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MASTER'S THESIS

Evaluation of Wood and Aluminum Stickers and their Stains on Heat Treated Spruce Boards

- Influence on Quality and Cost

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Master Thesis, Continuation Courses
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Abstract

Wood as a natural resource material can be modified by applying different drying techniques in order to have end products with improved properties. In wood drying industries, each parameter that has effect on end product quality and cost is elaborated intensively. In this context, stickers which are used to enable heat and moist air circulate through timber layers that are put in kilns for drying process are in concern, too. It is due to the fact that stickers are one of the major cost parameters in wood drying industries; not only the cost issue, but stickers also have direct effect on heat treatment process generated in kiln chambers, the total volume of timber that can be put in kilns and end product quality.

This thesis makes both an evaluation and comparison for wood and aluminum sticker types which were used in heat treatment of Norway spruce boards by ThermoWood process. It was in interest to use wood and aluminum stickers in one single wood stack and make investigations on them broadly. Therefore, the evaluation of stickers and sticker stains was conducted in four different dimensions which were referred as chemical, physical, statistical (multivariate analysis approach) and economical research aspects.

In chemical aspect, formation of the sticker stains was tried to be understood by literature reviews and a simple acidity test was made on sticker stained zones of sample boards. It was inferred that the sticker stain formation was generated due to a combination of both physical and chemical phenomenon which take place during drying. In the acidity test, the pH values of sticker underneath zones were lower (more acidic) than the sticker adjacent zones. However, the differences between pH values were not significant and both zones had pH values around 4 units.

In physical aspect, color measurements were made on sample boards in subsequently increasing planing depths in order to investigate the severity degree of sticker stains on heat treated wood surface. These color measurements were made in L* C* h color space and the sticker stains' severity degrees were successfully quantified by ΔE^*_{ab} color difference values. The sufficient planing depth required to have a uniform looking heat treated surface without sticker stains was determined 1-2 mms. The other issues which might affect the sticker stain severity degree and planing process were discussed.

In the statistical aspect, the data obtained from color measurements were used to make a multivariate analysis to investigate the variables which were influencing sticker stains and the relations between them. It was found that planing was the most influential factor on color variables.

In the economical aspect, cost estimation and comparison were made for wood and aluminum stickers for short and long term utilization periods. The results indicated that aluminum stickers were costing less than wood stickers in long term utilization periods. However, it was also found out that the handling issues of stickers (installation-sticker removing and conveying systems) in sawmill operations was in great importance for a facility to make a decision for using a certain sticker type.

***Keywords**: Heat Treatment, ThermoWood , Norway spruce, wood, aluminum, sticker, sticker stain, color, acidity, sticker cost*

Preface

When I consider this past two years, I see that it has really been amazing for me to spend more than two years in Sweden, regarding both for education and personal life. There are quite many people that I have to give my thanks and respects throughout the whole study period and during this thesis work.

First of all, I would like to thank my supervisor Jonas Danvind for the guidance and help that he had shown throughout the whole project duration. I had the opportunity to work on industrially applicable issue which I had intended to do so. Hereby, I have to give my thanks to Gustav Åström and Hudiksvall Heat Treated Wood AB for the interest they had shown to the stickers issue and making it real to establish experiments on an industrial scale. I also would like to thank people in Valutec AB for the support that they have shown to this study.

The Wood Physics Division is a special place for me; all the people there have been understanding and helpful to me. Thank you Olov Karlsson for the discussions that we had related to materials and chemistry; Margot I thank you for the photographs and moreover for the memorable lecture that you had given me in Wood Anatomy course. Tom Moren, I thank you for your brief, but concise thoughts hitting right spots to think and search more. Christer Peterson, thank you too, for the hints that you have shown for economy part. Micael Öhman also deserves a separate thank from me due to fact that he was one of the people who made it possible for me to study in Sweden.

I also have to thank to Marianne and Kerstin of student office for the helps that they have shown to me. Thank you, Birger Marklund for the help with the machinery and thank you Per-Olov for the help with the equipments.

My dear friend Carmen, you are a true friend and thank you for everything that you have made for me throughout this year…

In the end, I would like to thank my family here in Sweden for encouraging me throughout the whole study period. Guler Alici my dear aunt, I think you are the person who provided me a chance to change my life, without you I would not be here and this would never be possible...

My parents and my sister special thanks goes to you. Evrim, Aygül and Kazim, I am grateful to all of you for all the patience and support that you had shown me throughout the past years.

Skellefteå-Luleå, January 2009

Özgür Güner

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1. Introduction

Wood has been utilized as a natural resource material in different aspects of human life for many ages. Today, we see that the end uses of wood and wood based products have increased and the utilization fields of these products have expanded. In this sense, the importance of the progress and advance in scientific research studies also has to be emphasized due to their guidance for developments in industrial applications.

Heat treatment of wood at high temperatures is one of the innovative wood modification techniques which yield environmental friendly end products. Since, the concerns and regulations regarding environmental requirements have become more strict and severe in last decades; heat treatment technologies and heat treated wood have become more prominent under these circumstances. Besides, heat treated wood properties and production techniques have also become continuous research subjects.

Moreover, wood species which do not have much commercial value can be heat treated and by this way these species can become value added end products which also have improved material properties to some extent. Regarding this context, heat treated wood products are utilized in a wide range of application areas both for indoors and outdoors like floor elements, facades, garden furniture and deckings.

1.1 Scope of the Thesis

This study evaluates the issue of sticker stains on heat treated Spruce boards caused by five different sticker types that were used in an industrial application of ThermoWood process. The discolorations originating from stickers which are subject to the content of this study were named as “sticker stains” or “sticker marks”.

In this study, the evaluation of stickers and sticker stains is conducted in chemical, physical, statistical (Multivariate Analysis) and economical research aspects. The content of these research aspects can be summarized by the following points:

- To understand how sticker stains form.
- To inspect the severity degree of sticker stains on heat treated sample boards in subsequently increasing planing depths. Furthermore, to continue this inspection for the variation in size of sticker stains on heat treated boards among different layers throughout a stack. In this case, try to answer the question of” Can load be an effective factor for the severity degree of sticker stains?”
- To estimate possible sufficient planing depth in millimeters to have a uniform looking heat treated wood surface without sticker stains.
- To study variables influencing sticker stains using multivariate statistics.
- To make an approximate cost comparison between wood and aluminum stickers.

By studying these research aspects, it was aimed to make a study in which comparison of wood and aluminum stickers was presented by means of influence on cost and product quality (even surface color without sticker stains).

2. Background

2.1 Heat treatment of Wood

Earlier studies by Tarvainen (1995) put forward that high temperature drying of wood specimens could be a serious alternative for production in terms of technical and economical stand points. Today, it is seen that the heat treatment technologies have developed more and industrial scale productions have been established in Europe and North America.

Especially, in Europe, five different wood modification techniques regarding heat treatment of wood at high temperatures have been developed and these techniques are currently available in industrial scales. These processes are named as,

- Plato-Process (Netherlands),
- Retification Process (France),
- Bois Perdure (France),
- OHT-Process (Germany) and
- Thermo Wood Process (Finland)

The study of Militz (2002) brings descriptions for these processes and underlines the common property as temperature range between 160 □ C and 260 □ C, where the differences in these processes are also defined as process steps, oxygen or nitrogen steaming, wet or dry process, use of oils, steering gases, etc.

Furthermore, the importance of heat treatment technologies in Europe has been emphasized in studies of Xie Yan-jun (2002) and Cao Yong Jian (2007) whose studies point out that heat treatment of wood will take an important role in Chinese wood industry in near future, as well. These studies imply that heat treatment of wood will take an important role in wood industry not only in Europe, but also in Asia and other parts of the world.

2.2 Heat Treated Wood and ThermoWood Production

The increase in investment and production of heat treated wood in industrial scale is related to improved properties of the end product. Besides, wood species which do not have much commercial value can be heat treated and by this way more utilization fields can be created for these less valuable species.

The investments in heat treated timber sector and technologies increase year by year. And these investments are reflected towards production volumes. According to the study of Militz (2002), the total production of heat treated timber in Europe by the year 2001 was approximately 165 000 m^3/ year. The study of Militz (2002) had also estimated the total production of heat treated timber for the preceding years 2002/2003 with approximately

265 000 m^3. This corresponds to an increase of more than 50% production volume in one year.

In addition, Finnish ThermoWood Association which was established in 2000, have been announcing annual production volume statistics. The latest production volume statistics announced in 2008 show that the production volume of ThermoWood has increased from 18 799 m^3 in 2001 to 83 791 m^3 in 2007 (Ala-Viikari 2008). This corresponds to approximately 22 % increase in production volume each year.

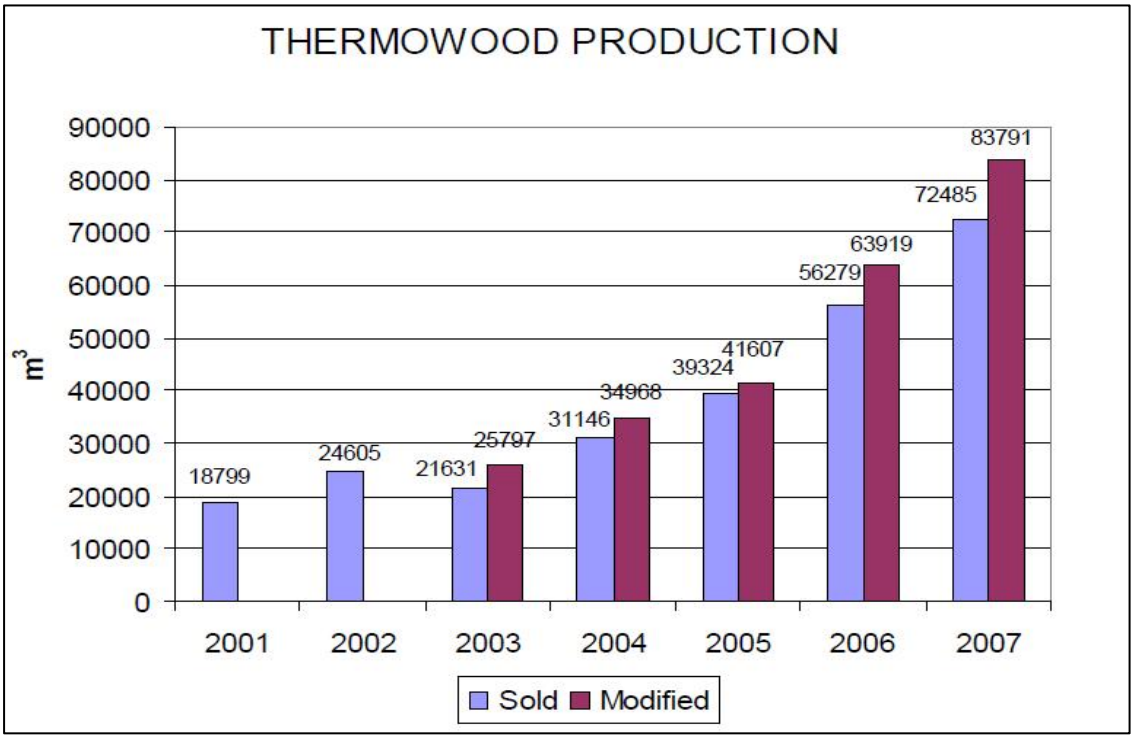

Figure 1 **ThermoWood production statistics. (Ala-Viikari 2008)**

2.3 Heat Treated Wood Properties

2.3.1 Strength Properties

The effect of high temperature on wood properties has been studied for some decades. The earlier studies by Hillis (1984), Bourgois and Guyonnet (1988) and later studies by Tjeerrdsma et al (1998b) show that the heat treated wood has improved dimensional stability and decreased hygroscopicity. The study of Kandem et al. (2002) points out that heat treated wood exhibits higher lignin content and lower acid number compared to untreated wood which indicates the degradation of some hemicelluloses and extractive compounds that results in less water absorption.

The other appreciated properties of heat treated wood is its improved resistance against biodegradation and better durability against weathering which are explained in the studies of Tjeerdsma et al (1998a) and Jämsä and Viitaniemi (2001). Regarding these improved

properties, heat treated wood comes up to be a product which can be used either indoor applications like flooring or outdoor applications like garden furniture and facades.

Here, it also has to be pronounced that drawback of the heat treatment process for wood is the decrease in mechanical properties to some extent. The study of Bekhta and Niemz (2003) have found an average of 44-50% decrease in bending strength and 4-9% reduced modulus of elasticity for heat treated spruce at 200 □ C for different time intervals. Also, the study of Shi et al. (2007) has found a decrease of 0-49% in modulus of rupture and 4-28% decrease in modulus of elasticity in Quebec, Canadian wood species which were heat treated regarding ThermoWood process.

2.3.2 Color and Acidity Properties

One of the other features of heat treated wood is its darker color which is aesthetically pleasing and enables the end products to be alternative for the hardwoods of tropical species. The studies which were concerning the color change of wood caused by heat treatment show that increased treatment temperature and duration in process result in darker color for wood. The study of Ahajji et al. (2008) where color stability of beech and spruce wood were investigated after heat treatment over 210 □ C for 1 hour shows darkening for all samples. Besides, the same study states that the intensity of darkening for samples were more profound for temperatures higher than 210 □ C. The study of Bekhta and Niemz (2003) point out that the color change in spruce wood (*Picea Abies*) was greater above 200°C and the darkening of wood was correlated with increasing temperature and treatment duration. The study of Boonstra et al. (2006) state that the color changes of wood was also dependent on the timber used and correlated with the density of wood where higher density could result in darker colors.

The study of Sundqvist (2002) refers color formation in wood subjected to hydrothermal treatment due to the degradation of wood polymers (hemicelluloses and lignin) and extractive compounds. Another study by Sundqvist et al (2006) correlates the low lightness (darker color) for heat treated birch with increased concentrations of acids. The study of Ayadi et al. (2003) also indicates browning for the color of retified wood at 240 □ C for two hours and moreover the same study shows the increase in acids products during the heat treatment process.

The study of Sehlstedt-Persson (2003) shows the coloring of sapwood and heartwood extractions of pine and spruce wood which were subjected to temperatures over 70 □ C in her study and explain this phenomenon with the degradation products deriving from hydrolysis of hemicelluloses. And the study of Terziev and Boutelje (1998) suggests that the degree of color change of wood caused in drying could be affected by the content of Low Molecule Weight sugars and nitrogen. A recent study by Hiltunen et al. (2008) found that vacuum dried birch wood under reduced pressure and elevated temperature had surface discolorations due to accumulation of phenolic compounds during drying or storage. In the same study it is also stated that the discolored surface layer had contained more sugars, low-molecular-weight phenolic extractives, Brauns' lignin and proanthocyanidin when compared to lighter colored wood layer.

The relation of color component L* which denotes the lightness and the treatment temperature for ThermoWood process is highlighted in figure 2. The lightness value of 100 corresponds to white color where lightness value of 0 corresponds to black color. (Minolta 1993)

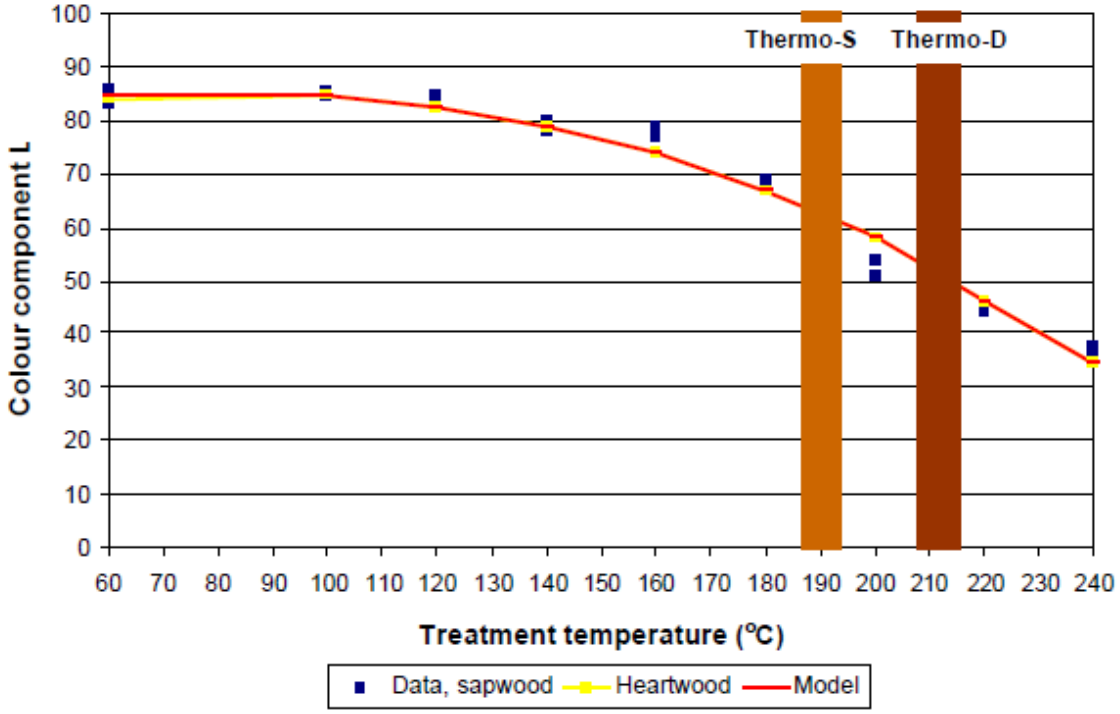

Figure 2 **Heat treatment temperature-color relation for ThermoWood. (Figure from ThermoWood handbook)**

2.4 Stickers and Sticker Stains

Either in conventional kiln drying or in the modern heat treatment processes stickers are being used now and will be used in the future. The function of stickers is separating the timber layers and enabling the heat and moist air circulate into timber stacks for proper drying. Since, stickers are needed for drying process to take place, the stains that they leave on dried timber is inevitable especially for rough condition (not planed wood surface).

The primary and most effective way of handling this issue is planing the wood surface until the stains will disappear, otherwise painting the wood surface can be the other alternative. These techniques have been practically applied by industry for a long time. The study by Larsson et al. (2005) suggests planing for reducing the color changes due to kiln drying. The planing process related to heat treated wood and especially for ThermoWood is explained in ThermoWood Handbook (2003) and ThermoWood Quality Planing Handbook (2004).

However, in some cases, like in the study of Forsman (2008), some of the heat treated boards which would be used in construction of a concept house had sticker stains remaining still after planing process. The reasons for this incident to take place were not fully understood; whether these stains were caused during kiln drying process or heat treatment process.

There have been various number of studies conducted which concerns the heat treated wood's physical and chemical properties including the color changes; like the studies by Tjeerdsma and Boonstra (1998b), Bekhta and Niemz (2003) and Sundqvist (2002). However, very few number of studies was found among the literature cited which were dealing with the stickers issue and explaining formation of the sticker stains.

2.5 Formation of the Sticker Stains

The earlier study of Mc Millen (1975) explains the formation of sticker stains in zones of wood that have oxygen from the air available and that also have moisture and temperature suitable for the chemical mechanisms involve to take place. Furthermore, in the same study it is stated that this kind of discolorations were associated with slow air drying under mild conditions or improperly controlled kiln drying.

In the study of Terziev and Boutelje (1998) where the effect of felling time and kiln drying on color and mould susceptibility of pine wood was the subject, the sticker stains became visible during drying. Especially after drying, the zones where stickers had been placed were light colored than the sticker adjacent zones. They refer this color difference formation due to migration of water-soluble substances that were deposited at the sticker positions towards adjacent zones, if free evaporation had been possible. And by this possible migration, the concentration of soluble substances in that area was presumably increased and in the end, this could have resulted in a darker color for these zones. They had measured a color difference ΔE^*ab of 4.2 units between two regions which is detectable for human eye. The lower limit for human eye to detect a color difference is approximately 2-3 units (Sundqvist 2004).

Terziev and Boutelje also points out the possible effect of reduced oxygen for lighter color underneath sticker zones. Furthermore, in the same study a comparison for the content of Low Molecule Weight sugars beside and within the sticker stained zone was made. And it was found that the concentration of Low Molecule Weight sugars beside the sticker stain was 3.55 times as high as the concentration content within the sticker stained zone. The same value measured for nitrogen was 2.62. In the end, they point out that Low Molecule Weight sugars and nitrogen were also affecting the surface color of wood.

2.6 Stickers' Influence on Production

Today, wood drying industries aim production towards higher quality and heat treatment technologies advance through higher temperatures and shorter durations in drying schedules. Besides, each parameter regarding production is considered very carefully. Therefore, technical properties of each component related to wood drying are important. At this point, the importance of stickers arises both as a major cost parameter and their direct effect on treatment process and production parameters. The issues which are directly or indirectly related to stickers can be aligned as follows:

- Appearance and quality of the end product.
- Cost of stickers in timber drying industry is one of the majors, especially in heat treatment processes at elevated temperatures like in the ThermoWood process. There may be the issue of renewing wood stickers after each heat treatment process. The

reasons for incidence to take place may be either the handling methods of stickers in sawmill processes or the significant decrease in strength of the wood stickers after thermal treatments at high temperatures.

- Production volume of heat treated timber is related to sticker dimensions, because the timber volume that can be put into the kilns is affected by sticker dimensions.
- The sticker thickness is also one of the factors which affect the air circulation in kilns. This air circulation practically affects the pressure in kiln and proper functioning of the kiln system. The design of the kilns is also restricted for a minimum sticker thickness dimension as well.
- Here, it also has to be mentioned that energy consumption, machinery depreciation and work power are the side cost parameters that generates due to planing the heat treated wood surface.

3. Material and Methods

3.1 Introduction

In this work, a combination of different aspects was used to evaluate the stickers and sticker stains. General overview of the aspects that were used in this work is shown in figure 3.

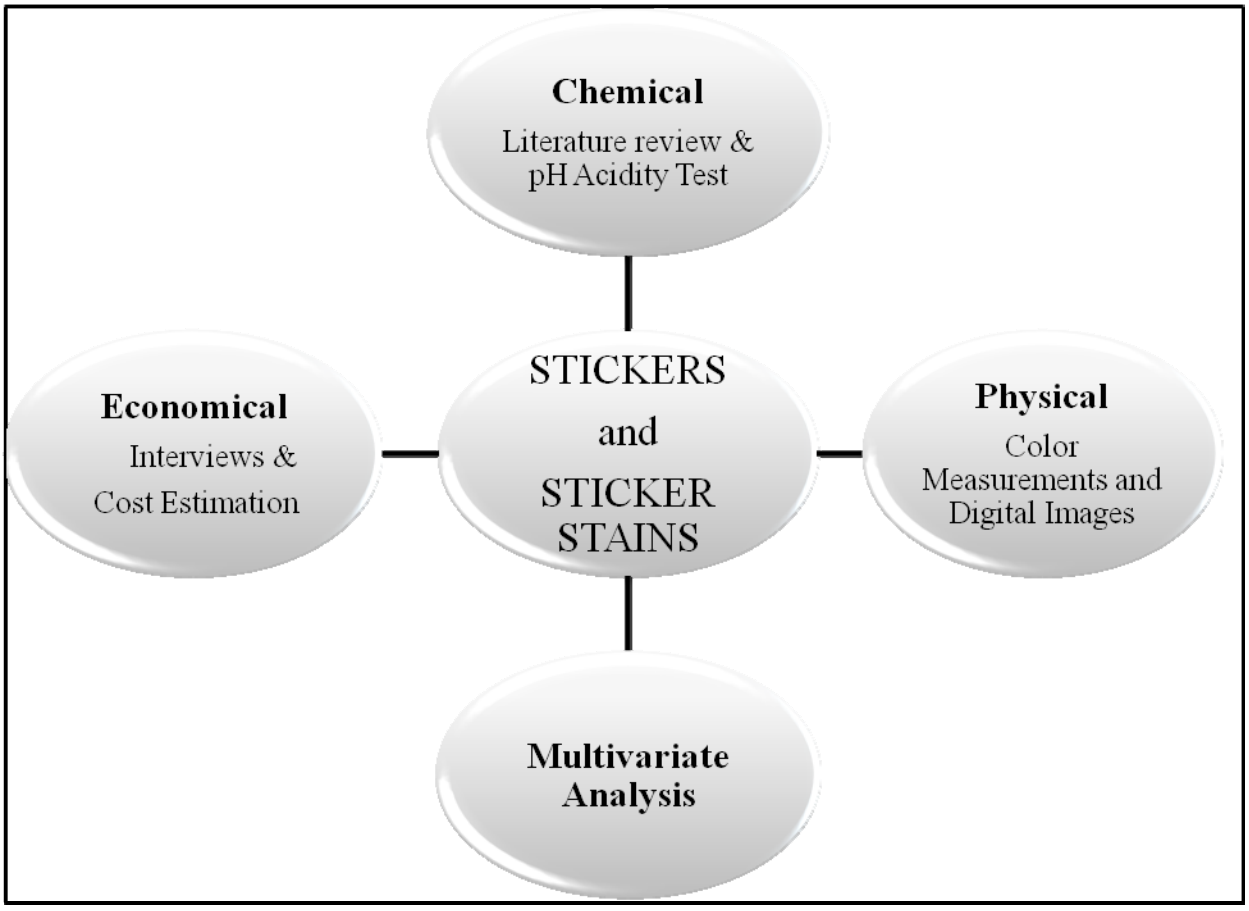

Figure 3 **The project aspects that were used to evaluate the issues of stickers and sticker stains.**

- Communication and information sharing and was held via telephone and internet between the author, supervisor and company correspondents during the study period.
- Interviews were held with companies via telephone and internet in order to have information about the current practices related to stickers in industrial applications.
- Literature reviews were kept ongoing throughout the whole study period like waves. These review waves helped to understand the formation of the sticker stains and also helped to learn more about heat treatment process and its effect on wood properties.
- A simple level pH acidity test was conducted in order to compare the acidity values of sticker underneath and adjacent zones. These values were also compared to pH value of heat treated wood surface as reference value.
- Color measurements on heat treated boards were made in order to inspect different sticker types' stains on heat treated boards. Digital images were also used to establish visual examinations as well.
- A multivariate analysis approach was conducted in order study variables influencing sticker stains.
- The costs of different sticker types; in this case wood and aluminum stickers were tried to be estimated and compared in short and long term utilization periods.

3.2 Wood Material & Stickers

The wood material and wood stickers which were studied in this work was kindly provided by Hudiksvall Heat Treated Wood AB. The aluminum stickers were supplied from Alutrade Aluminum AB with the finance by Valutec AB.

The heat treated boards were kiln dried by Norrskog AB prior to industrial heat treatment process again at Hudiksvall Heat Treated Wood AB. The experimental set up for sticker alignment in the wood stack was made by the author and Gustav Åström at the production site located at Hudiksvall. And after the heat treatment process, the wood stack was transported in a metal striped condition (stickers were not removed after process) to Wood Technology Department of Luleå University of Technology, Campus Skellefteå where further analysis had been carried out regarding the content of this study.



Figure 4 **The whole wood stack in striped condition right after delivered to Skellefteå.**

3.2.1 Wood Material

In this work, heat treated Norway spruce (*Picea Abies)* boards regarding Thermo-Durability product terms was studied. The dimensions of the boards were 4900 mm ×1150 mm × 32 mm where 4900 mm was in the longitudinal direction. 48 of 152 boards from a whole stack were chosen as sample boards in order to inspect the sticker stains.

3.2.2 Sticker Types

The aluminum stickers that were used in ThermoWood process were cut from 6000 mm in raw length to 1200 mm in final length at the production site by the author. The dimensions and the material types of the stickers that were used in heat treatment process are shown in table 1. Regarding the aluminum sticker types, the thickness of all stickers was 2 mm.

The sticker types are also referred as letters in order to be more comprehendible on further parts of the study.

Table 1 **Sticker types were used in ThermoWood process.**

Sticker Dimension (mm)	***Sticker Material***	***Sticker Code***
20 × 50 × 1200	Aluminum	A
25 × 45 × 1200	Profiled wood with two canals (canal depth 7,5 mm) (Birch)	B
20 × 40 × 1200	Aluminum	C
15 × 40 × 1200	Aluminum	D
20 × 40 × 1200	Wood (Spruce)	E

3.2.3 Experimental Set up for Sticker Alignment in the Wood Stack

The stickers were placed approximately 50 cm distance from each other on all 16 layers. Total number of stickers that were laid on each layer was 10. Each sticker type was used

three times on different layers throughout the stack. 15 layers were arranged regarding this regulation. One layer in wood stack was set up in a mixed alignment for wood and aluminum stickers to be able to compare the sticker stains of wood and aluminum stickers on the very same layer. This layer is referred as layer 0.The position of layer 0 in wood stack was the top layer above the other 15 layers. The layout order of the sticker types on layer 0 is described in table 2 and shown visually with a digital image in figure 5. The layer referred as "0" was primarily subjected to the visual examinations with digital images.

Table 2 **The mixed alignment of wood and aluminum stickers' description.**

	Pos. 1	***Pos. 2***	***Pos. 3***	***Pos. 4***	***Pos. 5***	***Pos. 6***	***Pos. 7***	***Pos. 8***	***Pos. 9***	***Pos.10***
Sticker Type	A	A	E	E	D	D	C	C	B	B



Figure 5 **The mixed alignment of wood and aluminum stickers are visible on the top layer where one of the boards is raised up.**

The sticker alignment is described in table 3. The upper most wood layer in the stack is referred as layer 0 and the lowest layer in stack is referred as layer 15.

Table 3 **The sticker types and their alignment throughout the wood stack.**

Layer	*Sticker Type*	*Sticker Code*	*Total Sticker Number on layer*
0	Mixed alignment of wood and aluminum	A, B, C, D, E	10
1	20 × 40 ×1200 mm wood	E	10
2	15 × 40 ×1200 mm aluminum	D	10
3	20 × 40 × 1200 mm aluminum	C	10
4	25 × 45 × 1200 mm profiled wood	B	10
5	20 × 50 × 1200 mm aluminum	A	10
6	20 × 40 ×1200 mm wood	E	10
7	15 × 40 ×1200 mm aluminum	D	10
8	20 × 40 × 1200 mm aluminum	C	10
9	25 × 45 × 1200 mm profiled wood	B	10
10	20 × 50 × 1200 mm aluminum	A	10
11	20 × 40 ×1200 mm wood	E	10
12	15 × 40 ×1200 mm aluminum	D	10
13	20 × 40 × 1200 mm aluminum	C	10
14	25 × 45 × 1200 mm profiled wood	B	10
15	20 × 50 × 1200 mm aluminum	A	10

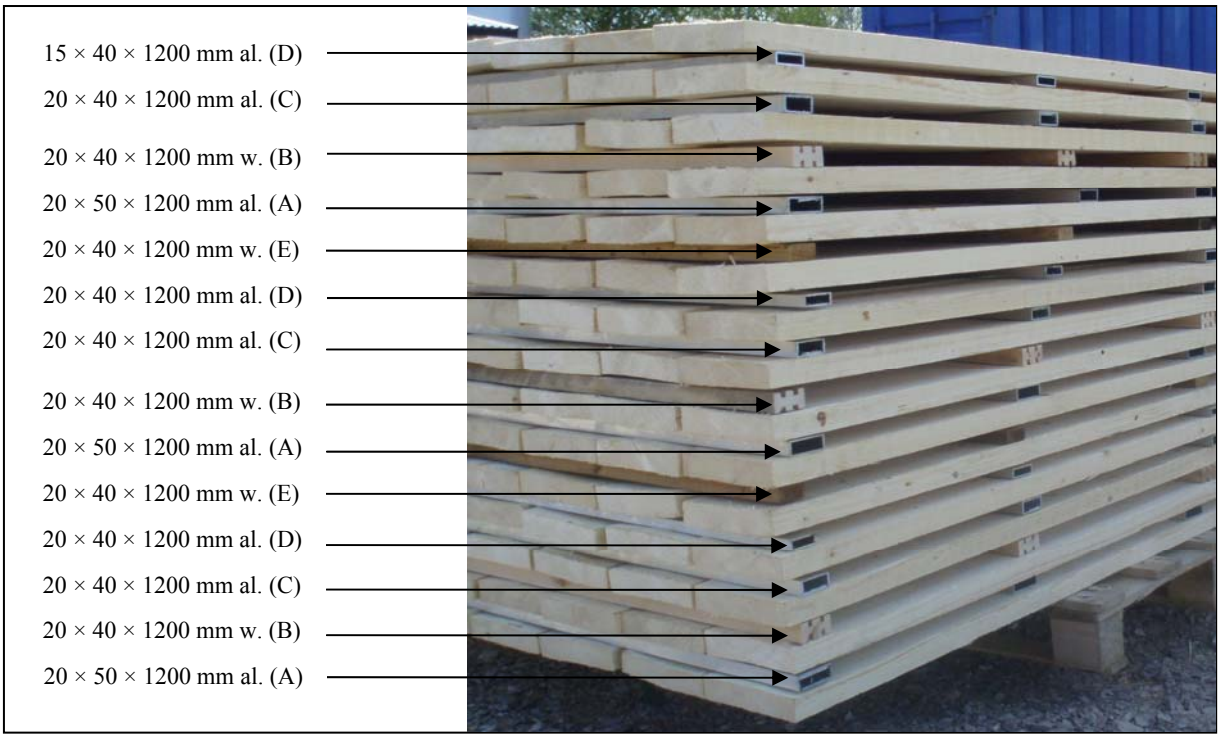

Figure 6 **The sticker types and their alignment throughout the layers of the wood stack in close plan.**

3.3 Heat Treatment Process

The heat treatment process duration was approximately 45 hours regarding the Thermo-Durability end product terms. This process and its parameters are further described in ThermoWood Handbook. (www.thermowood.fi)

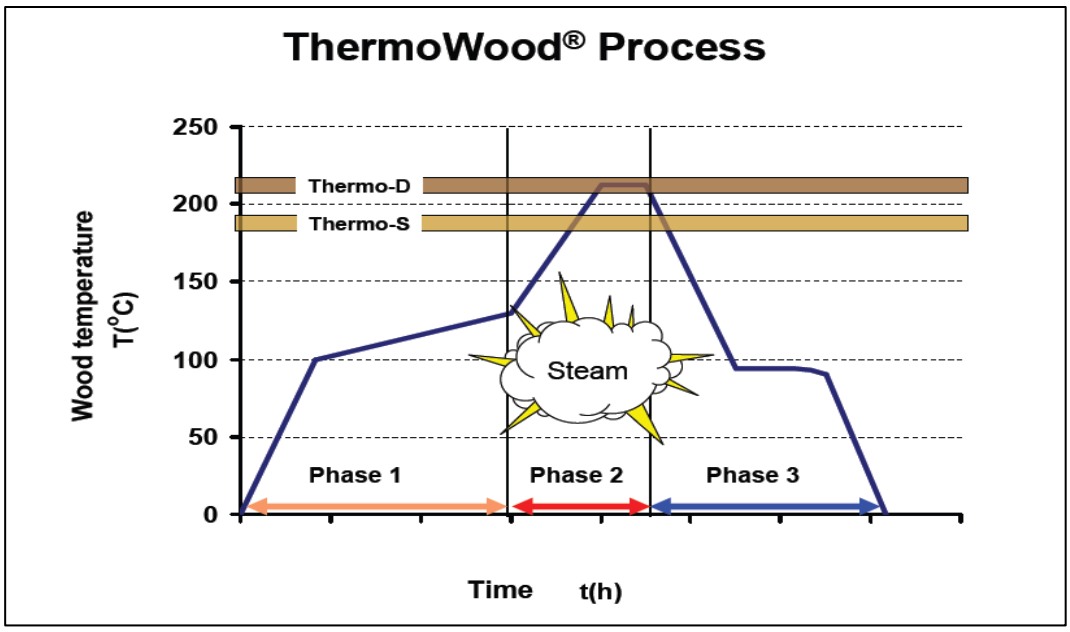

Figure 7 **ThermoWood process diagram (www.thermowood.fi).**

3.4 Chemical Analysis

The scientific research studies in literature were investigated for the explanation of sticker stain formation. Not only the sticker stain formation, but also the changes in wood structure and properties due to heat treatment and drying were studied as well.

Furthermore, a pH acidity test was conducted in order to find out whether there was a difference in pH values of sticker underneath and adjacent zones when they were compared to pH value of heat treated wood.

3.4.1 pH Test Acidity Test

1 gram of wood tissue under sticker zones and 1 gram of wood tissue from adjacent to sticker zones were scraped in order to compare their PH values with the heat treated wood's pH value on that very level. These wood tissues were collected from layer 11 and 13 where 20 × 40 × 120 mm wood (type E) and 20 × 40 × 120 mm aluminum (type C) stickers were used respectively. The heat treated wood was also scraped from these layers for reference pH values.

The scraped wood tissues were separately put into 20 grams of water in plastic bottles. The bottles were left closed for 2 days in room temperature. After 2 days, the PH values of these solutions were measured with a Metrohm 744 pHmeter.

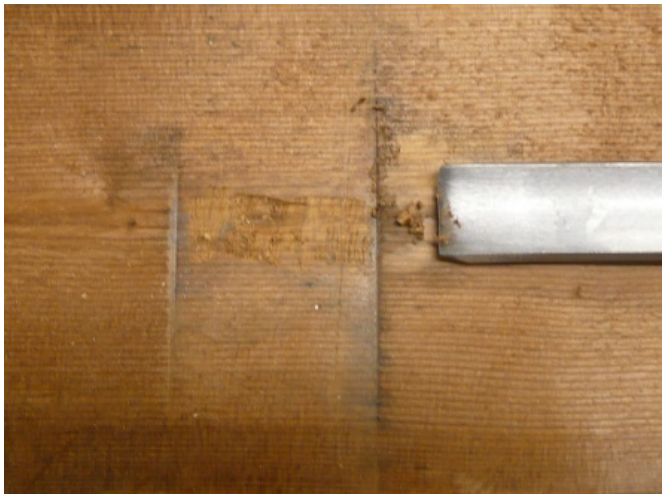

Figure 8 **Scraping of wood tissues from sticker underneath and adjacent zones.**



Figure 9 **Weighing of wood tissues.**

3.5 Physical Analysis

3.5.1 Sample Boards & Colorimetric Measurement Positions

Prior to colorimetric measurements, heat treated sample boards were coded regarding their height and width positions in the stack. Afterwards, sticker positions and their stains were marked on the sides of the sample boards in order to maintain the same measurement positions after each planing process.

For each layer, 3 of 9 boards on horizontal layout were chosen as sample boards. On every sample board, 6 of 10 sticker stained positions were chosen for colorimetric measurements. There were also 3 reference points chosen on each sample board in order to evaluate the color difference between sticker stains and heat treated wood. The visual description of measurement and reference positions are shown in figure 10.

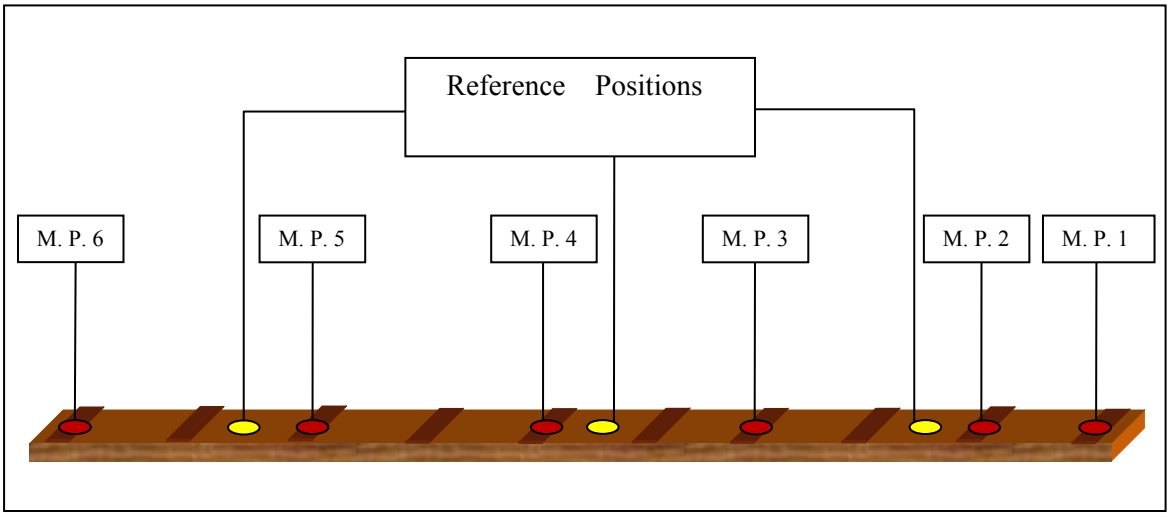

Figure 8 **"M. P." resembles measurement positions for sticker underneath zones. Reference positions resemble heat treated wood surfaces where no sticker was placed.**

This measurement method shown in figure 10 for one board was applied for 48 sample boards. The measurement procedure was repeated for every sample board for rough (not planed), 1 mm and 2 mm planing depths. The total number of colorimetric measurements that were made was 1296.

3.5.2 Color Spaces and Color Measurements

The color measurements were made by using a Minolta Chromameter CR 310 with a measuring head of 50 mms in diameter. The color system chosen was L* a* b* color space where L* denotes lightness, a* and b* denote the chromaticity coordinates.

The L* a* b* values measured were afterwards transformed into L* C* h and ΔE*ab values which are presented in this work. L* is lightness, C* is chroma (saturation), h is hue (shade) and ΔE*ab is the size of color difference without respect to direction (Minolta 1993). The color spaces and the color components are shown in figure 11.

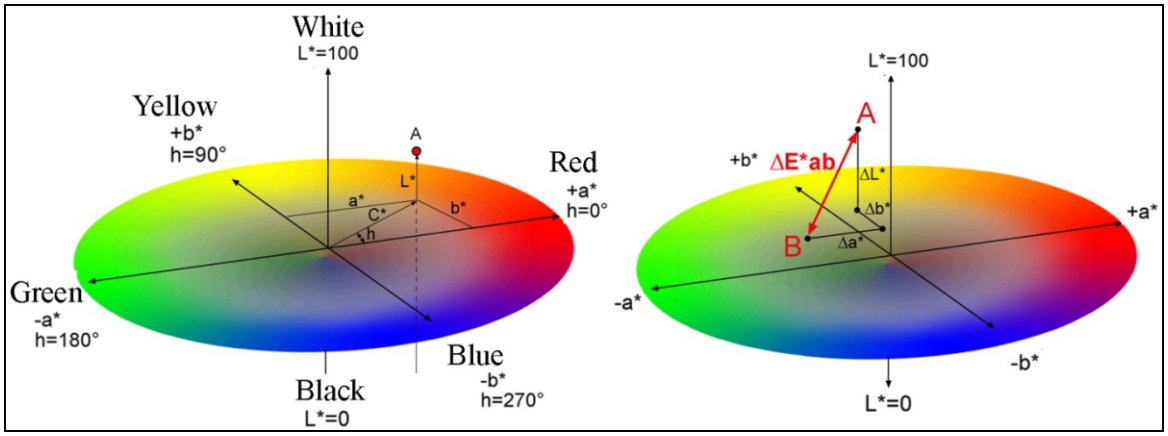

Figure 9 **CIE L*C*h*and CIE L*a*b* color spaces. (Figure from Sehlstedt-Persson 2002)**

The calculations were made by using the following formulas. (Minolta 1993)

$$\Delta L^* = L_s - L_r^* \quad (1)$$

$$\Delta a^* = a_s^* - a_r^* \quad (2)$$

$$\Delta b^* = b_s^* - b_r^* \quad (3)$$

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (4)$$

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (b^*)^2} \quad (5)$$

Where, L_s^*, a_s^* and b_s^* are the sticker stained zones and L^*_r, a^*_r and b^*_r are the heat treated wood surface where stickers were not placed as reference zones.

3.5.3 The Evaluation of Sticker Stains with Color Measurements and Digital Images

The color difference between reference zones and underneath sticker zones was measured on sample boards in terms of ΔE*ab values. These measurements were carried out for rough (not planed), 1 mm planed and 2 mm planed sample boards throughout the whole stack.

Furthermore, the ΔE*ab values measured on each layer in different planing depths were compared with each other to figure out whether there was a variation of decrease or increase in size of discolorations regarding upper or lower layers in the stack.

In addition to the color measurements, the sticker stains of 5 different sticker types were photographed with a Panasonic Digital camera on rough (not planed), 1mm planed and 2 mm planed sample board surfaces. It was intended to support the colorimetric measurement values with digital images in order to establish visual evaluations as well.

3.5.4 Evaluation of Sticker Stains in terms of L* C* h and ΔE*ab Values

The sufficient planing depth in millimeters needed to have a uniform looking heat treated wood surface without sticker stains was investigated.

Furthermore, the color components L*, C* and h belonging to sticker stained zones of 5 different sticker types on sample boards were compared with each other among subsequently increasing planing depths.

3.6 Multivariate Analysis

A multivariate analysis of the collected data was also made by using principle component analysis (PCA) and partial least squares (PLS) regression analysis with software tool Simca (Eriksson et al.), by Umetrics (2005).

The principle component analysis (PCA) is a useful tool to study relations in the data set and get an overview of the data. (Wold et al. 1987) The relations between sticker stains by means of color variables L* C* h color components, ΔE*ab (color difference), treatment temperature, planing and sticker types were investigated.

Partial least squares (PLS) regression is a bilinear regression method for creating prediction models of one or several responses, Y, from a set of factors, X (Danvind 2002). According to the study of Danvind (2002), partial least squares(PLS) regression can be used to study many correlated or uncorrelated variables at the same time and models with good predictive power which are avoiding noise and maximizing information have the possibility to be created.

The L*, C* h and ΔE*ab values were set as dependent variables/responses, so called Y variables and the process parameter, temperature, planing and the sticker types and their stains were set as the independent variables/predictors, so called as X variables. The study of Danvind (2002) further describes the definitions and the use of PCA and PLS.

3.7 Economical Analysis

3.7.1 Company Interviews

Interviews were held with companies which were currently in heat treatment industries via telephone and internet. The company names were supplied from the document which was prepared by ThermoWood Association (Ala-Viikari 2008). However, the names of these companies will not be highlighted due to the permission terms that are required for publishing. The companies that were made interviews are listed below by numbers:

1. Company 1, Finland.
2. Company 2, Finland.
3. Company 3, Finland.
4. Company 4, Finland.
5. Company 5, Sweden.

All of these companies except company 4 were ThermoWood Association members. The questions that were directed to the company correspondents were stable for e-mails. A part from these, it was for Company 5 interview that an exceptional discussion was held regarding heat treatment process and kiln operations. On the other hand, during telephone interviews, spontaneous additions to the answers of the questions and related topics were discussed with the interviewed people.

The questions listed below were directed to the company correspondents:

- What type of stickers are you using in your facility for heat treatment process? (dimensions and material type)
- How much do you plane (in millimeters) the wood surface to have a uniform looking wood surface without sticker stains?
- Do you have automatic separation process for stickers?
- What is the relative estimation that you can make for the lifetime of the stickers that you are using?
- What would be your choice for stickers, if you would make a selection between wood and aluminum stickers? And Why?

3.7.2 Cost Estimation for Wood and Aluminum Stickers

Relative lifetime values for wood and aluminum stickers were determined by the information gathered from company interviews that were acknowledged previously. These lifetime durations was considered to be the number of runs that one sticker could be utilized as many times as possible.

Approximate short and long term sticker cost estimation was made for a heat treated wood producing facility which was considered to have maximum production capacity. This capacity was considered to be 100 runs for one year. In this case, the costs of 5 different sticker types were compared with each other.

4. Results

4.1 Chemical Analysis

4.1.1 pH Test

The pH values of heat treated wood tissues scraped from sticker underneath and adjacent zones were compared to the pH value of heat treated wood for the very same layers. These wood tissues were scraped from rough (not planed) wood surfaces. The table 4 shows these pH values.

Table 4 Comparison of pH values that were measured sticker underneath and adjacent zones, together with pH values of heat treated wood where no sticker was placed.

Layer	*Sticker Dimensions and materials*	*Sticker Code*	*pH heat treated wood*	*pH under sticker zone*	*pH adjacent to sticker zone*
12	20 × 40 × 1200 mm wood	E	4, 36	4, 13	4, 61
14	20 × 40 × 1200 mm aluminum	C	4, 80	4, 47	4, 57

Both for aluminum and wooden stickers, the pH values of underneath sticker zones were lower than the pH values of heat treated wood and sticker adjacent zones. The amount of the pH difference for under and adjacent sticker zones was higher for wooden stickers.

For layer 12, where wooden stickers were used, the pH value of underneath sticker zones was 0, 23 units lower than heat treated wood's pH value and 0,48 units lower than pH value of sticker adjacent zones.

For layer 14, where aluminum stickers were used, the pH value of underneath sticker zones was 0, 33 units lower than heat treated wood's pH value and 0, 10 units lower than pH value of sticker adjacent zones.

4.2 Physical Analysis

This chapter involves the color measurements of the sticker stains on sample boards throughout 15 layers of the wood stack in subsequently increasing planing depths. The digital images of sticker stains were also added separately for each planing depth in order to establish visual perception for color difference ΔE*ab values.

The color measurements were made for each layer in 0 mm, 1 mm and 2 mm planing depths in order to inspect and compare the variation of sticker stains among different layers of the wood stack.

Furthermore, the sticker stains on sample boards were evaluated in terms of L*, C*, h color components regarding planing process. In the end, sticker stains of 5 different sticker types were compared with each other in terms of ΔE* ab values regarding planing process.

4.2.1 Color measurements on Each Layer of the Wood Stack for Rough (not planed) Phase

The size of the color differences between reference zones and underneath sticker zones was measured on sample boards throughout the layers of the wood stack for rough (not planed) phase. The size of sticker stains and sticker types that were used on each layer is shown in figure 12. There has to be paid attention to the fact that the limit for human eye to be able to detect a difference in color is approximately 2-3 units. (Sundqvist 2004)

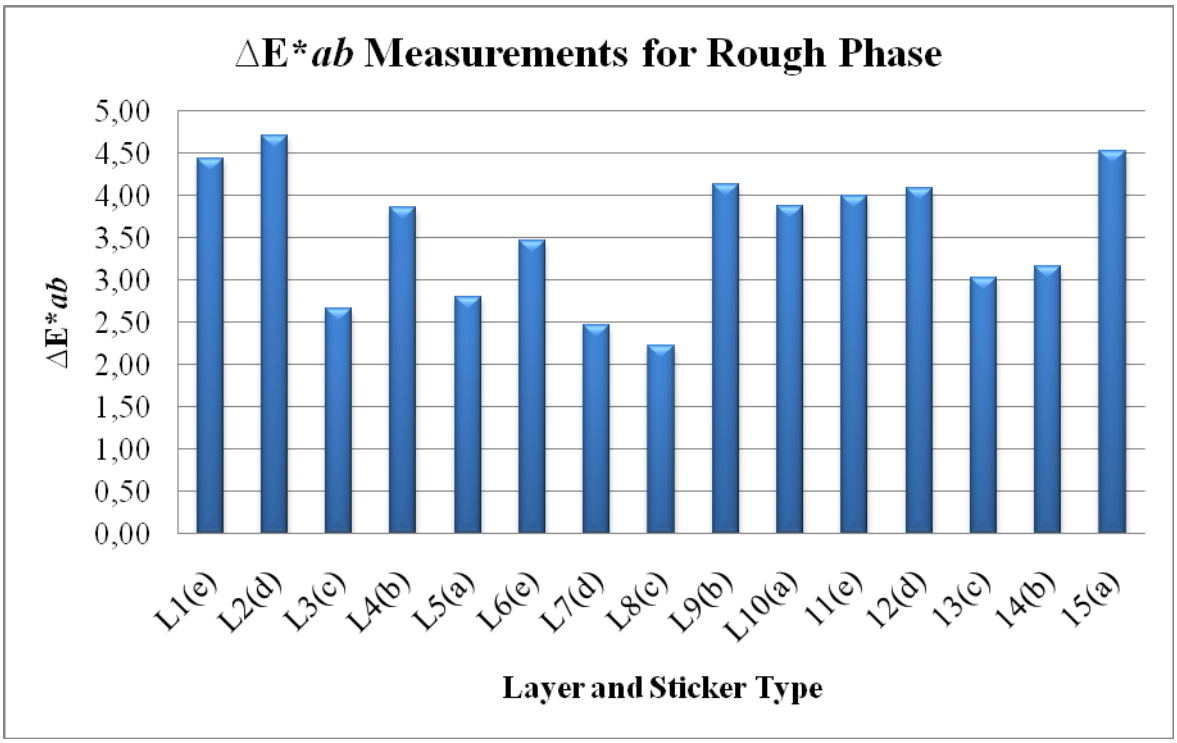

Figure 10 **The color difference measurements through layers of the wood stack for 0 mm planing depth. In figure, L 1 corresponds to top layer of the stack where L 15 corresponds to bottom layer.**

Table 5 **The size of the color differences (ΔE**ab*) on each layer of the wood stack for rough (not planed) phase. Standard deviation values of ΔE**ab* values for each layer are featured as well.**

Layer	*Sticker Dimension & Material*	*Sticker code*	*Planing (mm)*	*ΔE*ab*	*Std. Dev.*
1	20 × 40 × 1200 mm wood	E	0	4,44	1,56
2	15 × 40 × 1200 mm aluminum	D	0	4,72	3,62
3	20 × 40 × 1200 mm aluminum	C	0	2,66	1,86
4	25 × 45 × 1200 mm profiled wood	B	0	3,85	1,95
5	20 × 50 × 1200 mm aluminum	A	0	2,80	1,09
6	20 × 40 × 1200 mm wood	E	0	3,46	1,08
7	15 × 40 × 1200 mm aluminum	D	0	2,47	1,12
8	20 × 40 × 1200 mm aluminum	C	0	2,22	0,98
9	25 × 45 × 1200 mm profiled wood	B	0	4,13	1,52
10	20 × 50 × 1200 mm aluminum	A	0	3,87	2,22
11	20 × 40 × 1200 mm wood	E	0	3,99	2,56
12	15 × 40 × 1200 mm aluminum	D	0	4,09	2,10
13	20 × 40 × 1200 mm aluminum	C	0	3,03	1,51
14	25 × 45 × 1200 mm profiled wood	B	0	3,17	2,31
15	20 × 50 × 1200 mm aluminum	A	0	4,52	2,80

The ΔE**ab* values quantifying the size of the color differences varied within the range between 2, 22 and 4, 72 units.

The highest ΔE**ab* measured was on layer 2 where 15 × 40 × 1200 mm dimensioned aluminum (type D) stickers were used. The size of the color difference was 4, 72 units.

The lowest value of ΔE**ab* measured was on layer 8 where 20 × 40 × 1200 mm aluminum (type C) stickers were used. The size of the color difference was 2, 22 units.

There was not an increasing or decreasing phenomena observed for the size of ΔE**ab* values regarding stickers' location in the stack. The ΔE**ab* values which numerically explains the size of sticker stains were neither increasing nor decreasing regarding upper or lower layers in the stack.

The wooden and aluminum stickers' stains did not vary significantly from each other by means of the discolorations that they had left on wood surface. The ΔE**ab* values on layers 9, 10 and 11 were 4, 13 units, 3, 87 units and 3, 99 units where 25 × 45 × 1200 mm dimensioned profiled wood (type B), 20 × 50 × 1200 mm dimensioned aluminum (type A) and 20× 40 × 1200 mm dimensioned wood (type C) stickers were used respectively.

The highest standard deviation value for ΔE**ab* color difference was 3, 62 units belonging to 15 × 40 × 1200 mm aluminum (type D) stickers on layer 2.

The lowest standard deviation value for ΔE**ab* color difference was 0, 98 units belonging to 20 × 40 × 1200 mm aluminum (type C) stickers on layer 8.

4.2.2 Digital Images of Sticker Stains on Rough (not planed) Sample Boards

The digital images of different sticker types' stains on rough (not planed) sample boards are shown in this section. These digital images help to interpret the ΔE*ab color difference values visually. The original alignment of sample boards in horizontal direction was preserved in order to display sticker staining better.



Figure 11 **The stains of 20 × 50 × 1200 mm aluminum, type A stickers on not planed sample boards.**



Figure 12 **The stains of 25 × 45 × 1200 mm profiled wood, type B stickers on not planed sample boards.**



Figure 13 **The stains of 20 × 40 × 1200 mm aluminum, type C stickers on not planed sample boards.**



Figure 14 **The stains of 15 × 40 × 1200 mm aluminum, type D stickers on not planed sample boards.**



Figure 15 **The stains of 20 × 40 × 1200 mm wood, type E stickers on not planed sample boards.**

4.2.3 Color measurements on Each Layer of the Wood Stack for 1 mm planed Phase

The size of the color differences between reference zones and underneath sticker zones on sample boards was measured throughout the layers of the wood stack for 1 mm planing depth. The size of color differences and sticker types that were used on each layer is shown in figure 18. There has to be paid attention to the fact that the limit for human eye to be able to detect a difference in color is approximately 2-3 units. (Sundqvist 2004)

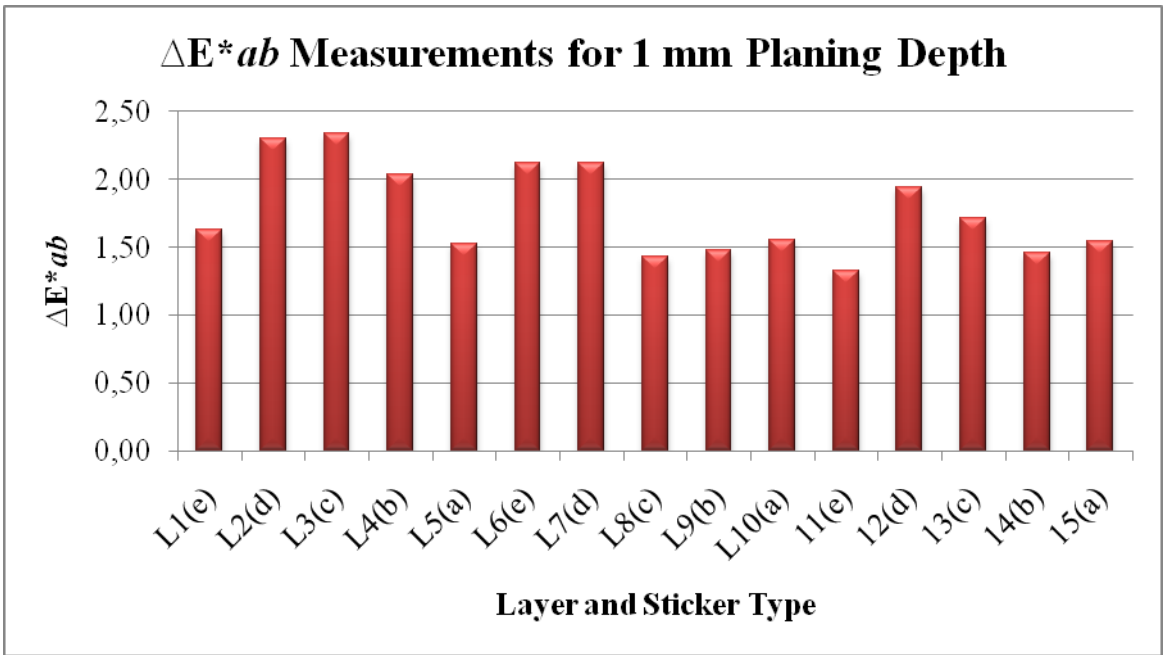

Figure 16 **The color difference measurements through layers of the wood stack for 1 mm planing depth. In figure, L 1 corresponds to top layer of the stack where L 15 corresponds to bottom layer.**

Table 6 **The size of the color differences (ΔE**ab*) on each layer for 1 mm planing depth. Standard deviation values of ΔE**ab* values for each layer are featured as well.**

Layer	*Sticker Dimensions and Materials*	*Sticker code*	*Planing (mm)*	*ΔE*ab*	*Std. Dev.*
1	20 × 40 × 1200 mm wood	E	1	1,63	1,17
2	15 × 40 × 1200 mm aluminum	D	1	2,30	2,16
3	20 × 40 × 1200 mm aluminum	C	1	2,34	1,84
4	25 × 45 × 1200 mm profiled wood	B	1	2,04	1,29
5	20 × 50 × 1200 mm aluminum	A	1	1,53	0,99
6	20 × 40 × 1200 mm wood	E	1	2,12	1,17
7	15 × 40 × 1200 mm aluminum	D	1	2,12	1,55
8	20 × 40 × 1200 mm aluminum	C	1	1,43	0,69
9	25 × 45 × 1200 mm profiled wood	B	1	1,48	0,88
10	20 × 50 × 1200 mm aluminum	A	1	1,56	0,86
11	20 × 40 × 1200 mm wood	E	1	1,33	0,94
12	15 × 40 × 1200 mm aluminum	D	1	1,94	1,15
13	20 × 40 × 1200 mm aluminum	C	1	1,72	1,49
14	25 × 45 × 1200 mm profiled wood	B	1	1,46	0,95
15	20 × 50 × 1200 mm aluminum	A	1	1,55	1,19

The ΔE**ab* values quantifying the size of the color differences varied within the range between 1, 33 and 2, 34 units.

The highest ΔE**ab* measured was on layer 4 where 20 × 40 × 120 mm dimensioned aluminum (type C) stickers were used. The size of the color difference was 2, 34 units.

The lowest ΔE**ab* measured was on layer 12 where 20 × 40 × 120 mm wood (type E) stickers were used. The size of the color difference was 1, 33 units.

The highest standard deviation value for ΔE**ab* color difference was 2, 16 units belonging to 15 × 40 × 1200 mm aluminum (type D) stickers on layer 2.

The lowest standard deviation value for ΔE**ab* color difference was 0, 86 units belonging to 20 × 50 × 1200 mm aluminum (type A) stickers on layer 10.

4.2.4 Digital Images of Sticker Stains on 1 mm planed Sample Boards

The sticker stained zones of sample boards were displayed by digital images before and after 1 mm planing process. The effect of planing process on wood surface is shown by these images. There has to be paid attention to the fact that only the sticker stained zones are shown in these images and these zones are the exact locations before and after planing process; as it also can be understood from the coding letters on the sides of the boards which are identical. These images also are given as examples for each sticker types' stain on heat treated wood surface and their relation with planing process with 1 mm planing depth.

1. The stain of 20 × 50 × 1200 mm aluminum; type A sticker is shown in figure 19 and 20, respectively before and after 1 mm planing process.



Figure 17 **The stain of type A sticker before 1 mm planing.**



Figure 18 **The stained zone of type A sticker after 1 mm planing.**

2. The stain of 25 × 45 × 1200 mm profiled wood; type B sticker is shown in figure 21 and 22, respectively before and after 1 mm planing process.



Figure 19 **The stain of type B wood sticker before 1 mm planing.**



Figure 20 **The stained zone of type B wood sticker after 1 mm planing.**

3. The stain of 25 × 45 × 1200 mm profiled wood, type B sticker is shown in figure 23 and 24, respectively before and after 1 mm planing process



Figure 23 **The stain of type C sticker before 1 mm planing.**



Figure 24 **The stained zone of type C sticker after 1 mm p**

4. The stain of 15 × 40 × 1200 mm aluminum, type D sticker is shown in figure 25 and 26, respectively before and after 1 mm planing process



Figure 25 **The stain of type D sticker before 1 mm planing.**



Figure 26 **The stained zone of type D sticker after 1mm planing.**

5. The stain of 20 × 40 × 1200 mm aluminum, type E sticker is shown in figure 27 and 28, respectively before and after 1 mm planing process.



Figure 27 **The stain of type D sticker before 1 mm planing.**



Figure 28 **The stained zone of type E sticker after 1 mm planing.**

4.2.5 Color Measurements on Each layer of the Wood Stack for 2 mm Planing Depth

The size of the color differences between reference zones and underneath sticker zones was measured on sample boards throughout the layers of the wood stack for 2 mm planing depth. The size of sticker stains and sticker types that were used on each layer is shown in figure 29. There has to be paid attention to the fact that the limit for human eye to be able to detect a difference in color is approximately 2-3 units. (Sundqvist 2004)

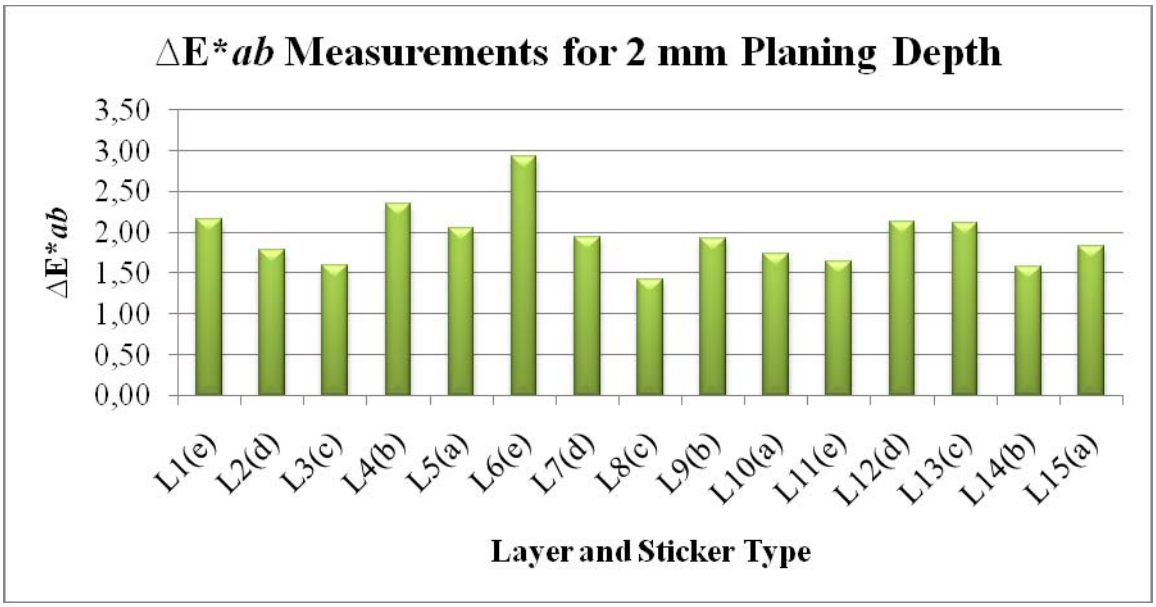

Figure 29 **The color difference measurements through layers of the wood stack for 2 mm planing depth. In figure, L 1 corresponds to top layer of the stack where L 15 corresponds to bottom layer.**

Table 7 **The size of the color differences (ΔE**ab*) on each layer for 2 mm planing depth. Standard deviation values of ΔE**ab* values for each layer are featured as well.**

Layer	*Sticker Dimensions and Materials*	*Sticker code*	*Planing (mm)*	*ΔE*ab*	*Std. Dev.*
1	20 × 40 × 1200 mm wood	E	2	2,16	1,81
2	15 × 40 × 1200 mm aluminum	D	2	1,78	1,05
3	20 × 40 × 1200 mm aluminum	C	2	1,60	1,03
4	25 × 45 × 1200 mm profiled wood	B	2	2,35	1,17
5	20 × 50 × 1200 mm aluminum	A	2	2,05	1,18
6	20 × 40 × 1200 mm wood	E	2	2,93	2,06
7	15 × 40 × 1200 mm aluminum	D	2	1,94	1,07
8	20 × 40 × 1200 mm aluminum	C	2	1,42	0,81
9	25 × 45 × 1200 mm profiled wood	B	2	1,92	1,57
10	20 × 50 × 1200 mm aluminum	A	2	1,73	1,06
11	20 × 40 × 1200 mm wood	E	2	1,65	0,97
12	15 × 40 × 1200 mm aluminum	D	2	2,13	1,13
13	20 × 40 × 1200 mm aluminum	C	2	2,11	1,35
14	25 × 45 × 1200 mm profiled wood	B	2	1,58	1,05
15	20 × 50 × 1200 mm aluminum	A	2	1,83	1,00

The ΔE*ab values quantifying the size of the color differences varied within the range between 1, 42 and 1, 42 units.

The highest ΔE*ab value measured was on layer 6 where 20 × 40 × 120 mm dimensioned wood (type E) stickers were used. The size of the color difference was 2, 93 units.

The lowest ΔE*ab value measured was on layer 8 where 20 × 40 × 120 mm aluminum (type C) stickers were used. The size of the color difference was 1, 42 units.

The highest standard deviation value for ΔE*ab color difference was 2, 06 units belonging to 20 × 40 × 1200 mm wood (type E) stickers on layer .

The lowest standard deviation value for ΔE*ab color difference was 0, 81 units belonging to 20 × 40 × 1200 mm aluminum (type C) stickers on layer 8.

4.2.6 Digital Images of Sticker Stains on 2 mm planed Sample Boards

The sticker types of A, B, C, D and E and their stains on sample boards are shown in figures 30, 31, 32, 33 and 34 respectively. The “not planed” and 2 mm planed boards of same layers are shown together to emphasize the color differences and disappearance of sticker stains due to planing process. The original layout of stickers on sample boards was preserved in vertical direction for sticker contact zones in order to establish a better visual evaluation.



Figure 30 **2 mm planed board surfaces where type A stickers were used.**



Figure 31 **2 mm planed board surfaces where type B stickers were used.**



Figure 32 **2 mm planed board surfaces where type C stickers were used.**



Figure 33 **2 mm planed board surfaces where type D stickers were used.**



Figure 34 **2 mm planed board surfaces where type E stickers were used.**

4.2.7 Comparison of Sticker Stains throughout the Layers of the Wood Stack in 0 mm, 1 mm and 2 mm Planing Depths

The size of sticker stains on sample boards covering the whole wood stack was measured separately for each layer in 0 mm, 1 mm, and 2 mm planing depths. An overall evaluation and comparison of sticker stains' degree of severity (sizes) on each layer for subsequently increasing planing depths is shown in figure 35.

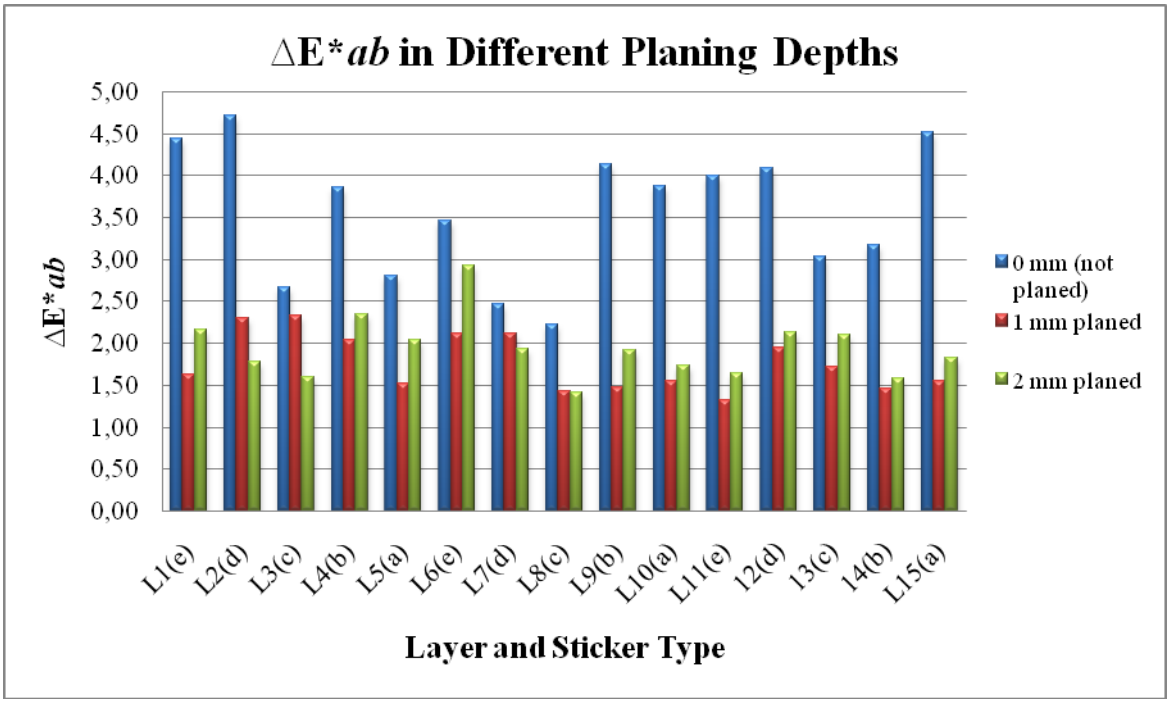

Figure 35 **The comparison for the size of color differences (ΔE*ab values) for each layer in different planing depths.**

The ΔE*ab color difference values were highest for not planed phase (in blue color) for all layers. After 1 mm planing the wood surfaces (dark red color), the ΔE*ab values show a significant decrease for all layers. However, there is not a similar kind of change in color difference values with the further 2 mm planing depth, regarding all layers.

From not planed phase to 1 mm planed phase, the highest change in size of ΔE*ab values, in a way of decrease belongs to layer 15 with 2, 98 units where 20 × 50 × 1200 mm dimensioned aluminum (type A) stickers were used.

From not planed phase to 1 mm planed phase, the least change in the size of ΔE*ab values, in a way of decrease belongs to layer 3 with 0, 33 units where 20 × 40 × 1200 mm dimensioned aluminum (type C) stickers were used.

Furthermore with 2 mm planing (green color), the ΔE*ab values do not show significant difference in terms of size from 1 mm planed phase. The size of color difference change from 1 mm to 2 mm planing was highest for layer 6 where 20 × 40 × 1200 mm wood (type E) stickers with 0, 81 units and lowest for 20 × 40 × 1200 mm aluminum (type C) stickers with 0, 01 units.

4.2.8 The Evaluation of Sticker Stains in L* C* h Color Components and ΔE*ab Values

The sticker stains of 5 different sticker types on sample boards were measured and compared with each other in terms of L* C* h and ΔE*ab values for subsequently increasing planing depths.

4.2.8.1 Evaluation of L (Lightness) regarding Planing Process*

The color component L* (lightness) belonging to sticker stains of 5 different sticker types were measured on sample boards and compared in 0 mm, 1mm and 2 mm planing depths. The L* values that were measured are presented in average values. The L* value of 0 corresponds to black and the L* value of 100 denotes white color. (Minolta 1993)

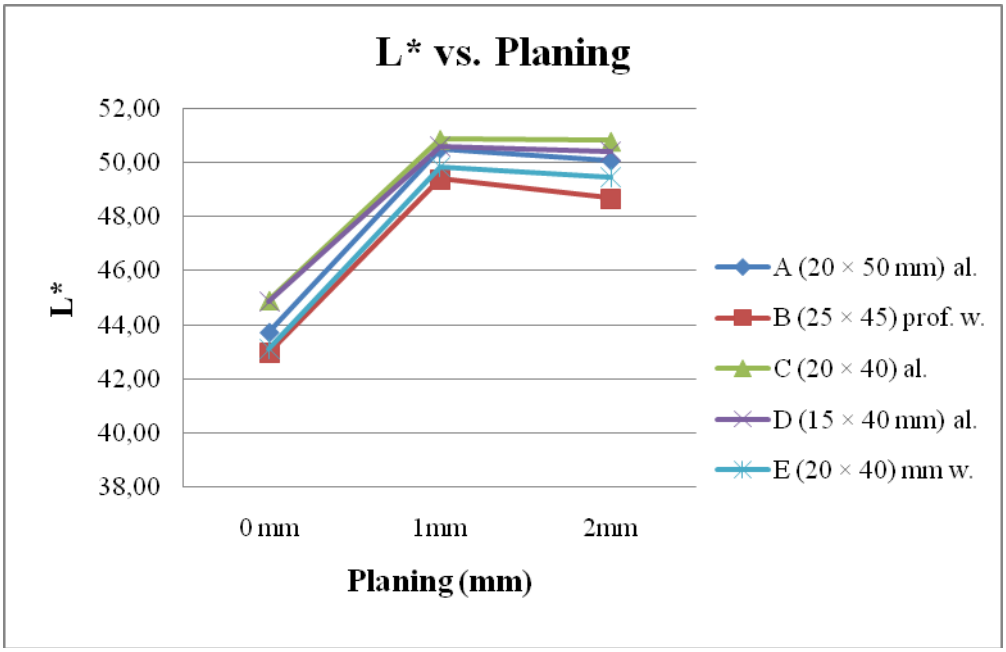

Figure 36 **The comparison of average L* values of underneath sticker zones in different planing depths.**

The average value for L*(lightness) of heat treated wood in different planing depths is shown in table 9 to be able to make comparison with the L* values of underneath sticker zones which are shown in table 10.

Table 8 **The average lightness values of reference zones in 0 mm (not planed), 1mm and 2 mm planing depths**

Av. L(0 mm pl. wood surface)*	*Av. L* (1 mm pl. wood surface)*	*Av. L* (2 mm pl. wood surface)*
46, 03	49, 95	50, 57

Table 9 **L* values of underneath sticker zones of different sticker types in different planing depths**

St. Type	*L* (0 mm pl.)*	*L* (1 mm pl.)*	*L* (2 mm pl.)*
A (20 × 50 × 1200 mm aluminum)	43,73	50,49	50,06
B (25 × 45 × 1200 mm profiled w)	42,96	49,39	48,67
C (20 × 40 × 1200 mm aluminum)	44,90	50,85	50,79
D(15 × 40 × 1200 mm aluminum)	44,86	50,60	50,40
E (20 × 40 × 1200 mm wood)	43,11	49,83	49,44

In rough (not planed phase), the comparison of lightness values of under sticker zones of 5 different sticker types show that the variation of L* was in the range of 42, 96 and 44, 90 units and all of these values are lower than heat treated wood's lightness value.

The highest value of L* which corresponds to lightest color for underneath sticker zones belonged to 20 × 40 × 1200 mm dimensioned aluminum (type C) stickers. This value was very close to 15 × 40 × 1200 mm dimensioned aluminum (type D) stickers, the difference was just 0, 04 units.

The lowest value of L* which corresponds to relatively darkest color for underneath sticker zones belonged to 25 × 45 × 1200 mm dimensioned (type B) stickers. This value was approximately 2 units lower than highest L* value.

In 1 mm planed phase, it was observed that L* values increased significantly due to planing process. The increase in L* values of underneath sticker zones were 6, 32 units in average after1 mm planing. The variation of increase was within the range of 5, 74 and 6, 76 units.

The highest L* value of 50, 85 after 1 mm planing, belonged to zones where 20 × 40 × 1200 mm dimensioned aluminum (type C) stickers were used on.

The lowest L* value of 49, 39 after 1 mm planing belonged to zones where 15 × 40 × 1200 mm dimensioned aluminum (type C) stickers were used on.

In 2 mm planed phase, it was observed that there were not significant differences in L* values of under sticker zones of different sticker types. The L* values varied within the range of 48, 67 and 50, 79 units. The average L* difference between 1 mm and 2 mm planed phases regarding under sticker zones of different sticker types was 0, 36 units.

4.2.8.2 Evaluation of C (Chroma) regarding Planing Process*

The color component C* (saturation) belonging to sticker stains that were measured on sample boards were compared for 5 different sticker types in 0 mm, 1mm and 2 mm planing depths. The C* values that were measured are presented in average values. An increase in chroma value corresponds to more saturation in color. (Minolta 1993)

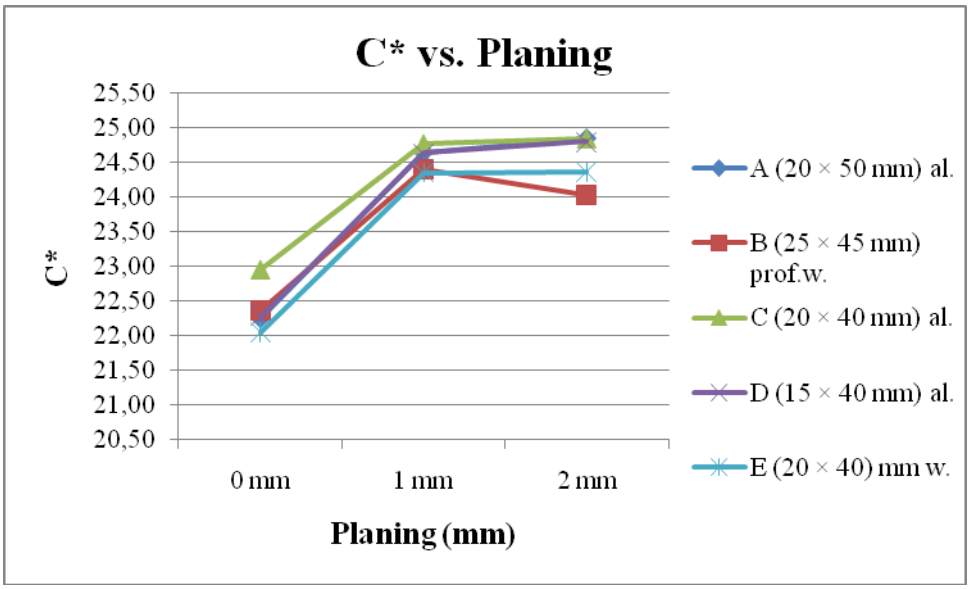

Figure 37 **The comparison of average C* values of underneath sticker zones in different planing depths.**

The average value for C* (chroma) of heat treated wood in different planing depths is shown in table 11 in order to make comparison with the C* values of underneath sticker zones which are also shown in table 12.

Table 10 **The average chroma values of reference zones in 0 mm (not planed), 1mm and 2 mm planing depths.**

Av. C(0 mm pl. wood surface)*	*Av. C* (1 mm pl. wood surface)*	*Av. C* (2 mm pl. wood surface)*
23, 97	24, 51	24, 88

Table 11 **C* values of underneath sticker zones of different sticker types in different planing depths.**

St. Type	*C* (0 mm pl.)*	*C* (1 mm pl.)*	*C* (2 mm pl.)*
A (20 × 50 × 1200 mm aluminum)	22,25	24,64	24,85
B (25 × 45 × 1200 mm profiled w)	22,36	24,40	24,03
C (20 × 40 × 1200 mm aluminum)	22,96	24,77	24,85
D(15 × 40 × 1200 mm aluminum)	22,28	24,63	24,80
E (20 × 40 × 1200 mm wood)	22,06	24,34	24,36

In rough (not planed phase), the comparison of chroma values of underneath sticker zones of 5 different sticker types show that the variation of C* was in the range of 22, 06 and 22, 96 units.

It was observed that the chroma values of all underneath sticker zones belonging to 5 sticker types had an increase of approximately 2 units after 1 mm planing the rough heat treated wood surface.

There was not a significant change in C* after 2 mm planing for under sticker zones when they were compared to C* values of 1 mm planed phase. The variation of change was within the range of 0, 01 and 0, 37 units.

4.2.8.3 Evaluation of h (hue angle) regarding Planing Process

The color component h (hue angle) belonging to sticker stains that were measured on sample boards were compared for 5 different sticker types in 0 mm, 1mm and 2 mm planing depths. The hue values that were measured are presented in average values. The hue angle of 0 □ corresponds to +a*(red), 90 □ corresponds to +b* (yellow), 180 □ corresponds to –a* (green) and 270 □ corresponds to –b* (blue). (Minolta 1993)

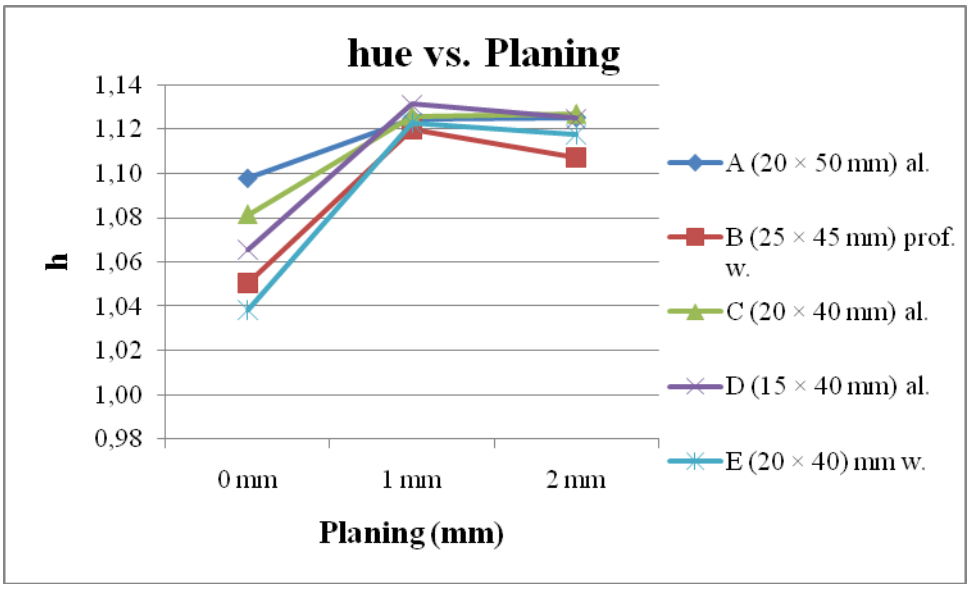

Figure 38 **The comparison of average hue values of underneath sticker zones in different planing depths.**

The average value for h (hue) of heat treated wood in different planing depths is shown in table 13 in order to make comparison with the hue values of underneath sticker zones.

Table 12 **The average hue values of reference zones in 0 mm (not planed), 1mm and 2 mm planing depths.**

Av. h (0 mm pl. wood surface)	*Av. h (1 mm pl. wood surface)*	*Av. h (2 mm pl. wood surface)*
1, 08	1, 12	1, 13

Table 13 **Hue angle values of under sticker zones of different sticker types in different planing depths**

St. Type	*h (0 mm pl.)*	*h (1 mm pl.)*	*h (2 mm pl.)*
A (20 × 50 × 1200 mm aluminum)	1,10	1,12	1,13
B (25 × 45 × 1200 mm profiled w)	1,05	1,12	1,11
C (20 × 40 × 1200 mm aluminum)	1,08	1,13	1,13
D(15 × 40 × 1200 mm aluminum)	1,07	1,13	1,12
E (20 × 40 × 1200 mm wood)	1,04	1,12	1,12

In rough (not planed phase), the comparison of hue angles of underneath sticker zones of 5 different sticker types show that the variation of hue was in the range of 1, 04 and 1, 10 degrees.

It was observed that the hue values of all underneath sticker zones belonging to 5 sticker types had an increase of approximately 0, 06 degrees after 1 mm planing the rough heat treated wood surface.

There was not a significant change in hue angle values after 2 mm planing depth when they were compared to 1 mm planing depth values. The variation of change was within the range of 0, 01 degrees.

*4.2.8.4 Evaluation of Color Difference ΔE*ab regarding Planing Process*

5 different types of stickers were compared with each other regarding size of the stains that they had left on sample boards. This comparison was carried out for subsequently increasing planing depths.

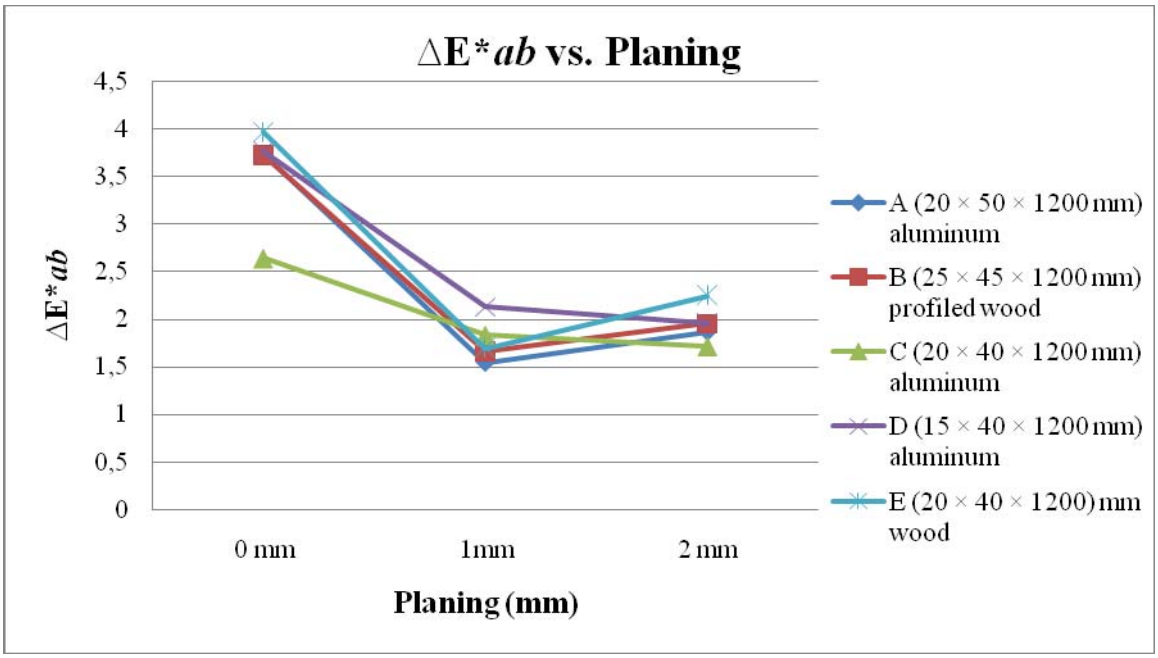

Figure 39 **The comparison of discolorations due to 5 sticker types on sample boards in terms of color differences on three different planing phases.**

Table 14 **The size of the color differences due to different sticker types throughout the whole stack.**

St. Type	*ΔE*ab (0 mm pl.)*	*ΔE*ab (1 mm pl.)*	*ΔE*ab (2 mm pl.)*
A (20 × 50 × 1200 mm al.)	3,73	1,54	1,87
B (25 × 45 × 1200 mm prof. w.)	3,72	1,66	1,95
C (20 × 40 × 1200 mm al.)	2,64	1,83	1,71
D(15 × 40 × 1200 mm al.)	3,76	2,12	1,95
E (20 × 40 × 1200 mm w.)	3,97	1,69	2,25

In the rough phase, the color difference values varied within the range of 2, 64 and 3, 97 units. The least color difference belonged to 20 × 40 × 120 mm dimensioned aluminum (type C) stickers with a size of 2, 64 units. This value was approximately 1 unit less than the other sticker types' color difference values. The other 4 sticker types had close ΔE*ab values within the range of 3, 73 and 3, 97 units.

In 1 mm planing depth, it was observed that all the color differences had decreased significantly. The average decrease in ΔE*ab for 5 sticker types was 1, 79 units. The least change in color difference in terms of a decrease belonged to 20 × 40 × 120 mm dimensioned aluminum (type C) stickers with 0, 81 units.

For 1 mm planing depth, all the color differences between sticker underneath zones and reference zones on heat treated wood were rather low values; varying within the range of 1, 54 and 2, 12 units.

The highest ΔE*ab value belonging to 15 × 40 × 1200 mm dimensioned aluminum (type D) stickers was 2, 12 units. The other 4 sticker types had very close ΔE*ab values within the range of 1, 54 and 1, 83 units.

In 2 mm planed phase, all the sticker types except for the 20 × 40 × 1200 mm dimensioned wood (type E) stickers, the color difference ΔE*ab values were within the range of 1, 71 and 1, 95 units. The color difference size was 2, 25 units for type E stickers.

In the mean time, it was observed that there were slight increases in ΔE*ab values of 20 × 50 × 1200 mm dimensioned aluminum (type A), 25 × 45 × 1200 mm dimensioned wood (type B), and 20 × 40 × 1200 mm dimensioned wood (type E) stickers. The numerical values of these slight increases were 0, 32 units, 0, 29 units and 0, 56 units respectively.

The change in ΔE*ab values of different sticker types between 1 mm planing and 2 mm planing depths was found within the range of 0, 12 and 0, 56 units.

4.3 Multivariate Analysis

First, a PCA-X analysis was conducted to obtain an overview of the collected data. The variables were layer number, board number, sticker type, measurement position, on/off sticker (whether there was a sticker or not for that measurement position), planing depth, temperature, L*, C*, h and ΔE**ab*.

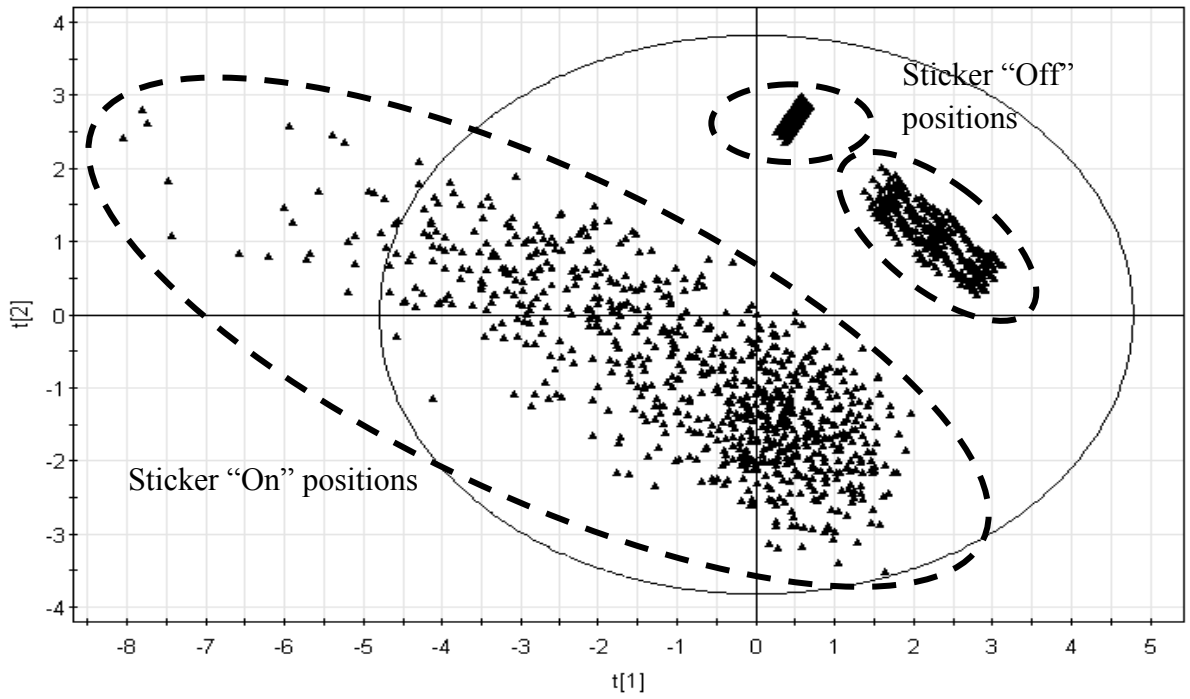

Figure 40 **The score scatter plot of the PCA-X analysis of whole data set.**

In the first PCA-X model including all variables, the score scatter plot showed that groupings on the graph were reflecting the measurement positions. The reference positions which were defined as" not sticker placed zones" (sticker off) formed a swarm of dots and measurement positions which were defined as "underneath sticker zones" (sticker on) showed another swarm of dots. These swarm of dots as clouds are shown in figure 40.

The goodness of fit R^2X value was 0, 6 and the goodness of prediction Q^2X value was 0, 4 for the model.

Further multivariate analysis continued with excluding the reference position (the “sticker off”) observations from dataset. Afterwards the loading scatter plot had one principal component which is shown in figure 41.

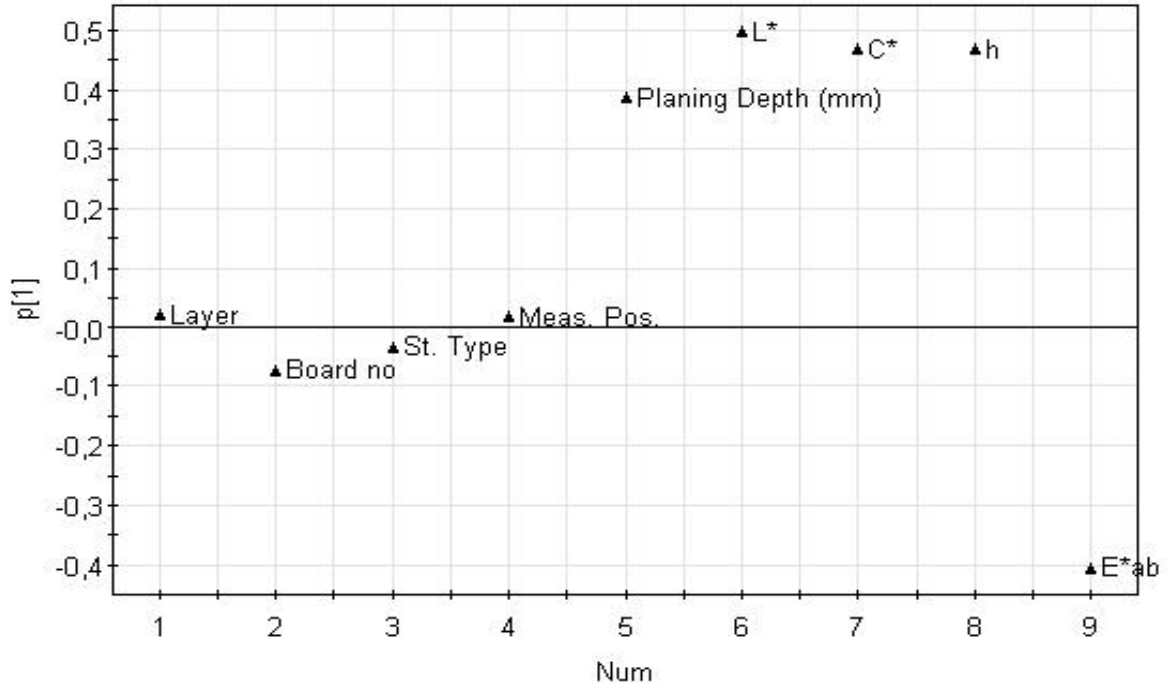

Figure 41 The loading scatter plot of the PCA analysis.

It was interpreted that layer, board number, sticker type and measurement position variables were weak variables and they had less influence on the model; since they were very close to origo.

However, the color difference variable ΔE*ab, L*, C*, h and planing depth were strong variables and they had more influence on the model.

The interpretation of the loading plot was that layer and measurement positions were the weakest variables. Besides, the sticker types and board number were weak variables, as well.

E*ab which was referred as the “color difference” was negatively correlated with planing depth, L*, C* and h variables. The planing depth was positively correlated with L*, C* and h variables. Also, an increase in planing depth would result in higher L*C* and h values.

After PCA analysis of the data, a PLS analysis was also conducted on whole data set which is shown in figure 42.

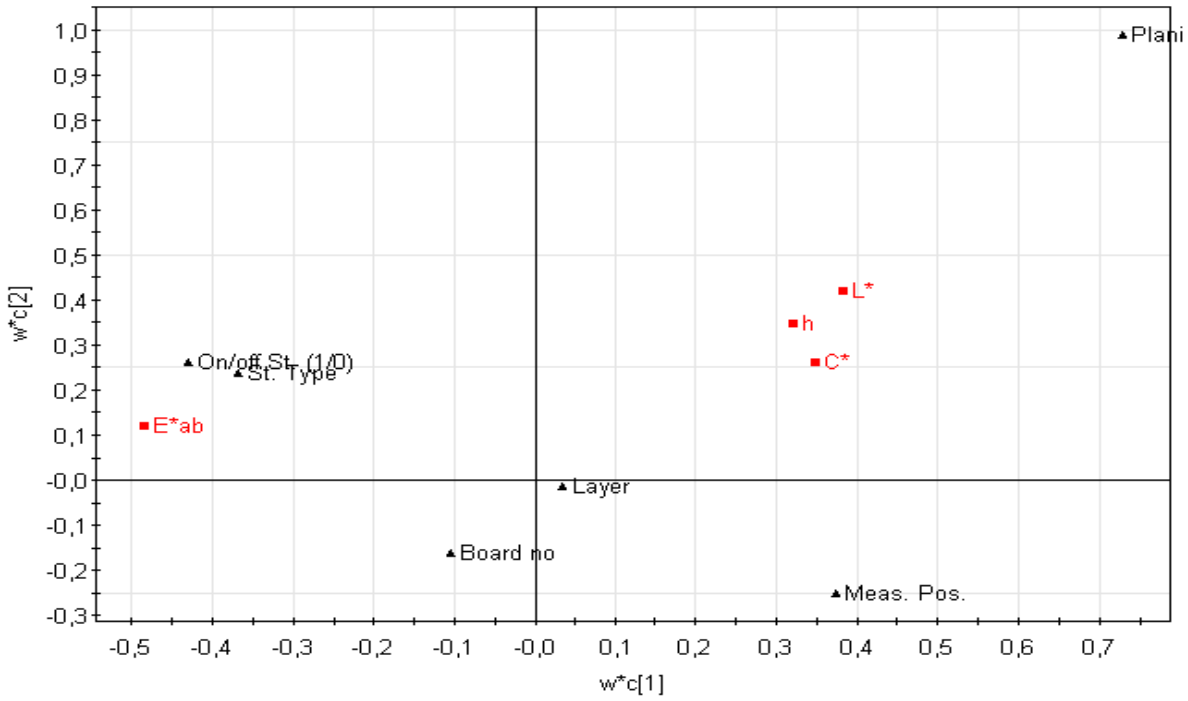

Figure 42 **The PLS weight plot, whole data set.**

The L*, C*, h and E*ab as "color difference" were set Y variables, so called as responses. And on/off sticker, sticker type, board number, layer, measurement position and planing depth were set as X variables, so called as "factors".

It is interpreted from the graph that layer and board number are weak variables and L*, C* and h are correlated with each other. It is also observed that planing variable which is positively correlated to L*, C* and h variables. In the mean time, the planing variable is also negatively correlated to E**ab* color difference. An increase in planing depth would result a decrease in color difference.

The goodness of fit R^2X value was 0, 5 and the goodness of prediction Q^2X value was 0, 3 for the model.

4.4 Economical Analysis

4.4.1 Interviews

Company 1

- Current sticker type in use was square aluminum with 1 mm thickness and 15 mm side dimension.
- The sufficient planing depth for ThermoWood varied within 1 mm to 4 mm. The average planing depth applied was 2, 5 mm.
- Regarding the use, the company utilizes both automatic and manual separation for stickers.
- The opinion for the lifetime of aluminum stickers was 3 to 5 years. These type of stickers were said to endure more than hundreds of times.
- The selection between wood and aluminum stickers was in the favor of aluminum stickers. The reasons for this decision are underlined as follows:

a. Wood stickers were said to leave more stains by means of lighter color tones than the heat treated wood color. This issue was said to be correlated with better heat conductivity of aluminum than wood as a material type.

b. Wood stickers were said to get damaged after one use. Most of the damages were said to occur not in heat treatment process but, during handling of the stickers.

c. The cost of the wood stickers would be much more than the aluminum ones due to onetime use. So, the wood stickers would need to be renewed after each process.

Company 2

- Current sticker type in use was spruce wood with dimensions of 28 × 50 × 1750 mm. High quality pine wood stickers (without knots) were tested as well, but the company gave up this implementation due to high cost reason.
- The sufficient planing depth for ThermoWood was 3 mm for each side of the board.
- The company utilizes automatic separation for stickers.
- The opinion for the lifetime of the wood stickers dependent on automatic separation machinery and sawmill processes. Therefore, they were using wood stickers for one time. It is said that, if sticker installation process were made manually, 3 or 4 time use for wood stickers could have taken place.
- The selection between wood and aluminum stickers was dependent on sticker installation and sawmills processes. If the company intended to use aluminum stickers now, it would be in need of one separate sticker installation machine.
- In this interview, the importance of stickers was emphasized as a major cost in ThermoWood production.

Company 3

This company was a member of ThermoWood Association, but they were not currently having production in ThermoWood branch. The company was following the progress in ThermoWood production techniques and applying some tests for production in near future.

Company 4

This company was the only one which was not a member of ThermoWood Association. As a matter of fact, they had similar process techniques of high temperature treatment techniques like in ThermoWood process. However, interview questions could not be answered due to industrial secrecy policy of the company.

Company 5

This interview and discussion was important in terms of understanding the kiln operating regulations related to stickers. The key points that have come up were lined as follows:

- Constructions of kilns were regulated for pressure and sticker thickness was one of the parameters which affected the air circulation in kilns. The risks due to pressure could be malfunctions in kiln and fire risk.

- Thinner sticker choice would affect the power that is spent and the operating parameters of the kiln such as; air velocity and therefore air circulation and after all, the pressure that occurs in the kiln chamber.

- In the end, quality of the end product could also get affected.

4.4.2 Cost Estimation for Wood and Aluminum Stickers

Approximate cost estimation was made for wood and aluminum stickers in short and long time utilization periods totally covering 5 years. It was estimated to be 100 runs for each year considering maximum production capacity and in the beginning of 101st run, aluminum stickers were supposed to be renewed. However, the possible increases in sticker material prices were neglected for these cost estimations. The sticker dimensions, costs and relative life spans are shown in table 16. The total number of stickers that would be required for heat treatment process was considered to be 1200 for all sticker types.

Table 15 **The parameters that were taken into notion for cost estimation calculations. The thickness of all aluminum stickers was 2 mm.**

St. Type and Dimensions (mm)	*Cost (SEK)*	*Lifespan (Runs)*	*Total number of Stickers*
Type D (15 × 40 × 1200) al.	40, 80	101	1200
Type C (20 × 40 × 1200) al.	45, 60	101	1200
Type A (20 × 50 × 1200) al.	54, 00	101	1200
Type B (25 × 45 × 1200) p. w.	7, 20	5	1200
Type E (20 × 40 × 1200) w.	3, 50	6	1200

The cost comparison of 5 different sticker types is shown in figure 43.

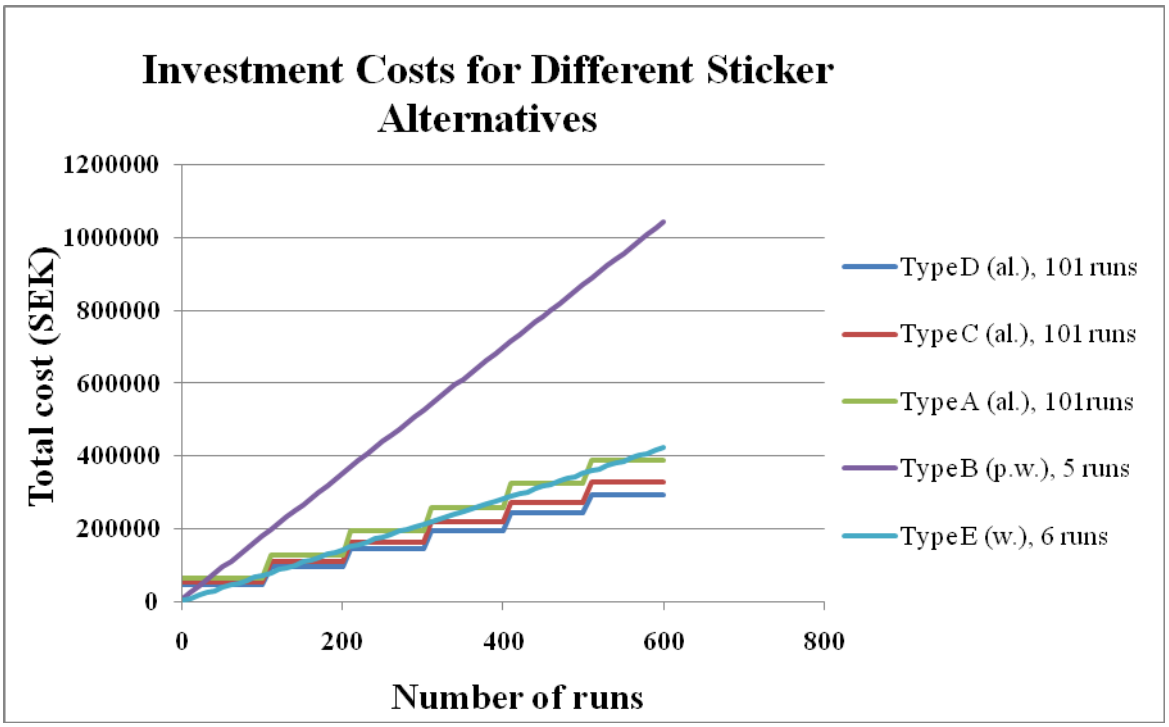

Figure 43 **The comparison of investment costs of wood and aluminum stickers.**

In the beginning, sticker purchasing costs for wood sticker types were less than aluminum sticker types due to less initial price of the wood material when it was compared to aluminum material. The wood sticker costs which were expressed in purple and light blue colors situated below the aluminum sticker cost lines highlighted in green, red and dark blue colors until the 35th run for "Type B" profiled wood sticker and 61st run for "Type E" wood stickers. The cost of "Type E" wood stickers exceeded the cost of the "Type D" aluminum stickers after 61st run and "type C" aluminum stickers after 71st run and the highest cost having "Type A" aluminum stickers after 85th run.

At the end of the first year, the highest cost belonged to "Type B" profiled wood sticker with 181 440 SEK and the lowest cost belonged to "Type D" aluminum stickers with 48 960 SEK. As a comparison, "Type E" wood stickers which have more common use in industry currently had a cost of 71 400 SEK which was 6 600 SEK more than the highest cost having aluminum sticker "Type A".

In the beginning of the second year, new aluminum stickers were purchased and the cost difference between wood and aluminum stickers were having the least cost differences between each other when they were compared in the further runs for following years. At this point, it also has to be stated that this least cost difference corresponded to 18 120 SEK between "Type D" aluminum sticker and "Type E" wood sticker type where "Type E" wood sticker did cost less after 10 run in second year.

As the runs had continued and at the end of 2nd year had been reached, it was calculated that the least unit cost having wood sticker "Type E" had 13 200 SEK more cost than the highest

cost having aluminum sticker “Type A”. At this point it also has to be noticed that the cost of “Type B” profiled wood stickers had reached a value of 354 200 SEK which was much more than the other sticker types’ costs.

After the end of the 2nd year, in the beginning of 3rd year, the cost of “Type E” wood stickers were already higher than “Type D” aluminum stickers, but lower than “Type A” and “Type C” aluminum stickers respectively for 10 and 70 runs. The cost of the wood stickers became more than aluminum sticker types except “Type A” stickers at the end of 3rd year, as it can be visually grasped with the graph in figure 43 and cost comparison table 17.The detailed sticker costs for further runs and years are listed from least to highest values in SEK covering 5 years time period in table 17.

Table 16 **The cost comparison of different sticker types in 5 years period. The costs are ordered from least to highest values regarding the end of each year in Swedish Krons.**

	Sticker Types and Dimensions(mm)	***1 year (SEK)***	***2 years (SEK)***	***3 years (SEK)***	***4 years (SEK)***	***5 years (SEK)***
1.	Type D (15 × 40 × 1200) al.	48 960	97 920	146 880	195 840	244 800
2.	Type C (20 × 40 × 1200) al.	54 720	109 440	164 160	218 880	273 600
3.	Type A (20 × 50 × 1200) al.	64 800	129 600	194 400	259 200	324 000
4.	Type E (20 × 40 × 1200) w.	71 400	142 800	214 200	281 400	352 800
5.	Type B (25 × 45 × 1200) p.w.	181 440	354 240	527 040	699 840	872 000

5. Discussion

5.1 Chemical Analysis

5.1.1 Sticker Stain Formation

The issue of sticker stain formation in timber drying processes is inevitable regardless of treatment method. This issue can well be observed both for conventional kiln drying or modern heat treatment processes. As a matter of fact, after drying process, when stickers are removed from the wood stack layers; the color of wood surfaces underneath and adjacent to sticker zones are different from each other. This issue was also observed in this work, on all sample boards regardless of sticker type. In this case, it did not matter whether the sticker was aluminum or wood. Furthermore, the dimensions of the stickers were just affecting the size of the sticker stains.

The stickers are somehow affecting the drying process for the locations that they are placed. Presumably, stickers create both physical and chemical phenomenon within the contact zones that they interact on wood surface. The study of Terziev and Boutelje (1998) shows that Low Molecule Weight Sugars concentration for sticker adjacent zones were 3.55 times as high as the content of concentration within the sticker zones. And the corresponding value for nitrogen was 2.62.

At this point, the study of Terziev and Boutelje which states the difference in concentration of Low Molecule Weight sugars between sticker underneath and adjacent zones is found partially related to the digital image shown in figure 44, which is from a technical report study of Nilsson and Samuelsson (2006). In their study they state that the concentration of Low Molecule Weight sugars were in favor of mould growth.



Figure 44 **Mould growth is not observed on wood boards for the zones where presumably stickers had been placed for drying. (Photograph from study of Nilsson and Samuelsson 2006)**

In figure 44, mould growth and spread is shown by a photograph on kiln dried wood boards which were used underneath a cold ventilated roof. Interestingly, the mould growth and spread is not observed for the zones where presumably, stickers were placed for drying process. The interpretation of this image can point out the possible migration of water soluble substances to sticker adjacent zones that helps mould growth. Figure 44, also shows possible lack of nutrition for mould growth, especially for underneath sticker zones. The stickers possibly prohibit the evaporation of the water soluble substances and extractives within the zone that they are placed on which are referred as contact zones. Here, it also has to be pronounced that these boards which are shown in figure 44 were not heat treated boards like in ThermoWood process, they were kiln dried boards.

The mould growth and the circumstance of growth is possibility related to the abundance of nutrition and in this case, under sticker zones possibly show less amount of Low Molecule Weight sugars which are essential for mould growth. In figure 45, a digital image from study of Sehlstedt-Persson (2008), shows another example of mould growth on wood boards that were used in an unheated outdoor space. In this figure, it is again observed that the mould growth has not taken place on the zones where presumably stickers had been placed for drying.



Figure 45 **Mould stained wood boards that are used in an unheated outdoor space. The growth of mould is not observed for the zones where presumably stickers had been placed for drying process. (Photograph by Mats Ekevad 2007 and from study of Sehlstedt-Persson 2008)**

Previously discussed issues related to sticker stain formation were regarding use of conventionally kiln dried timber. There is an example of sticker stain problem that was met in study of Forsman (2008) where a concept house was developed and built by heat treated timber. The wood material that was going to be used for cladding had some problems after planing process. One of these problems related to this study was sticker stains. In Forsman's study this problem was pronounced as sticker marks. Forsman (2008) refers the cause of this problem due to probable thermal resistance of wood stickers that were used in heat treatment process. The figure 46 shows the sticker stains that were observed after the planing process in Forsman's study.



Figure 46 **The sticker stains are observed after planing process in lighter color tones than the heat treated timber. These boards were dried regarding Thermo-Stability product terms. (Photograph from study of Forsman 2008)**

The same kind of problem by means of observing sticker stains after planing process was not met at all in this study, except few examples. Visual examinations were made regularly by the author before and after planing processes on sample boards to inspect whether planing process vanished sticker stains from wood surface or not. During these examinations, it was observed that few of the sample boards had sticker staining in light color tone than the heat treated wood. Interestingly, these locations were not sticker placed zones for heat treatment process. It was quite sure that no sticker was placed for this position for ThermoWood process due to the reason that all the sticker positions were marked throughout the wood stack prior to planing processes and the stickers had not been removed until the materials' investigation started in campus Skellefteå by the author.

In figure 47, a sticker stained wood sample is shown before planed phase where no sticker was placed for ThermoWood process. And figure 48 shows another wood sample which had sticker stain remained after 2 mm planing process.



Figure 47 **The sticker stain that was observed between wood and aluminum stickers. The stain in the middle is most probably due to a sticker that was used in kiln drying process prior to the ThermoWood process.**



Figure 48 **The evident sticker stain after 2 mm planing process. This mark possibly could have generated because of a sticker that was used in kiln drying process.**

The sticker stain on 2 mm planed wood sample which is shown in figure 48, might be due to staining of wood in conventional kiln drying. This is the phase of drying wood from approximately 80% moisture content to 18% moisture content prior to ThermoWood process.

This image is also interesting that the sticker stain is more visible on sapwood than heartwood part of the board. Since, stickers prohibit the evaporation of water soluble substances within the contact zones that they are placed on; the nutrients and water soluble substances which are higher concentrated in sapwood might have migrated to sticker adjacent zones. Thus, relatively lighter color on sapwood part than heartwood part incident could have taken place. This issue needs to be investigated separately with increased sample numbers to be understood better.

5.1.2 pH Acidity Test

The results of the pH test showed that both for aluminum and wooden stickers, the pH values of underneath sticker zones were lower than the pH values of heat treated wood and sticker adjacent zones. The amount of the pH difference for underneath and adjacent sticker zones was higher for wooden stickers.

The results also indicate that the pH differences were not significant between sticker underneath and adjacent zones when they were compared with the pH value of heat treated wood. This case was valid for samples where both aluminum and wood stickers were used. The pH values varied within 4, 13 and 4, 61 and pH differences that were measured varied within the range of 0, 10 and 0, 48. The detailed measured pH values are shown in table 3.

In general, all the measured pH values were around 4 units showing acidity properties for wood samples regardless of measurement positions. This low pH values around 4 units were similar to the pH values that were measured in study of Windeisen et al. (2007) where chemical changes of thermally treated beech samples were investigated at temperatures over 180 □ C to 219 □ C. The study of Ayadi et al. (2003) also indicates increase in acids products

during heat treatment of ash, beech, maritime pine and poplar at 240 □ C for 2 hours duration under nitrogen shielding.

The drawback of this pH test can possibly be the sampling of wood tissues from wood surface. The primary reason is that the wood tissue where discolorations were observed is a very thin layer. Regarding the experience from planing process, it is assumed that this layer which consists of the sugars and extractives that have migrated towards surface during drying is thinner than 1 mm. Therefore, sufficient amount of sample collecting from this very thin layer was a hard task. By this means, while scraping the discolored zones; regular heat treated wood tissues without sticker stains might have been scraped which in the end could have influenced the results. In order to have more solid and reliable results more samples are needed for an extended analysis.

5.2 Physical Analysis

5.2.1 Color measurements and Digital Images

In this study, ThermoWood sample board surfaces were analyzed both by colorimetric measurements and digital images in subsequently increasing planing depths. The numerical measurements of ΔE^*ab values were tried to be supported with the digital images in order to establish better visual perception for sticker stains. Another intention was to show that how sticker stains could vary in terms of darker and lighter colors on heat treated wood surface.

The results indicate that human eye can detect the discolorations due to stickers best for rough phase (not planed wood surface) measurements. It would probably be hard to distinguish the color differences on 1 mm and 2 mm planing depths on sample boards unless a visual assessment tool of colorimeter device would not have been utilized for color measurements.

In general, the color measurements that were made on sample boards with colorimeter device were effective to determine the size of the sticker stains by numerical quantities. However, in some cases, the head of the colorimeter device could not manage to measure the sticker stained locations on sample boards. The circular shape of the device was not sufficient in diameter to measure the stains on the edges of the sample boards.

The studies which were cited through literature showed that colorimetric measurements were useful in explaining the color changes in wood either for drying or related to some other discolorations. The study of Andoh-Dawson et al. (2004) shows that the utilization of colorimetric measurements was in good agreement with visual grading of discolored maple lumber. The study of Riley and Sargent (2005) also shows that the use of L* a* b* color space for the assessment of kiln brown stain had been successful.

Furthermore, the study of Brischke et al (2007) suggests utilization of color measurements for an application like quality control of thermally modified timber. These studies show the wide variety of application areas for color measurements. In addition, the color measurements and the changes in wood color are studied for the relevancies of alterations in material properties. In study of Bekhta and Niemz (2003), the changes in color of Spruce wood were associated with strength properties. Another study by Johansson and Moren (2006) had also investigated

correlation between the color changes of heat treated birch wood and reduction in strength properties where it was also found that color measurements were not suitable for strength prediction.

5.2.2 Comparison of Sticker Stains on Each Layer of the Wood Stack in subsequently increasing Planing Depths

The colorimetric measurements that were made on sample boards covering 15 layers of the wood stack showed highest color difference ΔE^*ab values for rough (not planed) phase. The results showed that color differences due to sticker stains decrease significantly after 1 mm planing the wood surface for all layers regardless of the sticker type.

From not planed phase to 1 mm planing depth, the highest change in size of ΔE^*ab values, in a way of decrease belonged to layer 15 with 2, 98 units where $20 \times 50 \times 1200$ mm dimensioned aluminum (type A) stickers were used.

From not planed phase to 1 mm planing depth, the least change in the size of ΔE^*ab values, in a way of decrease belonged to layer 3 with 0, 33 units where $20 \times 40 \times 1200$ mm dimensioned aluminum (type C) stickers were used.

Further planing process with 2 mm planing depth did not show significant color difference changes for the sticker stains when the ΔE^*ab values were compared between 1 mm and 2 mm planing depths. This issue pointed out that most of the discolorations due to sticker stains had vanished after 1 mm planing process. As a matter of fact, further planing with 2 mm planing depth, the wood surfaces were planed more evenly; for example, if the edges or the center parts of the boards were not touched uniformly by cutting blades due to little amount of cupping; these zones will be planed properly by applying 2 mm or more in planing depth. The detailed color difference measurements on sample boards for each layer regarding 0 mm, 1 mm and 2 mm planing depths are shown in table 8, in results section of the study.

5.2.3 Investigation of Sticker Stains' Degree of Severity through Layers of the Wood Stack

Prior to the analysis of the wood samples, during the planning phase of the project, the load factor by means of pressure applied on boards was in interest to inspect. Since, the sticker stains were most visible and detectable for rough (not planed) phase. It was assumed that the size or severity degree of the sticker stains could have tendency to increase through lower layers of the stack due to increased pressure related to load. The results showed that there was not an increasing or decreasing phenomena in severity degree of sticker stains regarding the sample boards' location in the stack. The size of the sticker stains by means of ΔE^*ab values are shown in figure 49 throughout different layers in the stack for rough phase.

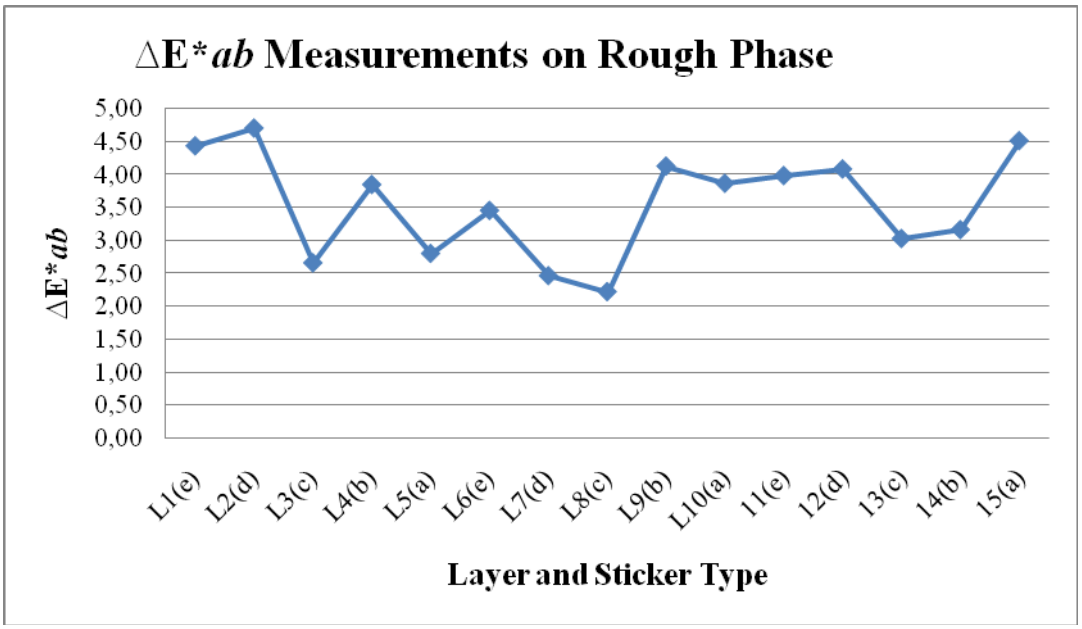

Figure 49 **The figure shows the ΔE*ab color differences in terms of sticker stains on each level throughout the wood stack.**

It is observed from the graph in figure 49 that no distinctive trend has occurred related to sticker stain degree of severity in different layers of the whole stack. The line explaining the color difference variation is quite irregular. However, it is also observed from the graph that color difference related to sticker staining is decreasing towards the middle of the stack while the load factor is probably increasing. As a matter of fact, the color difference has the least value in the middle layer, number 8 and afterwards increasing towards the bottom layers where load factor probably has more effect. Finally, the assumption of an increase has not been observed in color measurements for lower layers of the stack. Since, 1st and 2nd layers seem to be two of the highest color difference values measured where the load factor had the least influence on the stack.

5.2.4 The Evaluation of Sticker Stains on Sample Boards in terms of L* C* h and ΔE*ab Values regarding Planing Process

In this part, the results of the color measurements that were made on sample boards in terms of L* C* h and ΔE*ab values and their relation with planing process is discussed. The color component L* is useful by means of explaining color due to fact that L* value of 0 corresponds to black color and 100 corresponds to white color. Furthermore, an increase in chroma value corresponds to more saturation in color. And the hue angle of 0 □ corresponds to +a*(red), 90 □ corresponds to +b* (yellow), 180 □ corresponds to –a* (green) and 270 □ corresponds to –b* (blue). (Minolta 1993)

5.2.4.1 Evaluation of L (Lightness) regarding Planing Process*

The results of the color measurements showed that L* (lightness) was the color component which had affected most by planing process. The change in color component L* of wood and aluminum sticker stains due to planing process was in a way of increase between rough phase and 1 m planed phase. The L* values that were measured underneath of all sticker types showed an increase of approximately 6, 00 units after 1 mm planing. However, there were not

significant changes observed in L* values of wood and aluminum sticker stains between 1 mm and 2 mm planing depths, as it was observed between not planed and 1 mm planed phase.

In general, for not planed phase, sticker stains due to wood and aluminum stickers had lower L* values which corresponds darker colors on sample boards when they were compared with the L* value of reference zones. The color component L* for the heat treated spruce at 212 □ C described as reference zones in this study had similar L* values with the heat treated pine example shown in ThermoWood Handbook (2004).

The comparison of wood and aluminum stickers by means of less stain degree in terms of L* (lightness) was relatively in favor of the aluminum stickers for rough phase with an approximately 1 unit difference. The detailed L* values of underneath sticker zones and reference zones were shown in tables 10 and 11, in results section.

5.2.4.2Evaluation of C* (Chroma) regarding Planing Process

The chroma values measured underneath of wood and aluminum stickers were not significantly different from each other for 0 mm, 1 mm and 2 mm planing depths. It was for the rough phase that chroma values of underneath sticker zones had lower values than reference zones. The results of the color measurements also showed that C* (chroma) values of underneath sticker zones belonging to 5 sticker types had an increase of approximately 2 units after 1 mm planing the rough heat treated wood surface. There was not a significant change in C* after 2 mm planing for underneath sticker zones when they were compared to C* values of 1 mm planing depth. The variation of change was within the range of 0, 01 and 0, 37 units. The detailed C* values of underneath sticker zones and reference zones were shown in table 12 and 13, in results section.

5.2.4.3 Evaluation of h (hue) regarding Planing Process

The hue values measured underneath of wood and aluminum stickers were not significantly different from each other for 0 mm, 1 mm and 2 mm planing depths. The results of the color measurements showed that h (hue) values of underneath sticker zones belonging to 5 sticker types had an increase of approximately 0, 06 degrees after 1 mm planing the rough heat treated wood surface. There was not a significant change in hue after 2 mm planing for underneath sticker zones when they were compared to hue values of 1 mm planing depth. The variation of change was within the range of 0, 01 degrees. The detailed hue values of underneath sticker zones and reference zones were shown in table 14 and 15, in results section.

5.2.4.4 Comparison of Different Sticker Types' Stains on Sample Boards in terms of Color Difference ΔE*ab Values regarding Planing Process

The color differences that were measured between reference zones and underneath sticker zones by means of ΔE*ab values in different planing depths are shown in table 18. The size of color difference that can be detected by human eye is approximately 2-3 units. (Sundqvist 2004)

Table 17 **The average size of the color differences that were measured on ThermoWood boards that belongs to different sticker types are shown in subsequently increasing planing depths.**

St. Type	*ΔE*ab (0 mm pl.)*	*ΔE*ab (1 mm pl.)*	*ΔE*ab (2 mm pl.)*
A (20 × 50 × 1200 mm al.)	3,73	1,54	1,87
B (25 × 45 × 1200 mm prof. w.)	3,72	1,66	1,95
C (20 × 40 × 1200 mm al.)	2,64	1,83	1,71
D(15 × 40 × 1200 mm al.)	3,76	2,12	1,95
E (20 × 40 × 1200 mm w.)	3,97	1,69	2,25

The results of the colorimetric measurements showed that the sticker stains were most evident or detectable on rough (not planed) wood surface, in this case detectable for human eye. The color differences that were measured on wood samples regarding rough phase was highest for E sticker type (wood) and lowest for C (aluminum) sticker type. C sticker type has left approximately 1 unit lower staining than the other sticker types on ThermoWood boards that were analyzed in this work. But, there was not a significant difference in degree of stains due to different sticker dimensions and material types in rough phase which is shown in table 18.

Further assessment of sticker stains on sample boards with increasing planing depths showed that, different sticker types did not show significant color differences by means of stains for 1 mm and 2 mm planing depths. There was not a distinctive increase or decrease in of ΔE*ab values, when 1mm and 2 mm planing depth measurements were compared with each other respectively for different sticker types. These color differences might possibly have been due to color variation within the wood material itself, especially for measurements that were made after 1 mm planing depth. Because, the digital images of sample boards that were taken before and after 1 mm planing depths showed that sticker stains were planed away from wood surface regardless of different sticker types.

5.2.5 Comparison of Wood and Aluminum Sticker Stains with Digital Images

The digital images that were taken before and after planing the sample boards helped to describe and evaluate the sticker stains of different dimensioned wood and aluminum stickers. Figure 50 shows the character of discolorations due to wood and aluminum sticker types.



Figure 50 **The sticker stain difference between wood and aluminum stickers is shown in this image.**

In figure 50, it is seen that aluminum sticker stain is having slightly lighter color than the heat treated wood color. It is also observable that the aluminum sticker has remained darker shades on the locations where sticker edges contacted the wood surface. In the mean time, for the

same board, wood sticker has left a darker color toned stain on wood surface when it is compared to aluminum sticker stain.

It would not be easy to make a generalization for sticker stains of wood and aluminum stickers by means of color. Because, it was observed that the sticker stains can either be darker or lighter colored than the heat treated wood itself. The stains can be more severe on the edges of the aluminum stickers, as it is shown in figure 51. Again in figure 51, the wood sticker stains are not easily distinguished visually. Moreover, the stains can also be more significant on center parts due to shape and geometry of the boards. This issue is presumably related to the pressure applied on contact zone which is created between stickers and boards due to load.



Figure 51 **The image shows how different variations can occur between the stains of wood and aluminum stickers. It is seen that aluminum sticker has left darker color tones, almost black shady lines on wood surface, where wood sticker stains on the left side of the sticker is almost undetectable.**

In figure 52, another example of wood and aluminum sticker stains on sample boards is shown. In this case, it is hard to detect the stains for both sticker types, especially for aluminum sticker.



Figure 52 **The stain of wood sticker is hardly detectable on the left side of the wood sticker, but aluminum sticker's stain on the left side of sticker is even harder to detect.**

During the comparison of different sticker types' stains on sample boards, it was also observed that profiled wood stickers of birch wood caused more staining. This issue could probably be related to the moisture of these stickers. These stickers might have not been kiln dried properly to a moisture content of approximately 18% before the ThermoWood process. Due to this reason these stickers could have had more moisture interaction with spruce sample boards during thermal treatment. The stains of these stickers on sample boards are shown in figures 53 and 54.

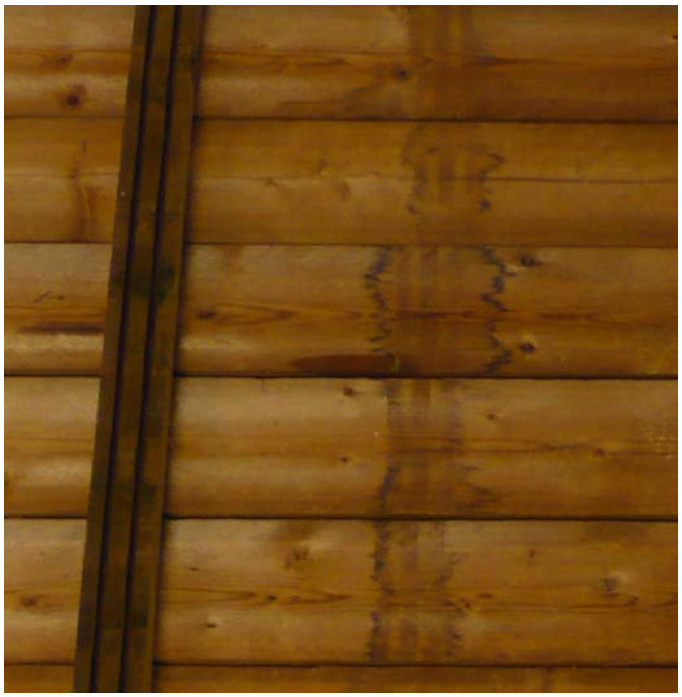

Figure 53 **The sticker stains that type B profiled birch stickers did leave on sample boards. The contact zones of the sticker had left darker color tones on wood surface, where the canals' color was almost the same tone with heat treated wood.**



Figure 54 **The sticker stains that type B profiled birch stickers did leave on sample boards. The significance of stains is rather less when it is compared to the staining in figure 53. This can point out that even the sticker types are the same, the stains that they leave on wood surface can vary in color.**

5.2.6 The sufficient planing Depth for a uniform looking ThermoWood Surface

The color difference results which were dependent on colorimetric measurements showed that after 1 mm planing depth, not much color difference in terms of detectable values for human eye remains on wood surface.

However, visual assessments which were supported by digital images showed that other factors like board geometry and cupping may affect the planing process and at least 2 mm or more planing depth could be needed for uniform looking wood surface in some cases. And probably for some worst cases as it was met in Forsman's study (2008) for heat treated wood, the wood material cannot be used for decorative uses unless covered with paint.

Interestingly, as it was met in few cases in this study, some of the sticker stains that were observed and shown in figures 47 and 48 might have been related to kiln drying process instead of ThermoWood process. Therefore, it is suggested that the wood materials which will be modified by advanced heat treatment techniques have to be controlled intensively prior to these applications in order to prevent problems before they exist. For example, the drying process can be studied and optimized for decreasing the amount of sticker stains after the heat treatment process. Finally, planing depth of 1-3 mm can be suggested in correlation with present industrial applications.

5.2.7 Effect of Cupping on Planing Process

Cupping of boards can also be an effective factor for the degree of sticker stain on specific locations on boards due to the contact zones that they create. Although, planing wood surface shaves off the sticker stained wood layer, there may be cases where some zones on wood surface can still remain in rough condition after planing process. By this means, the parameter

of cupping also affects surface planing process which is done in order to bring the rough product into end product specialties. The explanation of this issue is that the planing blade do not touch the board surface evenly, therefore some locations on boards remains not planed. The solution for this problem could be continuing planing process until whole board surface becomes planed properly. This case was also observed and was experienced during planing some of the sample boards in this work. The following figures 55 and 56 visually show this issue.



Figure 55 **Sticker stain zone before planing**



Figure 56 **Sticker stained zone after 1 mm planing**

In figure 55, the stain of aluminum sticker (type A) before planing is visible by the dark shades towards left side of the sticker location. It is also observable that the contact zone of sticker has created some pressure and its marks are also visible as thin lines corresponding to the edges of the sticker. The next figure, number 56 shows the same board after 1 mm planing process. Here it is observed that no significant sticker stain has left on board's center part. However, the cupping of board did not allow a proper planing process. Therefore, the edges of the board remained in partially not planed condition.

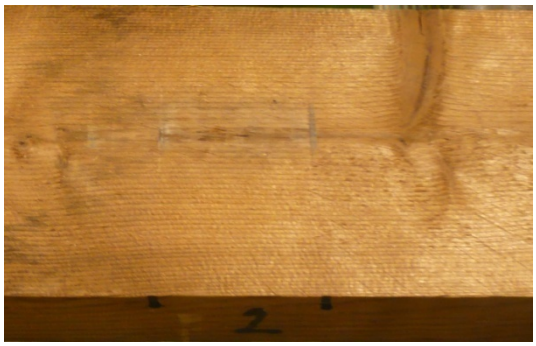

Figure 57 **Sticker stain zone before planing**

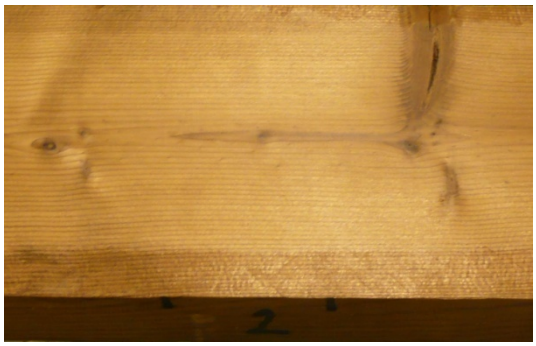

Figure 58 **Sticker stain zone after 1 mm planing**

The examples shown in figure 57 and 58 are quite interesting. Because, figure 57 which shows the sticker stained zone in rough phase and it can hardly be called as stained, unless the sticker position would not have been marked on the side of the board. Although, it can also be said that slight pressure marks are observed for the center part of the sticker contact zones. When the attention is paid on 1 mm planing depth, it is observed that the issue that seems

problematic is the not planed proportion of wood surface due to cupping. The solution might probably be continuing the planing process until the wood surface seems evenly planed and uniform. The techniques and key factors regarding ThermoWood boards and planing process is described in a detailed way in ThermoWood Handbook (2003) and ThermoWood Quality Planing Handbook (2004).

5.3 Multivariate Analysis

The multivariate analysis methods that were used in this work to study the relations among variables of L*, C*, h planing depth and ΔE*ab were in good correlation with the colorimetric measurements. The results of PCA analysis which indicate an increase in lightness (L*) and decrease in color difference ΔE*ab was correlated with an increase in planing depth. The relation of color component L* behavior to planing process was found similar to the study of Larsson et al. (2005) where a prediction modeling on spruce and pine boards were analyzed.

Regarding this study's content, it can be said that if more planing would be applied on board surfaces, it would result in brighter wood surface and less color difference between underneath sticker zones and reference zones. As a matter of fact, this statement matches the color measurement results showing the relation between ΔE* ab and planing process.

Additionally the load factor which was assumed to have a possible effect did not have any influence for the size of the sticker stains. This issue was understood from the reason that the layer variable was a very weak variable for explaining the color variations. Besides, the sticker type was not a strong variable which had influence on color variation.

In the end, the model creation trial in order to predict sticker stains of a certain sticker type could not be achieved regarding the collected data. Sticker stain prediction models can possibly be created, if utilization of image analysis tools could have been combined with multivariate analysis methods. Ultimately, if this type of a prediction method could be created, it probably could have been effective only for rough surfaces due to the reason that no significant sticker stain remains after planing processes.

5.4 Economical Analysis

5.4.1 Interviews

The interviews that were held with companies were satisfactory in terms of information gathering. These interviews had helped to learn more about the practical applications related to stickers and heat treatment technologies. Furthermore, the interest of the company correspondents to the content of this work showed that heat treatment industries were open for scientific studies which could lead innovations and improvements. However, there were also cases that information sharing was limited due to industrial secrecy policies which had also been another experience, too.

The interviews led to learn that sticker issue was one of the major cost parameters for wood drying industries. Besides, the importance of sticker handling methods during sawmill processes had also been realized, too.

The other important information part was the information about the relative lifespan of wood and aluminum stickers. This issue was a key factor to be able to make a cost estimation comparison between sticker types. However, it also has to be pronounced that different companies do have different sticker choices regarding lifetimes and sawmill handling issues. In this case, the relative lifetime estimation for wood stickers was conflicting with each other for different companies.

5.4.2 Cost Estimation

The results of the approximate cost estimation showed that both wood sticker types were costing more than aluminum stickers in long term utilization. Here, it also has to be emphasized that the calculations were made dependent on the information gathered by the interviews. The information regarding the lifetime of wood stickers was quite relative due to the fact that different companies has different estimations for the lifetime of wood stickers. Besides, the lifetime of the wood stickers were affected not only by heat treatment process, but also by the sawmill processes, as well.

Although, wood sticker utilizing companies were using the wood stickers for just one time due to sawmill processes (especially due to automatic separation). The assumption for manual handling of wood stickers could have the possibility to prolong the lifetime of these stickers. However, the exact run number was not certain. Therefore, the calculations were set for 5 and 6 numbers of runs respectively for type B, profiled wood stickers and regular wood stickers. The reason for 1 run less utilization number for profiled wood stickers was due to weakened material properties after heat treatment process related to geometrical shape of the sticker. The canals on the surface of the sticker caused the sticker to get cracked in an easier way. The author has noticed cracked profiled wood stickers during the visual evaluations and color measurements that were made on sample boards.

There is also another possibility of prolonging the lifetime of wood stickers, if they were handled manually; the defected stickers can be eliminated and the ones in proper conditions can be used continuously. At this point, it also has to be considered that heat treatment at temperatures of 200 □ C or more, the wood stickers could get more brittle due to on and on use.

Furthermore, the lifetime of the aluminum stickers were also limited by 1 year and most probably these stickers could have endured more time due to material properties. This relative lifetime for aluminum sticker may last more than 1 year and these stickers can be used on and on for some many years. Thus, the cost of aluminum stickers would have been less than the estimated cost regarding the increase in number of runs and utilization period by means of years.

In the end the importance of sawmill processes for sticker installation and separation must be emphasized. This is due to fact that sawmills either have automatic or manual sticker installation and separation systems. If a company which has wood stickers currently in practice with automatic separation intends to install aluminum stickers, they most probably would require new automation systems for aluminum sticker installing and also new conveying lines for separation, as well.

6. Conclusions

The project analysis aspects that were used to study the stickers and sticker stains issues revealed the following points as conclusions:

- Sticker stain formation is presumably a combination of both physical and chemical phenomenon that takes place while water soluble substances and extractives in wood migrate towards wood surface during drying. Eventually, after drying process, a color difference may generate between sticker underneath and adjacent zones due to the fact that stickers do partially prohibit the evaporation within the contact zones that they are placed on.

- Sufficient planing depth for a uniform looking heat treated wood surface varied within 1-3 mm. After 1 mm planing, the significance of sticker stains decreased noticeably; in this case became undetectable for human eye. The other parameter which affected the final planing depth was the cupping issue of the boards.

- The load had no influence on severity degree of sticker stains; in this case more stain severity degree was not observed for lower layers of a wood stack. The size of the sticker stains measured throughout the layers of the wood stack was quite irregular.

- Regarding the multivariate analysis of the collected data; Planing was the most influential factor on color variables; L*, C*, h and ΔE^*_{ab}.

- Aluminum 15 × 40 × 1200 mm dimensioned sticker type was the most cost effective one, regarding the relative lifespan durations in this study. Nevertheless, all aluminum sticker types were also more economical than wood stickers in long term utilization periods.

- Aluminum 20 × 40 × 1200 mm dimensioned sticker type was the one which leaved least stain on rough heat treated wood surface. After 1 mm planing depth, the sticker stains' degree of severity (sizes) decreased significantly regardless of the sticker material types and dimensions.

- A sticker choice should be made considering the sawmill processes as well. The handling issues of stickers like installation and removing in sawmill processes have to be considered for a suitable sticker choice for a certain facility.

- The material which is dried with conventional kiln drying has to be carefully examined in terms of sticker stains or other sort of discoloration issues before heat treatment process to prevent problems before existing.

7. Future Studies

There may be the possibility of further investigation issues related to stickers and sticker stains by the following points:

- An experimental set up can be arranged to measure the temperature underneath stickers and within the wood material. Afterwards, these values can be compared to wood surface temperature during drying process.

- During drying process, the position of the stickers on sample boards can be changed right after the moisture content of wood reaches approximately 18%. Afterwards, by proceeding heat treatment at temperatures around 200 □ C; the sticker stain formation can be investigated both for conventional kiln drying and heat treatment process. There may be the issue of understanding which drying phase has more influence on sticker stain formation.

- The wood samples can be separated according to sapwood and heartwood positions and the formation of sticker stains on these regions can be investigated.

- The wood stickers which were used in heat treatment process can be collected after heat treatment processes in order to investigate the strength loss of these stickers by crack tests. Eventually, the lifetime of wood stickers can be estimated for different wood species and different shapes.

- The handling issue of stickers in sawmill processes can also be investigated further to establish the right sticker type choice for a certain heat treatment facility.

References

Ahajji A., Diouf P. N., Aloui F., Elbakali I., Perrin D., Merlin A., George B. (2008) Influence of heat treatment on antioxidant properties and color stability of beech and spruce wood and their extractives. Wood Sci. Technology DOI 10.1007/s00226-008-0208-3, ISSN: 0043-7719

Ala-Viikari J. (2008) Finnish ThermoWood Association. COST E 37, Heraklion, Crete. Thermo Wood Production volume statistics via internet based source, web address: http://www.bfafh.de/inst4/45/ppt/10alavii.pdf

Ayadi N., Lejenue F., Charrier F., Charrier B., Merlin A. (2003) Color stability of heat treated wood during artificial weathering. Holz als Roh- und Werkstoff Volume 61, pp. 221-226

Bekhta P. and Niemz P. (2003) Effect of High Temperature on the Change in Color, Dimensional Stability and Mechanical properties of Spruce Wood. Holzforschung Volume 57, No.5, pp. 539-546

Boonstra M. J., Rijsdijk J. F., Sander C., Kegel E., Tjeerdsma B., Militz H., Van Acker J., Stevens M. (2006) Micro structural and Physical Aspects of Heat Treated Wood Part 1 Softwoods. Ciencia y Technologia Volume 8, No. 3, pp. 193-208

Bourgois J. and Guyonnet R. (1988) Characterization and Analysis of Torrified Wood. Wood Science and Technology 22:143-155

Brischke C., Welzbacher R. C., Brandt K., Rapp O. A. (2007) Quality control of thermally modified timber: Interrelationship between heat treatment intensities and CIE L* a* b* color data on homogenized wood samples. Holzforschung, Volume 61, pp. 19-22

Cao Yong Jian, LuJian Xiong, sun Zhen Yuan, Huang Rong Feng, zhou Yong Dong, Wu Yu Zhang (2007) Development and Application of overseas Heat Treated Wood, Scientia Silvae Sinicae, Volume 43, No. 2, pp. 104-110

Danvind J. (2002) PLS Prediction as a Tool for Modeling Wood Properties. Holz als Roh- und Werkstoff, Volume 60:130-140

Dawson-Andoh B. E., Wiemann M., Matuana L., Baumgras J. (2004) Infrared and Colorimetric Characterization of Discolored Kiln-Dried Hard Maple Lumber. Forest Products Journal, Volume 54. No.1

Forsman S. (2008) Heat treated wood-The Concept House Development. Master Thesis, ISSN: 1402-1617 ISRN: LTU-EX—08/166—SE

Hillis W. E. (1984) High Temperature and Chemical Effects on wood Stability Part 1: General Considerations. Wood Science and technology 18:281-293

Hiltunen E., Mononen K., Alvila L., Pakkanen T.T. (2008) Discoloration of birch wood: analysis of extractives from discolored surface of vacuum-dried European white birch (*Betula pubescens*) board. Wood Sci Technol. 42:103–115

Johansson D., Moren T. (2006) The Potential of Color Measurement for strength prediction of thermally treated wood. Holz als Roh- und Werkstoff Volume 64:2 pp.104-110

Jämsä S., and Viitaniemi P. (2001) Proceedings of Special Seminar on Heat Treatment of Wood, held in Antibes, France on 9th February, 2001

Kandem D. P., Pizzi A., Jermannaud A. (2002) Durability of heat treated wood. Holz als Roh- und Werkstoff Volume 60:1-6. ISSN: 0018-3768.

Larsson R., Danvind J., Imbaud O., Moren T. (2005) Prediction Modeling of Color Changes on Boards of Norway spruce and Scots Pine During Low Temperature Drying. In Proceedings of "Quality Control and Energy Saving in Wood Drying" 9th International IUFRO Wood Drying Conference, August 21-26, 2005, Nanjing, China

Militz H. (2002) Heat Treatment Technologies in Europe: Scientific Background and Technological State-of-Art. Proceedings of Conference on "Enhancing the durability of lumber and engineered wood products" February 11-13, 2002, Kissimmee, Orlando. Forest Products Society, Madison, US.

Mc Millen J. M. (1975) Physical Characteristics of seasoning discolorations in sugar maple sapwood. US For. Serv. Res. Pap. FPL-248

Minolta Camera Co. Ltd. (1993) Osaka 541, Japan. ISBN-9242-4830-91

Nilsson I. and Samuelsson I. (2006) Mould Stains on Wood. SP Swedish National Testing and Research Institute. SP Report 2006:43. ISSN 0284-5172

Riley S. G. Sargent R. (2005) Proposed Quantitative Method for Assessing Kiln Brown Stain in Radiata Pine. In Proceedings of "Quality Control and Energy Saving in Wood Drying" 9th International IUFRO Wood Drying Conference, August 21-26, 2005, Nanjing, China

Sehlstedt-Persson M. (2003) Color responses to heat treatment of extractives and sap from pine and spruce. In: 8th International IUFRO Wood Drying Conference, Brasov, Romania, pp. 459–464

Sehlstedt-Persson M. (2008) Impact of drying and heat treatment on physical properties and durability of solid wood. Doctoral Thesis/Luleå University of Technology, Nr: 2008:48, ISSN: 1402-1544

Shi Li Jun, Kocaefe D., Zhang J. (2007) Mechanical Behavior of Quebec wood species heat treated using ThermoWood process. Holz als Roh- und Werkstoff Volume 65:255-259

Sundqvist B. (2002) The influence of Wood Polymers and Extractives Wood Color Induced by Hydrothermal Treatment. Holz als Roh- und Werkstoff Volume 60 pp. 375-376

Sundqvist, B.(2002) Color Response of Scots Pine (*Pinus Sylvestris*), Norway Spruce (*Picea Abies*) and Birch (*Betula Pubescens*) subjected to heat treatment in Capillary Phase. Holz als Roh- und Werkstoff Volume 60 pp.106-114

Sundqvist B. (2004) Color Changes and Acid Formation in Wood during Heating, Doctoral Thesis, Luleå University of Technology, Thesis No 2004:10, ISNN: 1402-1544

Sundqvist B., Karlsson O., Westmark U. (2006) Determination of formic-acid and acetic acid concentrations formed during hydrothermal treatment of birch wood and its relation to color, strength and hardness. Wood Sci. Technology 40:549-561

Tarvainen V. (1995) High Temperature Drying a Serious Alternative, Holzforschung und Holzverwertung Volume 47 No. 5 pp. 78, 88-89

Terziev N. and Boutelje J. (1998) Effect of Felling Time and Kiln drying on Color and Susceptibility of Wood to Mold and Fungal Stain during an above Ground Field Test. Wood and Fiber Science Volume 30(4) pp. 360-367

Tjeerdsma B.F., Boonstra M., Militz H. (1998a) Thermal modification of non-durable wood species. IRG/WP 98-40124

Tjeerdsma B.F., Boonstra M., Pizzi A., Tekely P., Militz H. (1998b) Characterization of thermally modified wood: molecular reasons for wood performance improvement. Holz Roh-Werkstoff Volume 56(3):149–153

ThermoWood Handbook. (2003) web address: www.thermowood.fi

ThermoWood Quality Planing Handbook. (2004) web address: www.thermowood.fi

Umetrics AB. 2005, Address: Tvistevägen 48, P. O. Box 7960, SE-90719 Umeå, Sweden

Windeisen H., Strobel C., Wegener G. (2007) Chemical Changes during the Production of Thermo-Treated Beech Wood. Wood Science and Technology 41: 523-536

Wold S., Esbensen K., Geladi P. (1987) Principal Component Analysis, Chemometrics and Intelligent Laboratory Systems 2 (1987):37-52

Xie Yan-jun, Liu Yi-xing, Sun Yao-xing. (2002) Heat Treated Wood and its development in Europe, Journal of Forestry Research 13(3):224-230

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