupa podataka I. faze

Quality characteristics *Obilježja kvalitete*	Number of data *Broj podataka*	Minimum *Najmanja vrijednost*	Maximum *Najveća vrijednost*	Mean *Srednja vrijednost*	Standard deviation *Standardna devijacija*	Variance *Varijanca*
MOR	50	32.69	37.05	34.696	1.053	1.11
MOE	50	2958.88	3531.50	3258.820	110.976	12315.72
SSHA	50	1403.20	1834.60	1606.128	91.521	8376.02
ESHA	50	904.20	1155.20	1046.628	53.339	2845.06

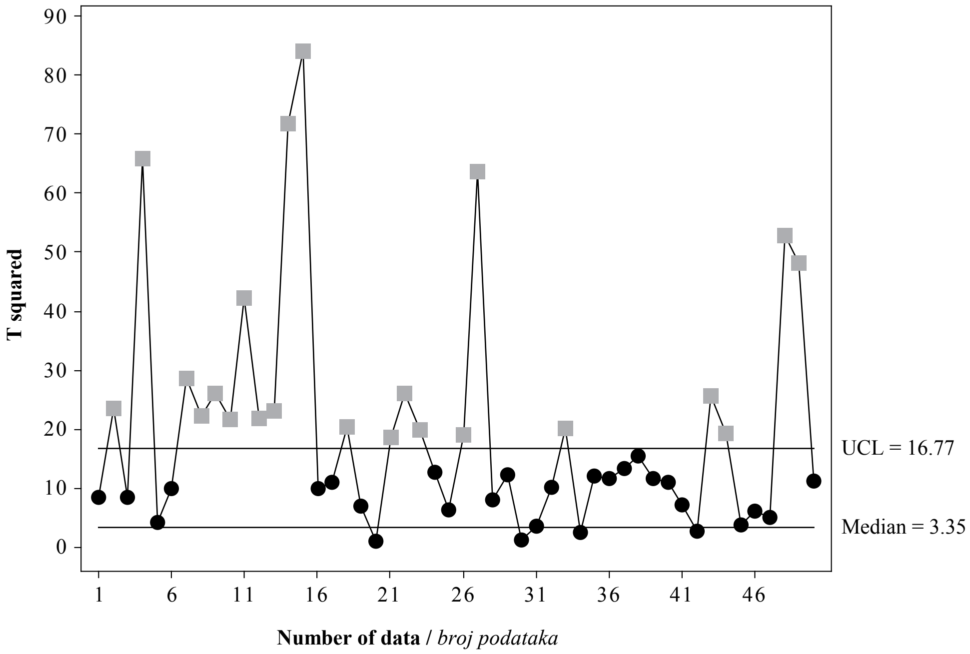

Figure 1 Hotelling T^2 control chart for 50 data
Slika 1. Kontrolni dijagram *Hotelling* T^2 za 50 podataka

Accordingly, the process was brought into a state of statistical control by following the steps below:

Firstly, the Hotelling T^2 chart for all data of phase I was generated, and the resulting chart is given in Figure 1.

As the Hotelling T^2 chart obtained in the first step of phase I was examined, it was seen that the *UCL* was 16.77, and 22 data exceeded the *UCL* value. As mentioned earlier, in such a case, in order to obtain a data set in a state of control, the data above the *UCL* must be removed from the data set. Therefore, the analysis was continued with the remaining 28 data after removing the data points whose T^2 value was above the *UCL*. The Hotelling T^2 chart was then generated with the remaining 28 data in the second step of phase I, and the resulting chart is given in Figure 2.

The Hotelling T^2 chart drawn in the second step of phase I showed that all of the T^2 values or 28 data were smaller than the *UCL*. It is possible to say that the MDF manufacturing process is in control since there is no data above the *UCL*. Thus, the chart now clearly shows that the process is statistically stable. All steps of phase I are briefly summarized in Table 2.

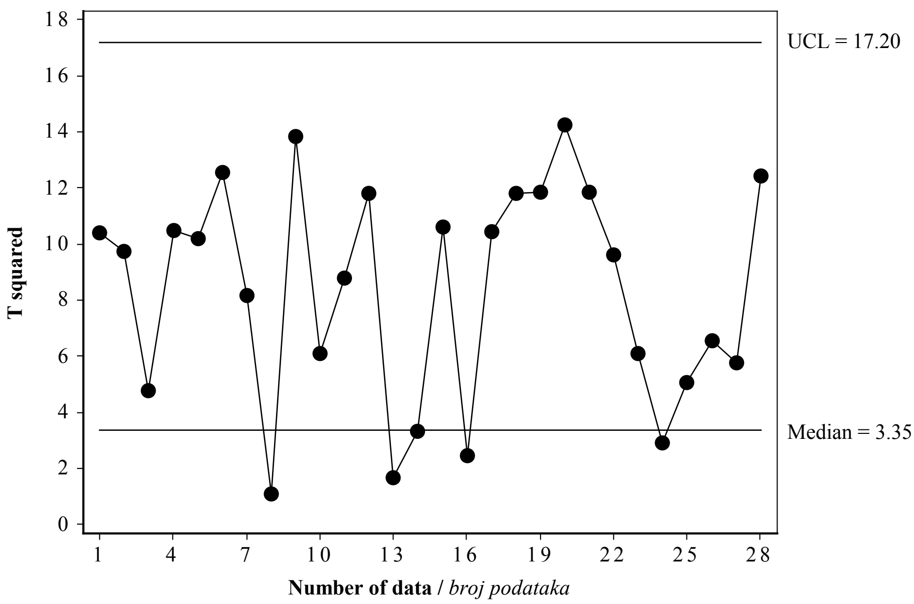

Figure 2 Hotelling T^2 control chart for 28 data
Slika 2. Kontrolni dijagram *Hotelling* T^2 za 28 podataka

Table 2 Summary of phase I for Hotelling T^2 chart
Tablica 2. Sažetak I. faze za dijagram *Hotelling* T^2

Application of phase I *Provedba I. faze*	**UCL**	**Number of out of control data** *Broj podataka izvan kontrole*	**Removed data** *Uklonjeni podatci*	**Number of remaining data** *Broj preostalih podataka*
Phase I - Step I	16.77	22	2, 4, 7-15, 18, 21-23, 26-27, 33, 43-44, 48-49	28
Phase I - Step II	17.20	0	-	28

Table 3 Statistical summary of HDS
Tablica 3. Statistički sažetak HDS-a

Quality characteristics *Obilježja kvalitete*	**Number of data** *Broj podataka*	**Minimum** *Najmanja vrijednost*	**Maximum** *Najveća vrijednost*	**Mean** *Srednja vrijednost*	**Standard deviation** *Standardna devijacija*	**Variance** *Varijanca*
MOR	28	33.37	36.77	34.756	0.838	0.70
MOE	28	3171.57	3353.13	3256.634	57.362	3290.37
SSHA	28	1511.40	1756.40	1609.900	70.887	5024.92
ESHA	28	975.20	1137.40	1041.743	33.698	1135.53

The sets consisting of 28 data were accepted as the HDS. The statistical summary of the HDS is given in Table 3.

After obtaining the HDS, phase II should be started to test the future performance of the MDF manufacturing process. However, before proceeding to this stage, some assumptions were investigated for the HDS, which is the basis for phase II.

4.2 Evaluation of assumptions results
4.2. Evaluacija rezultata pretpostavki

It was stated that the unknown parameters for phase II must be estimated from a normally distributed data group that does not include outliers. It was also notified that multivariate data analysis is based on linear correlation. Hence, the significant relationships between quality characteristics are sought (Montgomery, 2012). On the other hand, neglecting the assumptions could negatively influence the reliability of the results (Abo-Hawa *et al*., 2016). Table 4 shows the matrix of the correlation coefficients calculated with 28 data of the quality characteristics.

As the correlation matrix in Table 4 was examined, it was seen that there is a significant relationship between the *MOR* and *MOE*, and also *MOE* and *SSHA*. In addition, although it was not significant at a p = 5% level, there was a notable relationship between the *SSHA* and *ESHA*, with a correlation coefficient of 0.305. When a literature search was conducted, it was seen that there are some studies in which coefficients similar or lower than the correlation coefficients reached in the current study were statistically significant (Gonzalez-de la Parra and Rodriguez-Loaiza, 2003; Haridy and Wu, 2009). This may be due to the characteristics of the datasets considered in the studies. It was noted that very small correlation coefficients

Table 4 Matrix of correlation coefficients for 28 data
Tablica 4. Matrica koeficijenata korelacije za 28 podataka

Quality characteristics *Obilježja kvalitete*		***MOR***	***MOE***	***SSHA***	***ESHA***
MOR	Pearson correlation	1	0.451	-0.204	-0.079
	P	-	0.016	0.297	0.688
	N	-	28	28	28
MOE	Pearson correlation	-	1	-0.380	-0.009
	P	-	-	0.046	0.964
	N	-	-	28	28
SSHA	Pearson correlation	-	-	1	0.305
	P	-	-	-	0.114
	N	-	-	-	28
ESHA	Pearson correlation	-	-	-	1
	P	-	-	-	-
	N	-	-	-	-

with large datasets can be statistically significant (Schober *et al*., 2018).

Following the investigation of the relationships between quality characteristics, regardless of whether the characteristics were normally distributed or not, they were analyzed by applying Kolmogorov-Smirnov test. The results of the Kolmogorov-Smirnov test are given in Table 5.

Table 5 Kolmogorov-Smirnov test results for 28 data
Tablica 5. Rezultati Kolmogorov-Smirnova testa za 28 podataka

Quality characteristics *Obilježja kvalitete*	**Kolmogorov-Smirnov**		
	Test statistic	*df*	*P*
MOR	0.079	28	0.200
MOE	0.138	28	0.184
SSHA	0.163	28	0.054
ESHA	0.136	28	0.197

When Table 5 was examined, it was understood that the significance level of all quality characteristics were greater than 5 %, in other words, all quality characteristics showed normal distribution.

Since the Hotelling T^2 control chart is a multivariate analysis, in some cases, providing the univariate normal distribution assumption may not produce sufficient and reliable results. Therefore, multivariate normal distribution assumption was also investigated in this study. For this test, the Mahalanobis distance values were calculated using SPSS software and the values were ordered. The chi-square values corresponding to Mahalanobis values were then obtained. In order to see the relationship between ordered Mahalanobis values and chi-square values, a plot was created using Microsoft Excel software and the correlation analysis was performed. The plot showing the relationship between the ordered Mahalanobis values and the chi-square values is presented in Figure 3.

Figure 3 demonstrates that there is a linear relationship between the Mahalanobis values and chi-square values. In addition, a correlation analysis was performed to reveal the power of the relationship between the Mahalanobis and the chi-square values. The result of the analysis showed that the Pearson Correlation coefficient was very close to 1 and the coefficient was at the 1 % level of significance. This means that the multiple normal distribution assumption was provided.

4.3 Evaluation of phase II results
4.3. Evaluacija rezultata II. faze

As seen above, the manufacturing process was successfully brought into a state of statistical control by applying the phase I procedure. This part of the study includes the application of phase II to test whether the process remains in control when future subgroups are drawn. It was notified that the charts created in this phase help the practitioners to monitor the process for any deviation from an in-control state (Bersimis *et al*., 2007). In addition, in the literature, it has been noted that Hotelling T^2 chart is a very popular tool used to simultaneously monitor quality characteristics in multivariate processes (Shabbak and Midi 2012; Hossain and Masud, 2016). On the other hand, attention was drawn to some disadvantages of the chart. As stated earlier, one of the disadvantages of this chart is that the quality characteristics causing an out of control signal cannot be detected easily (Bersimis *et al*., 2005). In the current study, all T^2 values that generate the signal were decomposed to deal with this difficulty. By applying this method to the out of control signals, one or more responsible quality characteristics for each signal were determined.

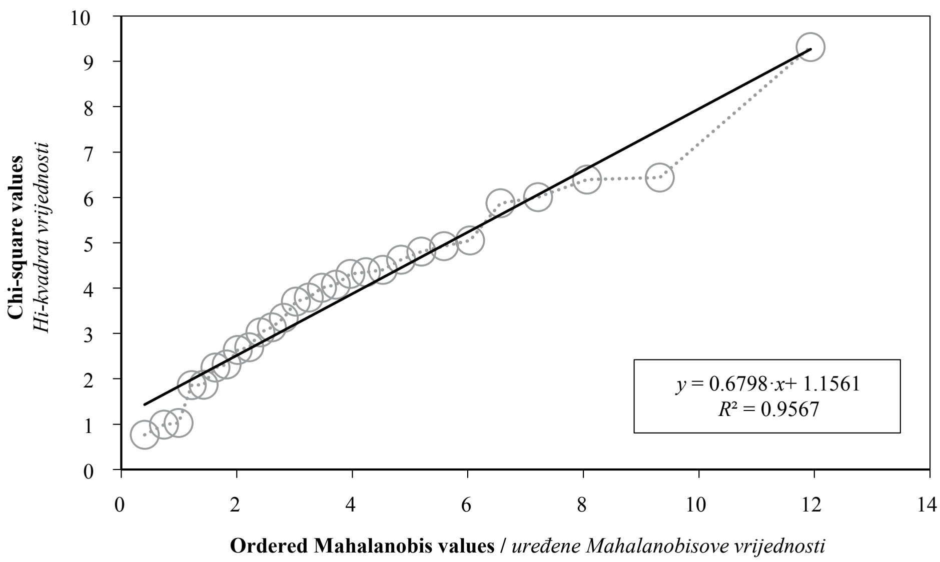

Figure 3 The plot showing the relationship between Mahalanobis values and chi-square
Slika 3. Grafikon koji prikazuje odnos između Mahalanobisovih vrijednosti i Hi-kvadrata

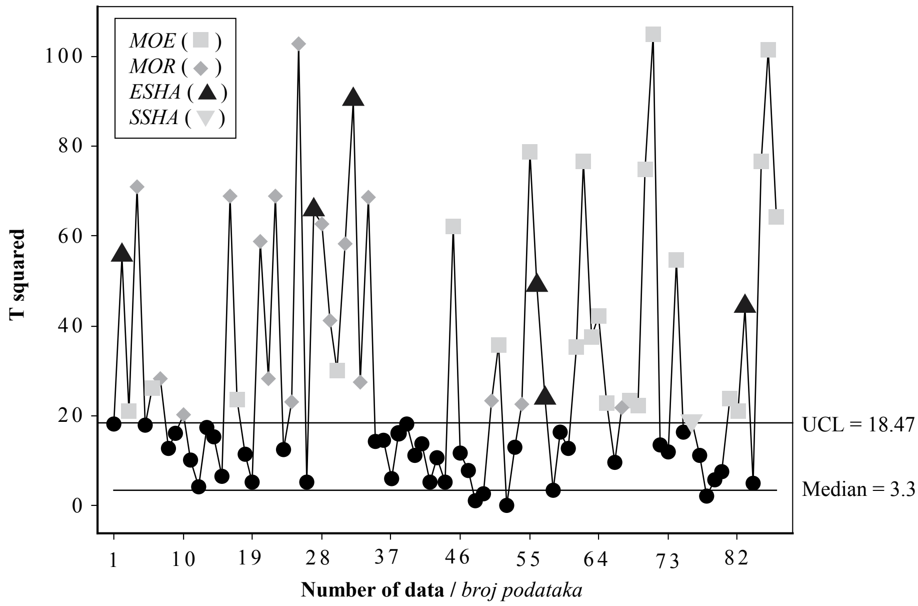

Figure 4 Hotelling T^2 chart for phase II and quality characteristics that contribute most to each signal as a result of T^2 decomposition
Slika 4. Dijagram *Hotelling T^2* za II. fazu i obilježja kvalitete koja najviše pridonose svakom signalu kao rezultat T^2 dekompozicije

Figure 4 presents the T^2 control chart created for phase II. It also shows the quality characteristics that contribute the most to each signal as a result of T^2 decomposition.

A summary of phase II created to reveal the future state of the process is presented in Table 6.

As Figure 4 and Table 6 were examined, 46 out of control signals were identified for the MDF manufacturing process. In other words, 46 out of control data points with T^2 values greater than an *UCL* of 18.47 were observed. The Hotelling T^2 chart generated for phase II demonstrated that there were major shifts in the process and that the process was not in control. This revealed that the variability in the mean vector of the process subject to the research was high.

Figure 4 also showed that the *MOE* to 22 signals, the *MOR* to 17 signals, the *ESHA* to 6 signals and the *SSHA* quality characteristic to 1 signal provided the maximum contribution. It should be noted that the quality characteristics marked in Figure 4 are not the only factor that leads to the signal or signals in most cases. In general, more than one quality characteristics to each signal make the contribution at different significance levels. The significance levels of the contribution of the quality characteristics to the signals encountered in the Hotelling T^2 chart are given in Table 7.

As can be seen in Table 7, in many circumstance, more than one quality characteristics contributed significantly to the signals observed in the T^2 chart. For example, it was found that the 45th data point on the T^2 chart was detected as the 22nd data point out of control. At this point, all quality characteristics were found to be effective in signal formation. On the other hand, it was understood that only the *MOE* contributed to the signal at the 35th data point out of control (68th data point on the chart).

In brief, it was seen that the MDF manufacturing process was out of control in terms of the process mean vector calculated by taking into account all quality characteristics. In other words, significant shifts were observed from time to time in the process. In order to reveal the reasons of these major shifts in the manufac-

Table 6 Summary of phase II for Hotelling T^2 chart
Tablica 6. Sažetak II. faze za dijagram *Hotelling T^2*

Application of phase II *Provedba II. faze*	**UCL**	**Number of out of control data** *Broj podataka izvan kontrole*	**Out of control data** *Podatci izvan kontrole*	**Number of data in control** *Broj podataka pod kontrolom*	**Data in control** *Podatci pod kontrolom*
Phase II	18.47	46	2-4, 6, 7, 10, 16, 17, 20-22, 24, 25, 27-34, 45, 50, 51, 54-57, 61-65, 67-71, 74, 76, 81-83, 85-87	41	1, 5, 8, 9, 11-15, 18, 19, 23, 26, 35-44, 46-49, 52, 53, 58-60, 66, 72, 73, 75, 77-80, 84

Table 7 Significance levels of contribution of quality characteristics to signals generated in Hotelling T^2 chart
Tablica 7. Razine značajnosti doprinosa obilježja kvalitete signalima generiranim u dijagramu *Hotelling* T^2

Quality characteristics *Obilježja kvalitete*		**Out of control data** *Podatci izvan kontrolne vrijednosti*																						
		2	3	4	6	7	10	16	17	20	21	22	24	25	27	28	29	30	31	32	33	34	45	50
Significance level (*p*) *razina značajnosti (p)*	*MOR*	NS	NS	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	MOE	**	**	**	**	**	**	**	**	**	**	**	NS	**	NS	*	**	**	**	NS	NS	**	**	**
	SSHA	*	*	NS	*	NS	**	NS	NS	NS	NS	**	NS	NS	**	NS	NS	**	NS	**	**	**	*	NS
	ESHA	**	*	**	NS	*	NS	*	NS	NS	*	**	**	**	**	**	*	NS	NS	**	NS	NS	**	NS

Quality characteristics *Obilježja kvalitete*		**Out of control data** / *Podatci izvan kontrolne vrijednosti*																						
		51	54	55	56	57	61	62	63	64	65	67	68	69	70	71	74	76	81	82	83	85	86	87
Significance level (*p*) *razina značajnosti (p)*	*MOR*	**	**	**	NS	NS	**	**	**	**	NS	**	NS	NS	**	**	**	NS	**	**	*	**	NS	**
	MOE	**	NS	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	SSHA	NS	NS	NS	*	NS	NS	NS	NS	**	**	NS	NS	NS	NS	NS	*	**	NS	NS	NS	NS	**	NS
	ESHA	NS	**	**	**	**	NS	**	**	NS	*	NS	NS	*	NS	**	NS	*	*	NS	**	**	**	**

**$p < 0.01$, * $p < 0.05$, NS: Statistically not significant. / *Statistički nije značajno.*

turing process and contribute to the improvement of quality, great efforts have been made to identify the factors that may cause the poor quality or out of control signal. It is a clear fact that the quality of the MDFs manufactured is affected by many manufacturing parameters in the process. Hence, information about the wood species used in the manufacture and their usage rates, adhesive type, moisture content, the density of MDF panels and the pressing parameters such as press time and press pressure etc. were comprehensively evaluated.

As a result of the comparative analysis of the data points on the charts and the values of the manufacturing parameters corresponding to these points, it was thought that one of the main reasons for variation in the quality characteristics or strength values of MDF was the use of the different wood species during the manufacture and especially major variation in the usage rate of these species from time to time. As stated in the materials and methods section of the present study, both coniferous and deciduous wood species were generally used in different rates in MDF manufacture. Wood species might have a significant effect on the strength values of MDF due to their different anatomical structures. Akbulut and Ayrılmış (2001) mentioned that more than 90 % of MDF is made up of wood material and thus wood species have a great impact on MDF properties. Another important factor that can be effective on the quality characteristics in the MDF manufacturing process was the variation in press parameters. İstek (2006) reported that an increase in the value of the press pressure applied during the manufacturing increased the *MOR* and *MOE* of the fiberboard. Balkız (2006) notified that an increase in the press time and pressure generally improved the *MOR*, *MOE* and *SSHA* properties of MDF manufactured by using *Rhododendron Ponticum* L., however, it had no important effect on the *ESHA*. Sihag *et al*. (2017) evaluated the effect of the press pressure on the strength values of MDF made from bamboo (*Dendrocalamus strictus*). They observed that an increase in the pressure value improved the *MOR*, *SSHA* and *ESHA*. Aisyah *et al*. (2013) stated that the impact of press pressure and time on some strength values of MDF varied. As a result, it was concluded that the press parameters had generally an important influence on the strength values or quality characteristics of MDF. On the other hand, considering the complexity of the MDF manufacturing process, in addition to the main factors identified in the present study, other factors might have affected in different ways the variability in quality characteristics.

5 CONCLUSIONS
5. ZAKLJUČAK

This study presented an application of Hotelling T^2 chart to monitor simultaneously the *MOR*, *MOE*, *SSHA* and *ESHA* quality characteristics and contribute to the improvement of quality in the MDF manufacturing process of a medium-size forestry products company. For this aim, the Hotelling T^2 chart was applied to the data obtained from the process. In order to determine the contribution level of the quality characteristics to the signals encountered in Hotelling T^2 chart, the T^2 values were also decomposed. The main conclusions that may be drawn from the study are as follows.

In phase I, the MDF manufacturing process was brought into a state of control using the Hotelling T^2 chart. Then, in phase II, the chart was again created for 87 new data and it was seen that 46 data points were out of control. This revealed that the process was out of control with respect to the considered quality characteristics of MDF.

As a result of the decomposition of T^2 values of the signals detected by employing the Hotelling T^2 chart, it was understood that the *MOR* and *MOE* contributed more to out of control signals when compared to other quality characteristics. On the other hand, it was also determined that in most cases more than one quality characteristics contributed significantly to each signal.

In the examination of the manufacturing process, it was concluded that the major reason of the signals or high variability in strength values was that the usage rates of the wood species used in the manufacture indicated major differences sometimes. The press parameters were other important factors that contribute to out of control signals.

In this respect, it is obvious that the studies to be carried out by using statistical process control methodologies to keep the processes in control will make major contributions to the companies. The results of the study demonstrated that the Hotelling T^2 chart allows practitioners to control and monitor the MDF quality characteristics simultaneously.

Finally, using these methodologies, it is possible to identify quality problems, act in time against the problems, reduce the costs of poor quality and thus manufacture competitive high quality products in international markets.

Acknowledgements – Zahvala

This research was supported by the Scientific Research Projects Fund of Karadeniz Technical University, Trabzon Turkey; FDK-2016-5390.

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Corresponding address:

SEBAHATTIN TİRYAKİ, PhD
Karadeniz Technical University, Arsin Vocational School, 61900 Trabzon, TURKEY,
e-mail: sebahattintiryaki@hotmail.com