Universitatea
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HABILITATION THESIS

SURFACE QUALITY EVALUATION OF WOOD AND WOOD BASED COMPOSITES

Domain: FORESTRY ENGINEERING
(INGINERIE FORESTIERĂ)

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(A) REZUMAT

Evaluarea calităţii suprafeţelor din lemn, ca expresie a stării suprafeţelor, caracterizată prin neregularităţi şi devieri de la suprafaţa nominală, a constituit o provocare pentru cercetare, încă din anii '80 şi a rămas şi în prezent un subiect în continuă dezbatere, datorită faptului că lemnul este un material eterogen, conţinând, în comparaţie cu materiale omogene, precum metalul, o serie particulară de neregularităţi (cavităţi) generate de anatomia lemnului şi specifice fiecărei specii. Anatomia lemnului face dificilă atât măsurarea datelor de pe suprafaţă, cât şi evaluarea datelor măsurate şi exprimarea numerică obiectivă a calităţii suprafeţei, fie că este vorba despre rugozitatea suprafeţei generată de prelucrare sau tratamente aplicate lemnului sau alte neregularităţi precum ondulaţii, erori de formă, defecte ale suprafeţei sau alte tipuri de neregularităţi. Metodele și recomandările oferite în standardele generale, privind **măsurarea şi evaluarea calităţii suprafeței**, adică **metrologia suprafeţelor**, nu se aplică bine la suprafețele din lemn, generând erori imprevizibile şi valori nerealiste privind calitatea suprafeței. Rapoartele științifice privind calitatea suprafeței lemnului sunt numeroase și, în general, cercetătorii au utilizat standardele și recomandările pentru metrologie existente, fără a testa adecvarea lor pentru un material eterogen ca lemnul și fără a căuta un consens. Acest lucru face că rapoartele de calitate a suprafeței să fie nesigure și dificil de comparat.

Subiectul cercetării științifice, prezentată în această teză de abilitare, "**Surface quality evaluation of wood and wood based composites"/, „Evaluarea calității suprafețelor din lemn şi a compozitelor pe bază de lemn**", a fost inspirat de faptul, recunoscut, că **nu există un set de recomandări unanim acceptate** privind metrologia suprafețelor din lemn sau a compozitelor pe bază de lemn, autoarea propunându-şi să găsească răspunsuri şi soluţii la această problemă. Primele cercetări în această direcţie, au fost inițiate prin doctoratul desfăşurat în Marea Britanie "**The roughness of sanded wood surfaces"/"Rugozitatea suprafeţelor şlefuite din lemn**" finalizat prin acordarea diplomei de "doctor în ştiințe", de către **Universitatea Brunel, în 2004**. Doctoratul în Marea Britanie a fost echivalat în 2005 de către Ministerul Educației, Cercetării și Tineretului. Cercetările tezei de doctorat au vizat diverse aspecte ale metrologiei suprafeţelor din lemn, privind atât măsurarea, cât şi evaluarea calităţii în cazul particular al suprafeţelor şlefuite din lemn masiv. Astfel, au fost analizate aspecte ale măsurării suprafeţelor cu diverse instrumente de măsurare, aspecte legate de cele mai adecvate filtre pentru rugozitate, dar şi de posibilitatea de a separa anatomia de celelalte neregularităţi ale lemnului, autoarea dezvoltând metode proprii de analiză. Plecând de la aceste cercetări inițiale, studiul a fost aprofundat de către autoare, timp de 15 ani (2005-2019) după finalizarea doctoratului, urmărindu-se testarea fiecărui aspect, în detaliu, al metrologiei suprafeţei şi adecvarea la cele mai recente comunicări ştiinţifice pentru **definirea şi validarea prin diseminare în circuitul ştiinţific a unei metode originale aplicabilă pentru metrologia suprafeţelor din lemn şi compozitelor pe bază de lemn**.

Prin urmare, scopul cercetării autoarei, efectuate în perioada 2005-2019, cu un accent in intervalul 2005-2014, a fost să dezvolte, să testeze în detaliu și să disemineze o metodă de metrologie a suprafețelor adecvată pentru lemn (material structurat în capitolul 1) și să o utilizeze în continuare, în perioada 2014-

2019, pentru o evaluare obiectivă a calității suprafeței lemnului și a compozitelor pe bază de lemn (capitolul 2). În paralel, în perioada 2006-2016, autoarea a abordat şi o altă direcție de cercetare, despre o resursă ignorată, resursa lemnoasă secundară, calitatea și potențialul acesteia pentru aplicații/produse cu valoare adăugată (capitolul 3), în timp ce o a treia direcție de cercetare, desfăşurată în perioada 2009-2015, urma să exploreze, pentru prima dată, potențialul utilizării unui software de prelucrare a imaginii-ImageJ, în evaluarea diferitelor aspecte ale morfologiei suprafeței lemnului (capitolul 4).

Capitolul 1 s-a axat pe diversele componente ale metrologiei suprafețelor din lemn prezentând cercetări despre problemele asociate în cazul evaluării calității suprafețelor din lemn și soluțiile posibile, oferind la final un set de recomandări privind cele mai bune practici de măsurare si evaluare a calității/rugozității suprafeței (este menționată de-a lungul tezei de abilitare ca fiind „**metoda metrologiei pentru suprafețe din lemn**”). Este pentru prima dată că se propune o metodă de metrologie pentru suprafețele din lemn cu scopul de a unifica viitoarele abordări în acest domeniu și de a face ca rezultatele obținute de diferiți cercetători să fie obiective și comparabile. Aceste secvențe de operații recomandate de metoda metrologiei suprafețelor din lemn, dacă sunt automatizate într-un software dedicat, pot servi pentru optimizarea regimurilor de prelucrare în aplicațiile industriale. În capitolul 1, metoda de evaluare a calității a fost testată pe suprafețe de stejar, fag și molid șlefuite cu diferite granulații.

Rezultatele cercetării din capitolul 1 au fost diseminate, **ca prim autor**, în **28 de publicații (dintre care 10 lucrări în ISI Web of Science, 2 capitole de carte în edituri internaționale)** și au fost recunoscute prin **138 citări în ISI Web of Science**. Informații detaliate privind diseminarea rezultatelor sunt prezentate la finalul capitolului 1.

Capitolul 2. Odată stabilită o metodă privind măsurarea și evaluarea calității suprafețelor din lemn, aceasta a oferit posibilități multiple de a aplica aceste cunoștințe în diverse domenii și pentru diverse materiale și nu se limitează la acestea. Metoda metrologiei suprafețelor din lemn a fost utilizată, în acest capitol, pentru a evalua calitatea suprafeței lemnului, apoi a lemnului modificat prin diferite tratamente termice, suprafața lemnului modificată cu plasmă sau modificată prin gravare cu laser. Mai departe, studiul a fost extins pentru panouri pe bază de lemn, sub formă de MDF și PAL, dar și pentru compozite din lemn-plastic (WPC). Analiza a fost completă, s-a bazat pe metoda de metrologie propusă și, în acest fel, s-au observat multiple aspecte ale calității suprafeței, care nu au fost discutate în publicațiile anterioare din literatura de specialitate.

Prin cercetare, s-a putut vedea ***efectul celor două zone de creștere a lemnului, lemn timpuriu și lemn târziu, la măsurarea calității suprafeței***. O concluzie importantă a fost aceea că suprafețele măsurate ar trebui să conțină și lemn timpuriu și lemn târziu, pentru a fi relevante pentru evaluarea calității suprafeței lemnului. ***Studiile efectuate la rindeluirea, frezarea și șlefuirea lemnului de fag modificat termic*** au arătat că tratarea termică la temperaturi de 200 ° C crește rugozitatea suprafeței în comparație cu lemnul netratat și acest efect devine mai pronunțat la o creștere a duratei tratamentului. Un alt tip de tratament al lemnului, cercetat în acest capitol, și efectele sale asupra lemnului, inclusiv cele asupra calității suprafeței lemnului a fost cel reprezentat de **tehnica patentată EDS** (prin afumare a lemnului), ca parte a unui

contract internațional la care **autoarea a fost coordonator**, "**Experimental research regarding the characteristics of beech (*Fagus japonica*) heat treated by EDS technology"/ „Cercetări experimentale privind caracteristicile lemnului de fag (*Fagus japonica*) tratat termic prin tehnologia EDS**" (nr. 15826 / 2016-2017) și încheiat între Universitatea Transilvania din Brașov și Laboratorul EDS-Japonia. S-a observat, printre altele, o tendință benefică a tratamentului de a omogeniza proprietățile lemnului. Studiile asupra ***efectului gravării lemnului cu laser***, *primul de acest fel din literatura de specialitate*, pe suprafețe de fag și paltin, au arătat că rugozitatea suprafeței a crescut liniar cu puterea laserului și a scăzut după o corelație logaritmică cu viteza de scanare. Curbele de corelație dintre rugozitatea suprafeței și modificarea culorii lemnului pot fi utilizate când se aleg parametrii de gravare cu laser (putere, viteză de scanare) astfel incât să se obțină modificarea de culoare dorită cu o rugozitate minimă a suprafeței. Cercetarea privind ***calitatea suprafeței lemnului după modificare cu plasmă*** a fost un bun exemplu de cercetare interdisciplinară în care rezultatele s-au coroborat pentru o mai bună înțelegere a morfologiei suprafeței și a comportamentului materialului. ***Metoda de metrologie a suprafeței a fost aplicată în continuare la panouri pe bază de lemn și la compozite lemn-plastic***. Determinarea rugozității suprafeței pentru aceste materiale este importantă atunci când panourile sunt utilizate ca substrat pentru acoperiri, cum ar fi hârtie melaminică subțire sau, în cazul compozitelor lemn-plastic, suprafețele trebuie să fie netede pentru a perimite o finisare directă.

Rezultatele cercetării din capitolul 2 au fost diseminate, în **14 publicații** (**9 articole în ISI Web of knowledge**), la care se poate adăuga contribuția autoarei la un studiu doctoral pe lemn tratat termic, ca membră a comisiei de indrumare, și la un al doilea studiu de doctorat privind efectul laserului asupra lemnului, în calitate de consultant privind calitatea suprafeței. Informații detaliate privind diseminarea rezultatelor sunt prezentate la finalul capitolului 2. **Contribuția ştiințifică a fost în calitate de „autor principal" sau "autor corespondent" pentru marea majoritate a acestor publicații.**

Capitolul 3 a cuprins o altă direcție de cercetare, ***despre resursa lemnoasă secundară (crengi, lemn din operații de rărituri forestiere, lemn juvenil versus lemn matur), cu scopul de a găsi aplicații și de a adăuga valoare acestei resurse ignorate.*** Au fost create tipuri de panouri din lemn cu o estetică deosebită, realizate din lemn din crengi sau lemn din trunchiuri subtiri tăiate transversal pentru a crește valoarea acestei resurse. Cercetările privind caracteristicile și proprietățile materiei prime au fost completate cu cercetarea privind proprietățile fizice și mecanice ale panourilor, precum și cu investigații privind calitatea suprafeței panourilor respective după șlefuire. Această cercetare a făcut parte dintr-un **proiect finanțat de CNCSIS (Consiliul Național al Cercetării Științifice în Învățământul Superior) tip A 450/2006: „Eco-concepție și eco-tehnologie pentru mobilier și alte produse din lemn obținute din resurse naturale secundare" (2006-2008)**, unde **autoarea a fost membră** activă. Pentru realizarea cercetării privind resursa lemnoasă secundară, ***autoarea și-a folosit experiența în microscopie a lemnului, precum și în interpretarea proprietăților fizice și mecanice ale lemnului. Cercetarea a fost completată cu evaluarea calității suprafeței panourilor nou create din resurse lemnoase secundare.***

Rezultatele cercetării din capitolul 3 au fost diseminate, în **32 de publicații** (**6 articole în ISI Web of knowledge**), **3 brevete** în calitate de coautor, în ISI Web of Knowledge, la care se poate adăuga **contribuția la două studii doctorale** asupra resurselor secundare din lemn, ca membră a comisiei de îndrumare de doctorat. Informații detaliate privind diseminarea rezultatelor sunt prezentate la finalul capitolului 3. **Contribuția științifică a fost în calitate de „autor principal” sau “autor corespondent” pentru marea majoritate a acestor publicații.**

Capitolul 4 reprezintă **o abordare originală a evaluării suprafețelor prin utilizarea unui software de prelucrare a imaginii -ImageJ**, disponibil gratuit pe internet, dezvoltat la “the National Institutes of Health” din Statele Unite ale Americii. ***Autoarea a experimentat acest software în cazul suprafetelor din lemn și compozitelor pe bază de lemn și a reușit să găsească aplicații utile și originale.*** Una dintre aplicațiile ImageJ a fost ***evaluarea calității suprafeței panourilor pe bază de lemn (PAL) după prelucrarea prin gaurire***. ImageJ a fost folosit și ca instrument ajutător pentru ***identificarea speciilor, din probe detașate din structura diferitelor obiecte supuse restaurării***. O aplicație similară a ImageJ a fost utilizată pentru ***evaluarea caracteristicilor microscopice ale unui material mai puțin cunoscut, resursa lemnoasă secundară***, în comparație cu lemnul din trunchi. ImageJ a fost utilizat, deoarece oferă o metodă cantitativă obiectivă de separare, măsurare și prelucrare statistică a datelor măsurate, pentru anumite caracteristici anatomice de interes. O altă aplicație a ImageJ a fost aceea de ***a evalua adâncimea de pătrundere în lemn a substanțelor de consolidare a lemnului***, pentru a evalua calitatea acestei operații. Ultimele trei aplicații au fost **realizate de autoare în cadrul proiectului CNCSIS PN2 Idei 856 / 2009- „Dezvoltarea și implementarea unei metodologii avansate de cercetare științifică pentru restaurare și conservare sustenabilă a lemnului (mobilierului) si ecodesign”,** unde autoarea a fost membră activă.

Rezultatele cercetării din capitolul 4 au fost diseminate în **23 de publicații** (**2 lucrări în ISI Web of Knowledge**), la care se poate adăuga contribuția la un studiu doctoral privind microscopia resursei secundare din lemn, ca membră a comisiei de îndrumare de doctorat. Informații detaliate privind diseminarea rezultatelor sunt prezentate la finalul capitolului 4. **Contribuția ştiinţifică a fost în calitate de „autor principal” sau “autor corespondent” pentru marea majoritate a acestor publicații.**

Cercetări în desfăşurare şi cercetări viitoare

Autoarea acestei teze de abilitare **coordonează, în calitate de partener UTBv, două proiecte internaționale finanțate de către UE, care sunt în derulare în acest moment.** Acestea vor contribui la dezvoltarea activităților de cercetare și academice ale autoarei privind creativitatea, materialele și tehnologiile inovative pentru mobilier. Acestea sunt:

- DITRAMA – “Digital transformation manager: leading companies in Furniture value chain to implement their digital transformation strategy”/ “Managerul transformării digitale: conducând companii din domeniul mobilierului, pentru a-și implementa strategia de transformare digitală”, PN: 601011-EPP-1-2018-1-ES-EPPKA2-SSA, cu 12 parteneri din 8 țări europene, **valoare totala: 994094 euro; partea UTBv:46175 euro**. Perioada de desfăşurare:**01/01/2019-31/12/2021**

- FACET- “Furniture sector Avant-garde Creativity and Entrepreneurship Training”/ “Sectorul mobilierului. Formare avansată în creativitate și antreprenoriat”, PN: 2018-1-IT01-KA202-006734, cu 8 parteneri, din 6 ţări europene, **valoare totală: 324163 euro; partea UTBv: 25342 euro**. Perioada de desfăşurare:**01/11/2018-04/30/2021**

În privința cercetărilor științifice viitoare, posibilitățile sunt nelimitate. Calitatea suprafeței rămâne un subiect de interes pentru orice material pe bază pe lemn, orice tip de prelucrare, orice proces de tratare sau modificare a lemnului. De asemenea, este deschis cercetării interdisciplinare, unde lemnul se combină cu alte materiale. Cunoscând valorile obiective ale rugozității suprafeței și înțelegând morfologia suprafeței, procesele pot fi optimizate și costurile vor fi reduse. Studiile ulterioare nu vor avea în vedere numai calitatea suprafeței. Autoarea a dovedit abilități în cercetarea proprietăților fizice și mecanice ale lemnului, în microscopia lemnului, dar și în cercetarea lemnului tratat sau modificat, **cunoștințe care vor fi utilizate și dezvoltate în echipe de cercetare si vor genera studii de doctorat sub indrumarea autoarei acestei teze de abilitare.**

Rezultatele tuturor cercetărilor, desfasurate de către autoare în perioada 2005-2019 au fost validate prin **156 de citări în ISI Web of Science-fără autocitări (h-index 7).** Cele mai importante sunt **29 de articole în ISI Web of Science** (***21 ca prim autor și 2 în calitate de autor corespondent***), 2 capitole de carte, ca prim autor, în edituri internaționale (ISTE-Willy, Nova Science), 5 cărți-Ed.Transilvania Univ., 20 lucrări în reviste ştiințifice indexate în baze de date internaționale (11 ca prim autor), 43 lucrări în conferințe internaționale (dintre care 7 în baze de date internaționale) și 3 brevete în ISI Web of Science-Dervent.

(B) SCIENTIFIC AND PROFESSIONAL ACHIEVEMENTS AND THE EVOLUTION AND DEVELOPMENT PLANS FOR CAREER DEVELOPMENT

(B-I) SCIENTIFIC AND PROFESSIONAL ACHIEVEMENTS

INTRODUCTION

The evaluation of the wood surface quality, as an expression of the state of the surfaces, characterized by irregularities and deviations from the nominal surface, has been a challenge for research, since the 80s and has remained a topic in continuous debate, due to the fact that wood is a heterogeneous material, containing, in comparison with homogeneous materials, such as metal, a particular series of irregularities (cavities) generated by its anatomy specific to each species. The wood anatomy makes it difficult to measure the surface data, as well as the evaluation of the measured data and the objective numerical expression of the surface quality, whether it is the roughness of the surface generated by processing or treatments applied to wood or other irregularities such as waviness, form errors, surface defects or other types of irregularities. The methods and recommendations offered in the general standards, regarding **the measurement and evaluation of the surface quality**, that is the **metrology of the surfaces**, do not apply well to the wood surfaces, generating unpredictable errors and unrealistic values regarding the surface qualiy. Scientific reports on the wood surface quality are numerous and, in general, researchers have used existing metrology standards and recommendations, without testing their suitability for a heterogeneous material such as wood and without seeking consensus. This makes surface quality reports unreliable and difficult to compare.

The topic of scientific research, presented in this habilitation thesis, "**Surface quality evaluation of wood and wood based composites**" /, " **Evaluarea calității suprafețelor din lemn şi a compozitelor pe bază de lemn** ", was inspired by the recognized fact that no agreed guidelines exist in wood surface metrology or on how to objectively measure and evaluate the surface quality of a wood or wood based surface and the author is proposing to find answers and solutions to this problem. The first researches in this direction were initiated by the doctorate in the United Kingdom "**The roughness of sanded wood surfaces**" / "**Rugozitatea suprafețelor şlefuite din lemn** " finalized by the PhD degree, awarded by **Brunel University, in 2004**. The doctorate in the United Kingdom was validated in 2005 by the Ministry of Education, Research and Youth in the domain of “Industrial Engineering”. The doctorate researches focused on various aspects of the metrology of wood surfaces, regarding both the measurement and the quality evaluation in the particular case of the sanded wood surfaces. Thus,in the doctoral thesis were analyzed aspects of surface measurement with various measuring instruments, aspects related to the most suitable filters for surface roughness, but also the possibility of separating the anatomy from other wood irregularities, the author developing her own methods of analysis. Starting from these initial researches, the study was deepened by the author, for 15 years (2005-2019) after the completion of the doctorate, testing each aspect, in detail, of the metrology of the surface, adapting them to the latest scientific communications, in order **to define and validate, by dissemination in the scientific circuit, an original method regarding the metrology of wood surfaces and wood-based composites.**

Therefore, the purpose of the research pursued from 2005 to 2019, with a strong focus from 2005-2014, was meant to develop, test in minute details and disseminate a metrology method suitable for wood (material structured in chapter 1) and to use it further for a reliable evaluation of surface quality of wood and wood based products (presented in chapter 2). In similar time framework, during 2006-2016, the author approached also another research direction about an ignored material, the seconday wood resource, its quality and potential for value added applications (chapter 3), while a third research direction, during 2009-2015, was to explore, for the first time, the potential in evaluating the various aspects of the wood surface morphology by using an imaging software-ImageJ (chapter 4).

Chapter 1 has focussed on various components of wood surface metrology informing about problems associated with evaluation of wood surface quality and solutions found by the author, finally **providing a set of best practice recommendations on how to best measure and evaluate the surface quality/roughness** (it is referred along the habilitation thesis as "**the metrology method for wood surfaces**"). It is for the first time that a metrology method for wood surfaces is proposed with the purpose to unify further approaches in this domain and make results obtained by different researchers reliable and comparable. This set of best practice recommendations, if automated in dedicated software can serve for optimisation of processing parameters in industry applications. In chapter 1, the metrology method was tested on oak, beech and spruce surfaces sanded with various grit sizes.

The research results from chapter 1 were disseminated, **as first author**, in **28 publications** (among which **10 papers in ISI Web of Science**, 2 book chapters in international publishing houses) and were acknowledged by **138 citations in ISI Web of Science**. Detailed dissemination information is given at the end of chapter 1.

Chapter2. Once a metrology method for measuring and evaluating the quality of wood surfaces was established, it offered the multiple possibilities to apply this knowledge in various domains and materials and it is not limited to these. **The wood metrology method was used** to **evaluate the surface quality of two growth areas of wood**, then **wood modified by various thermal treatments**, **wood surface modified by plasma** and **by laser engraving**. Further, the study was **extended for wood based panels**, as **MDF and chipboard**, but also **wood plastic composites**.The analysis was thorough, it was based on the proposed wood metrology method, with multiple roughness parameters and, in this way, multiple aspects of the surface quality were observed, which were not discussed in previous literature publications. A type of wood treatment under investigation and its effects on wood, including those on wood surface quality was **the EDS patented technique (by smoking wood)**, as part of an international contract, where **the author was coordinator**, "**Experimental research regarding the characteristics of beech (Fagus japonica) heat treated by EDS technology**" (No. 15826/11.11.2016; period 2016-2017) and concluded between Transilvania University in Brasov and EDS Laboratory-Japan (section 2.2.4).

The research results from chapter 2 were disseminated, in **14 publications (9 papers in ISI Web of knowledge)** to which can be added the contribution to **one doctoral study on thermally treated wood as member of the PhD advisory board** and to a second doctoral study on the laser effect on wood as surface quality consultant. Detailed dissemination information is given at the end of chapter 2. The author was **"main author" or "corresponding" author** to the vast majority of those publications.

Chapter 3 comprised another direction of research, **about the quality of secondary wood resource** (wood branches, wood from thinning operations, juvenile wood versus mature wood), **with the purpose to find applications and add value to this ignored resource. Inovative type of wood panels** with increased aestetics **were created**, made of crosscut wood branches or from crosscut thin logs, in order to increase the value of this resource. The research on the characteristics and properties of the raw material was complemented with research on the physical and mechanical properties of those panels, as well as with investigations regarding the surface quality of those panels after sanding. This research was part of a **project granted by the CNCSIS (The National Council of Scientific Research in the Higher Education) type A 450/2006: "Eco-conception and eco-technology for furniture and other wood made products obtained from natural secondary resources" (2006-2008),** where the author was active member. For pusuing the research on secondary wood research, the author has used her experience in wood microscopy as well as in interpretation of wood physical and mechanical properties. Research was complemented with evaluation of surface quality of newly designed panels from secondary wood resource.

The research results from chapter 3 were disseminated, in **32 publications (6 papers in ISI Web of knowledge),** 3 patents as co-author in ISI Web of Knowledge, to which can be added the **contribution to two doctoral studies on secondary wood resource**, as member of the PhD advisory board. Detailed dissemination information is given at the end of chapter 3. **The author, contributed as "first author" or as "corresponding author" in the majority of them**.

Chapter 4 represents **an original approach to the evaluation of surfaces by using an imaging software -ImageJ**, freely available on the internet, developed at the National Institutes of Health in the United States of America. The author has experimented with this software on wood and wood based materials and **managed to find useful and original applications**. One of the applications of ImageJ was to **evaluate the surface quality of wood based panels after being processed by drilling**. ImageJ was also used **as supporting tool, for species identification** of samples detached from the structure of various **objects subject to restoration**. A similar application of ImageJ was employed for evaluating the microscopic characteristics of a less known material, **the secondary wood resource**, in comparison with wood from stem. ImageJ was used, because it offers an objective quantitative method to separate, measure and statistical data process for some anatomical features of interest. Another application of ImageJ was **to evaluate the depth of penetration for wood consolidants**, in order to assess the quality of this operation. The last three applications were performed by the author in the framework of **the project CNCSIS PN2 Idei(Ideas) 856/2009-"Development and implementation of an advanced**

scientific research methodology for sustainable wood (furniture) restoration-conservation and ecodesign" where the author was active member.

The research results from chapter 4 were disseminated, in **23 publications (2 papers in ISI Web of knowledge),** to which can be added the **contribution to one doctoral studies on the microscopy of secondary wood resource**, as member of the PhD advisory board. Detailed dissemination information is given at the end of chapter 4. **The author, contributed as "first author" or as "corresponding author" in the majority of them**.

Many of the above studies were pursued as international collaboration and were issued in response to international research needs in this domain. Contacts, joint research ideas and international networks were developed. As example, the author is UTBv partner in an international network called „**Networking of Wood Research Centers of the Danube Region to improve the educational, scientific and economic efficiency and infrastructure of the Regions due to a strengthened competitiveness of wood material and products- Danube Wood Region**" (2017-2019), financed by The Federal Ministry of Education and Research, Germany. The partners agreed to support, without payment, scientific collaboration in common research projects, with specific relevance to the Wood Research Centers in the Danube Region. One of the outputs was a **catalogue with research infrastructure** and devices from each of the 10 partners, **allowing exchange of staff and access to equipment**, to optimize and strengthen joint research. **This collaboration will continue in joint projects, seeking for EU funds**.

Ongoing and further work:

The author of this habilitation thesis **coordinates, as UTBv partner, two international projects financed by the EU**, which are ongoing at this moment of writing. They will contribute to develop the research and academic activities of the author on furniture creativity and innovative materials and technologies for furniture. They are:

- DITRAMA – "Digital transformation manager: leading companies in Furniture value chain to implement their digital transformation strategy", PN: 601011-EPP-1-2018-1-ES-EPPKA2-SSA,with 12 partners from 8 European countries, t**otal grant: 994094 euro; UTBv share:46175 euro**. Period of implementation:**01/01/2019-31/12/2021.** *The **wood furniture** manufacturing industry will offer **personalised smart products and services based on digital manufacturing systems** supplied by resource-efficient and sustainable industries with an immense **need for enough digitization talents and skills** securing a competitive transformation of the industry.*
- FACET- "Furniture sector Avant-garde Creativity and Entrepreneurship Training", PN: 2018-1-IT01-KA202-006734, **total grant: 324163 euro; UTBv share: 25342 euro**. Period of implementation: **01/11/2018-04/30/2021**. FACET project will guide professionals through the idea creation and implementation process improving their **creativity** and entrepreneurship skills **as they work in projects**

For further scientific work, ***the possibilities are unlimited.*** Surface quality remains a subject of interest ***for any material based on wood, any processing, any wood treatment or modification process***. It is also open to interdisciplinary research, where wood combines with other materials. By knowing the objective values of surface roughness and by understanding the surface morphology, the processes can be optimized and costs will be reduced. Not only surface quality will be envisaged by further studies. The author has proven skills in researching the physical and mechanical properties of wood, in wood microscopy, but also in modified and treated wood, **knowledge that will be used and developed in research teams and will generate doctoral studies under the guidance of the author of this thesis.**

The author scientific and professional achievements, in the field of *Forestry Engineering*/*Inginerie Forestieră*, can be outlined as:

- **coordinator of:**
  - **two (2) international projects, where UTBv is partner, granted through international competition**:
    - DITRAMA- UTBv share **46175 EUR (total project grant: 994094 euro) -** project with 12 partners
    - FACET- UTBv share **25342 EUR (total project grant: 324163 euro)**, project with 8 partners
  - **one (1) international research contract** with Japan (value **16109.41** EUR)
- coordination as **UTBv partner in other (1) research international project** (research networking in the Danube region) (project grant 79.317 euro, UTBv has no financial share)
- member in 4 other international research projects
- member in 5 national projects awarded through national competition
- publication of **29 papers in ISI Web of Science** (**21 as first author and 2 as correspondent**).:
  - **25 papers in ISI Web of Science, in journals** ranked as top journals according to CNCSIS criteria (**red zone for the majority**), **1 review paper with impact factor 3.548-** Gurau and Irle (2017).
  - 4 papers in ISI Proceedings
- publication of **20 papers in journals indexed in international databases** (**11 as first author**), respectively CABI, DOAJ, DRJI, EBSCO Publishing Ltd. Academic Search Complete, INDEX COPERNICUS, Google Scholar;
- publication of 43 papers in **international conferences** (**7 in international databases**) and of 6 in national conferences
- publication of **2 book chapters in international publishing houses** (ISTE-Willy and NOVA Science Publishers) **as first author** and of 1 book, as co-author.
- publication of 5 books (2 as sole author)-Ed.Transilvania University
- recognition of **3 patents in Web of Science-Dervent**

Those results were acknowledged by

- **156 citations in ISI Web of Science-without self citations (h-index 7)** and by **539 citations in Google Scholar (h-index 16)**

The didactic, professional and research activity, as well as the performance with regard to the recognition and the impact of the activity, have led to the fulfillment of the necessary and obligatory criteria according to CNATDCU standards, for the specialized commission **"*Engineering of plant and animal resources*"/"*Ingineria resurselor animale si vegetale*".** The score of 2850.39 points obtained by the author of this thesis was higher 6.8 times than the minimum of 420 points to meet and were distributed as follows:

- **A1 criteria/criteriul A1." Didactic and professional activity"/ „Activitatea didactică şi profesională"-**178.85 points achieved against 100 points to be met, criteria 1.1. "Books and chapters in specialty books"/ „Cărţi şi capitole în cărţi de specialite" - 6 books şi 2 international book chapters achieved relative to the minimum number to be met - 2, among which 4 as main or first author compared to the minimum required number of 2. Six books were published after the last academic promotion relative to the minimum of 1 required.
- **A2 criteria/criteriul A2. "Research activity"/ „Activitatea de cercetare"-** 1360.43 points achieved against 260 points to be met, criteria 2.1. "Articles in ISI Thomson Reuters and ISI indexed volumes "/„Articole în reviste cotate ISI Thomson Reuters şi în volume indexate ISI" - 29 articles published *in extenso*, against the minimum number to be met – 8; 25 in ISI journals compared to minimum 4, main and correspondent author to 23 ISI papers compared to a minimum of 4; 25 ISI papers published after the last academic promotion against the minimum number of 3 papers; criteria 2.2. "Articles in journals and volumes of scientific events indexed in other international databases "/„Articole în reviste şi volumele unor manifestări ştiinţifice indexate în alte baze de date internaționale" – 27 published papers as relate to the minimum required of 15 papers, criteria 2.4. "Grants / projects won by competition, including research / consultancy projects (value of at least 10,000 Euro equivalent "/„Granturi/proiecte câştigate prin competiţie, inclusiv proiecte de cercetare/consultanţă (valoare de minim 10 000 Euro echivalent)" – 3 against minimum 2 required.
- **A3 criteria/criteriul A3 "Recognition and impact of the activity"/ „Recunoaştere şi impactul activităţii"** – 1311.11 points achieved against 60 points to be met

1. CHAPTER 1. METROLOGY OF WOOD SURFACES. CHALLENGES AND SOLUTIONS

Although surface quality can have a huge impact on finishing costs and the perceived quality of wood products, there is a lack of consensus on wood surface metrology. One reason for this is that the presence of anatomical features can bias the measuring and evaluation of surface data. Consequently, the methods and recommendations given in general standards on surface metrology do not apply well to wood surfaces. This chapter is reviewing the general metrology concept for surface quality assessment and the way in which it was applied for wood surfaces, by researchers, with various degrees of success. The sequence of standard metrological steps, with various results from previous researchers is complemented with the original contributions of the author of this habilitation thesis. This contribution, focussed on the specific metrology of wood surfaces.

The first researches in this direction were initiated by the doctorate in the United Kingdom "The roughness of sanded wood surfaces" finalized by the PhD degree, awarded by Brunel University, in 2004. The doctorate researches focused on various aspects of the metrology of wood surfaces, regarding both the measurement and the quality evaluation in the particular case of the sanded wood surfaces. Thus, there were analyzed aspects of surface measurement with various measuring instruments, aspects related to the most suitable filters for surface roughness, but also the possibility of separating the anatomy from other wood irregularities, the author developing her own methods of analysis. Starting from these preliminary researches, the study was deepened for 15 years (2005-2019) after the completion of the doctorate, testing each aspect, in detail, of the metrology of the surface, adapting them to the latest scientific communications, in order to define and validate, by dissemination in the scientific circuit, **an original method regarding the metrology of wood surfaces and wood-based composites**.

Therefore, the purpose of the research pursued from 2005 to 2019, intensively before 2014-2015, and included in chapter 1, was meant to develop, test in minute details and disseminate an original metrology method suitable for wood (material structured in chapter 1) and to use it further for a reliable evaluation of surface quality of wood and wood based products (presented in chapter 2).

The first question in understanding **how do we measure** a surface quality is **what do we need to measure**? In this respect, it is important to understand the surface topography and types of features occuring on a proccessed surface prepared for quality evaluation. A literature review of various aspects of the surface topography is presented next.

1.1 Topography of processed surfaces. What do we measure?

The study of surface topography as a property of materials began prior to 1939 primarily in the metal industry, while studies on wood followed later in the early 1950s (Stumbo, 1963). Stumbo (1963) has defined the surface topography as being the irregularity of the interface between a substance and its surroundings (generally air).

Surface texture data can be "read" with various measuring methods and instruments, and varying levels of accuracy. Early subjective visual and tactile examinations have generally been replaced by more accurate contact measurements such as stylus tracing or non contact instruments such as the laser, which allow the digital transfer of data from the surface to a computer. A correct evaluation of the surface quality requires that the measured data must match, as closely as possible, the shape and real dimensions of the surface irregularities.

Measured data can be further separated by filtering. The purpose of filtering is to retain from a surface only the data that is relevant for characterising the quality of the manufacturing process. Finally, the quality of the processing can be evaluated by numerical parameters calculated from the filtered data.

Standardised classifications of surface topography (ASME B46.1: 1995) assume that the measured data represents an ideal surface on which a pattern of roughness, waviness and form is superimposed together with random flaws (Figure 1).

Flaws are unintentional and unwanted deviations consisting of individual and unusual features such as scratches, gouges and burrs. **Form errors** are a result of faults in machine tool guides, deflection of machine or workpiece or incorrect clamping of workpiece. Form error encompasses the longest wavelength deviations of a surface from the corresponding nominal surface followed by waviness and then roughness. **Waviness** can be a result of eccentric clamping, deviations in the geometry or running of a cutter, vibrations of the machine or tool chatter. **Roughness** represents the finer irregularities of the surface texture that usually result from the inherent action of the production process or the material condition (ASME B46.1: 1995).

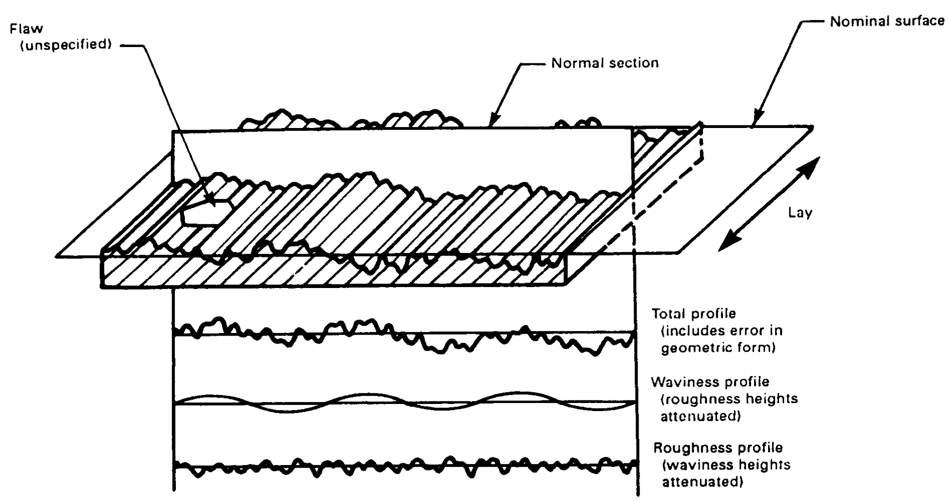


Figure 1 Schematic diagram of surface characteristics (ASME B46.1: 1995).

However, standardised classifications of surface topography (ASME B46.1: 1995) do not include structural surface deviations. The classification above is valid only as long as the texture of interest is much larger than the texture due to the structure. In homogeneous materials such as metals, plastics and glass this is usually the case, but not in wood. The deviations in wood surface texture associated with its anatomic structure are often as great as, if not greater than the deviations caused by machining (Stumbo, 1963).

In 1980, Ebewele et al.(1980) remarked that there was no standardised recommendation for assessing the quality of processed wood surfaces and nor was there a consensus on the definition of wood surface roughness or how to measure it. These observations are still valid today. As each species has a characteristic anatomy and wood is a porous material the definition of the surface texture becomes difficult in comparison with homogeneous materials. This is why existing standards for measuring and evaluating surface quality are not always applicable to processed wood since they only anticipate roughness due to a machining process (Westkämper and Schadoffski 1995a and 1995b, Krisch and Csiha 1999, Thoma et al. 2015, Thibaut et al. 2016).

Indeed the wood surface can be considered as a composite of several surface textures. As long ago as 1958, Marian, Stumbo and Maxey made the first classification of wood surface textures as follows:

I. First degree texture comprises the irregularities on the surface caused by the natural anatomic texture of wood and are produced by opening cell cavities during machining. First degree texture also includes elastic deformation in earlywood especially at softwoods, caused by a high cutting pressure.

II. Second degree texture comprises tool marks caused by inherent machining variables (mode of cutting, cutting speed, feed velocity, contact pressure, tool geometry), but also cells or fragment of cells or tissues torn out from the wood structure by the action of tools and permanent cell wall deformation through impact.

III. Third degree texture is produced by incidental machining variables (vibrations, worn tools) and incidental variations in the wood material (differences in growth ring density, compression wood, resin pockets, fibre deviations).

A more comprehensive scheme of classification was first configured by Radu (1966) and later developed by Dogaru (1981). The irregularities of the surface are grouped in two main categories as a result of the anatomical texture or machining (Figure 2).

Irregularities classification for wood surfaces

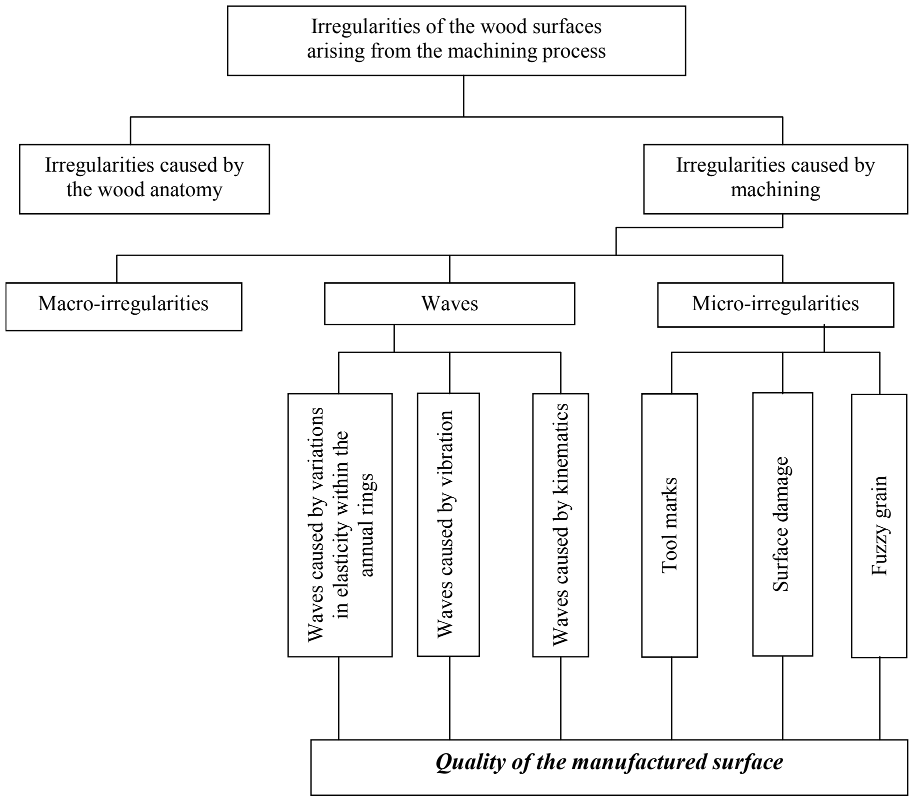


Figure 2 Irregularities classification for wood surfaces (Dogaru, 1981).

Irregularities caused by the wood anatomy

During the machining process, the wood cells are cut by the tool, which leaves some cell cavities open (Figure 3). The size of these cavities varies between species, within species and by cell type. Within a surface, the cell type and size varies between earlywood and latewood. The cavity size will also vary depending on which section; transverse, radial or tangential is dominant in the surface. Since the irregularities caused by wood anatomy are independent of the type of machining they should be excluded from any assessment of the quality of the processed surface (Westkämper and Riegel, 1993a; Magross and Sitkei, 1999; Krisch and Csiha, 1999; Schadoffsky, 2000; Kilic et al., 2006; Gurau et al. 2007; Magross, 2015). The irregularities caused by wood anatomy are often called textural roughness or **anatomical roughness** (Westkämper and Riegel, 1993a; Schadoffsky, 2000). Anatomical roughness is important not only for the appearance of the product, but also in some lacquering applications for determining the consumption of finishing material (Westkämper and Riegel, 1993a).

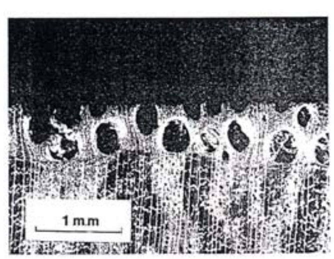


Figure 3 Irregularities caused by wood anatomy (Triboulot, 1984).

Irregularities caused by machining

These fall into three types: macro-irregularities, waves and micro-irregularities

Macro-irregularities

Macro-irregularities are deviations from the nominal shape given in the product's technical drawings, for instance a normally flat surface may be concave or convex, or a nominal cylinder may be conic. Possible causes are: internal stresses in the wood, inaccuracies in the machine-tool-workpiece system and tool wear. Macro-irregularities characterise the machining accuracy and should be excluded from any assessment of the surface, as they do not characterise the processing.

Waves

Waves can be grouped into three types:

a) Waves caused by variation in elasticity within the annual rings

b) Waves caused by vibration

c) Waves caused by kinematics

Waves caused by variation in elasticity within the annual rings (Figure 4h, i).

These particular waves occur as a result of difference between the hardness and the elasticity of the late and earlywood in species with abrupt transition, which are frequent in softwoods (Stewart, 1980). This defect can be caused when using a high cutting pressure when the earlywood recovers from an elastic deformation as compared to latewood (Cotta *et al.*,1982). Distortion also takes place in surfaces sanded at a low moisture content and later exposed to humidities reaching to a higher equilibrium moisture content.

Waves caused by vibration (Figure 4j)

These are grooves, which appear more or less regularly as a result of oscillations in the machine-tool-workpiece system. Possible causes are unbalanced tools or inadequate restraint of the worpiece. These defects are more likely to occur in a milling process than abrasive one.

Waves caused by kinematics (Figure 4a)

These irregularities are different from those caused by vibration because they depend on the processing kinematics and have a regular shape which repeats with approximately the same pitch. Sanding does not lead to this type of irregularities as the sanding belt is in continuous contact with the surface. This is not the case with the cutters used in peripheral milling and the distance between cutter marks can be used as a quality criterion for planed solid wood surfaces (Westkämper and Riegel, 1993b). Sanding does not cause kinematic waves.

Micro-irregularities can be classified into three further types: tool marks, surface damage and fuzzy grain

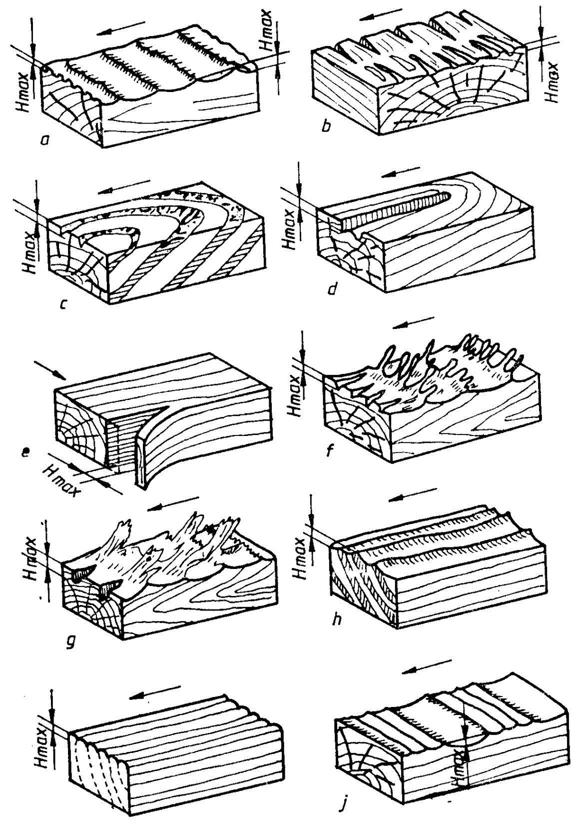


Figure 4 Types of irregularities on wood surfaces (Dogaru, 1981); *Hmax* represents a roughness height parameter from an old standard GOST 7016: 1975

Tool marks

These are indentations on the surface produced by the tool regardless of whether it is an abrasive or cutting tool. The direction and size of the marks depends on the process kinematics and the tool geometry. Tool marks in Figure 4a are characteristic of a milling process, whereas Figure 5 shows longitudinal scratches produced by abrasive grit particles in a process of sanding.

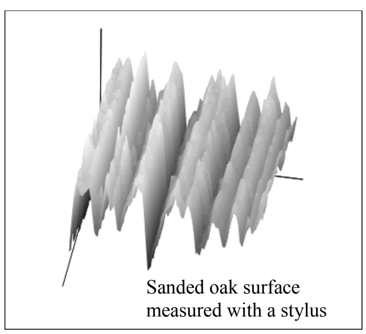


Figure 5 Tool marks characteristic to a sanding process. Image taken from a measurement with a stylus of an oak surface sanded with grit P60.Area scanned 1 mm × 1 mm (Gurau, 2004).

Surface damage

Surface damage includes cavities, cracks and pull-out, and can reach values of several millimetres, which can influence the quality of the surface considerably (Figure 4b, c, d, e). They can be caused by worn cutting tools or when the depth of cut is too high or if the wood has little resistance to cutting. These defects are specific to cutting and do not occur with sanding.

Fuzzy grain

Fuzzy grain denotes individual fibres or groups of fibres that have not been cleanly removed by machining and are still attached to the processed surface (Figure 4f, g). They could lie on the surface or could stand up above the surface.

Fuzzy grain is generally associated with tension wood, which is characterised by a weaker cohesion between cells than normal wood and also shrinks and swells more with changes in moisture content. It also occurs when sanding low density species (Stewart, 1980). Moisture content is another important factor that can cause fibre to rise. This is the case when sanding wood at higher or lower moisture content than the environment where the product is kept (Stewart, 1980). Dull tools can also induce fuzzy grain because they exert excessively high cutting forces that increase crushing and do not cleanly remove wood fibres (Stewart, 1980).

Another type of surface damage not mentioned in the scheme above is **crushing of the subsurface** (Figure 6). This describes a layer of crushed wood below the surface; it is a permanent or semi-permanent deformation of the wood characterised by cell deformation or layers of different density invading one another (Stewart, 1980; Carrano, 2000). It frequently occurs with softwoods and mostly in earlywood areas. This phenomenon was associated with the use of blunt tools in cutting operations and high contact pressure in abrasive sanding and Caster *et al*. (1985).

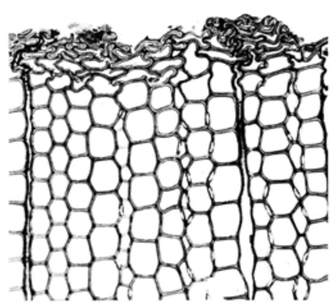


Figure 6 Crushing of the subsurface visible at Douglas Fir earlywood sanded with 80 grit size (Caster *et al*., 1985).

Carrano (2000) studied subsurface damage in oak after machining with a knife planer and gave a qualitative and quantitative classification of the type, occurrence and frequency of damage. Deep subsurface damage is not usually visible immediately after machining, but becomes apparent, to the extent that it affects the quality of the surface, after water-based staining and lacquering, changes in humidity or simply with time.

Caster *et al.* (1985) noted that the crushing of the subsurface caused by sanding can be minimised by using a fine grit size. A fine grit penetrates less deeply into the wood surface and leaves narrower marks than larger grits. This results in a smaller force component normal to the surface of the workpiece and less damage.

In conclusion, from the general classification by creating proper processing conditions some irregularities can be entirely avoided (Dogaru, 1981; Radu, 1966); these include those caused by vibration. Some others can be greatly diminished; for example waviness caused by elasticity differences within the annual ring, by using conditioned specimens with 8 – 10 % moisture content and controlling the contact pressure. Fuzzy and torn grain can be much reduced by avoiding dull tools, variation in moisture content and by pre-wetting the surface before sanding (Westkämper and Riegel, 1993a). Tool marks cannot be entirely eliminated and they represent the **processing roughness** (Radu, 1966, Riegel, 1993). The existence of subsurface damage makes surface finishing difficult, but it can be avoided by the use of fine grit sizes and a reduced contact pressure.

From the above classification, it can be seen that characterization of a wood surface is a much more complex case in comparison with a homogeneous material, as metal. Now, **the following question is how can different features present on a wood surface be measured and how one can distinguish the contribution of processing to the surface quality in isolation from some other wood inherent irregularities or accidental flaws**? Even when a measuring instrument is used for surface characterization and this gives some roughness parameters as a result of software evaluation, **how one can understand the significance of values given the fact that the instrument does not separate specific wood features for us?** In order to answer all these questions, the following sections will present the general steps undertaken in surface metrology, by insisting on challenges they rise for wood, but also on approaches of different researches from literature, including solutions and recommendations from the studies of the author of the habilitation thesis.

1.2 How do we measure and evaluate wood surface quality?

1.2.1 General approach for measuring and evaluation of wood surface quality

The quality of a processed surface is important because it determines the final quality of a finished wood surface and influences the finishing costs. In spite of this, opinions on the quality of sanding commonly rely on human perception by visual and tactile assessments based on experience rather than on quantitative measurements (Sandak and Tanaka, 2002). Both are subjective methods, which may bias the evaluation of the quality of sanding, to the extent that some rough surfaces may be judged smooth or a smoothly processed surface may be considered rough.

An objective, quantitative evaluation of surface quality requires the use of **measuring instruments** to collect data from the surface, followed by a series of **filtering procedures** and finally, by a **numerical evaluation** of the surface roughness. A numerical evaluation implies the calculation of **standard roughness parameters** that allow comparisons to be made between different surface textures.

The principal measure of the quality of processing is the **surface roughness**, so a greater understanding of the effect of process parameters on surface roughness would encourage the optimisation of processing operations. Although methods for measuring surface roughness have been standardised for homogenous materials, they are not applicable to wood, and no other specific guidelines have been developed (Krish and Csiha, 1999, Thoma et al. 2015, Thibaut et al. 2016).

Roughness represents the finer irregularities of the surface texture that are inherent in a machining process (ASME B46.1: 2009). However, profile data from any nominally flat surface contains not only roughness, but also form errors and waviness that do not characterise the processing. Form errors and waviness should be excluded from any assessment of the surface roughness. **Form errors** constitute large deviations from the nominal shape of the workpiece. They may be due to internal stresses in the wood or inaccuracies in the machine/tool/workpiece system. Form errors are removed by a least-squares regression to obtain what is called **the primary profile** (ISO 3274: 1996).

Waviness is caused by incidental variables such as machining vibration or differential shrinkage within the growth ring. Waviness is removed by numerical filtering of the primary profile. Filters are categorised by their wavelength cut-off value λ, which separates the wavelengths that are within the range of interest for a particular feature from those that are not (ISO 11562: 1996). The line corresponding to the wavelength suppressed by the profile filter is called **the mean line**. **The roughness profiles** are obtained by a standard procedure of subtracting the mean line (supressed waviness) from the primary profile.

Roughness parameters can be calculated from roughness profiles that allow comparisons to be made between different surfaces. If these parameters are to be useful, they **must be repeatable**, which **implies some standardisation** of factors affecting their measurement and calculation. Such factors include the measuring instruments, measuring and filtering methods and the choice of standard or non-standard parameters.

A detailed set of recommendations for accurately measuring and evaluating the processing roughness of sanded wood surfaces was first outlined by Gurau (2004) and **intensively tested, after the PhD graduation, for reliability and accuracy, on different types of surfaces and species and results were disseminated**. The following sections contain a review of those studies in the context of up-to-date literature data.

1.2.2 Which measuring instrument or method should be used?

1.2.2.1 Measuring by touch and visual assessment

For wood and wood based products, ASTM D1666-11, first implemented in 1987, defines testing procedures for operations which are common for wood industry, such as planing, routing/shaping, turning, mortising, boring, and sanding, but the processing quality is evaluated by visual inspection. A visual examination of a wood surface can be affected by wood lustre, grain characteristics and the light source. However, opinions on the quality of sanding commonly rely on subjective human perception by visual and tactile assessments based on experience rather than by quantitative measurements (Sandak and Tanaka 2002).

Fujiwara et al.(2004) defined a numerical parameter, the relative area of roughness profile peaks above a threshold height, Arp, and found a good correlation between this and a qualitative tactile roughness parameter. However, Galley et al. (1998) stated that tactile methods are affected by human subjectivity, which is negatively influenced by anatomical roughness and variation in grain angle. Either method, visual or tactile, may bias the evaluation of the quality of sanding, to the extent that some rough surfaces may be judged smooth or, inversely, a smooth surface to be considered rough. Another disadvantage of both visual and tactile evaluation is that only gross comparisons are possible; specific information about surface characteristics cannot be determined (Sandak and Tanaka 2002) An objective, quantitative evaluation of surface quality requires the use of measuring instruments to collect data from the surface, followed by a numerical evaluation of the surface roughness (Sinn et al. 2009, Goli and Sandak 2016).

1.2.2.2 Measuring with an instrument

Neither specific instrumentation nor rigorous universal methods have been developed for the evaluation of the surface roughness of wood and wood composites (Sinn and Sandak 2009, Thoma et al. 2015).

Many methods and instruments have been tested for evaluating wood surface. One method is light sectioning (Yang et al. 2006), which involves casting a thin line of light onto a wood surface at an angle and observing the reflection using a microscope to magnify the light sections. The main advantage of light sectioning is that it requires no physical contact with the wood surface and can easily detect fuzzy grain (Peters and Cumming 1970). A disadvantage is that only a narrow line across the surface is evaluated and numerical evaluation is difficult and time consuming, plus, the measuring length is short.

Another method is image analysis, which consists of shining incident light from a collimated light source at an angle on to a surface. The 3D image from the illuminated surface can be captured with a digital video camera and then the data is processed by a series of coding, filtering and segmentation procedures to remove image features not related to roughness (Schadoffski 2000). A limitation is that features with the same optical characteristics are hard to differentiate. Also, the nature and angle of light incidence and the grey scale level are critical parameters in the roughness determination.

Gloss meters (Fujimoto and Takano 1999), which compare the intensities of a given incident light and that reflected from a surface can be used to estimate surface roughness; the rougher the surface the lower the amount of reflected light. However, the variable reflectance properties of wood make this method unreliable; the presence of ridges and torn fibres results in light diffusion and the flatter the irregularities the greater the gloss and the reflectivity.

A pneumatic method exists that uses the amount of airflow through the gap between the sample surface and a smooth, flat surface of the measuring gauge (Hiziroglu 2005). The method cannot distinguish between very smooth surfaces containing a few large pores and rougher surfaces with no large pores and it only provides a single reading that is an average for the surface and cannot be analysed further (Westkämper and Schadoffski 1995a).

The capacitance method is another area averaging method and it measures the capacitance of the void space between an electrically insulated sensor and the surface under evaluation. Westkämper and Schadoffsky (1995a) stated that it is difficult to apply the capacitance method to wood surfaces since the dielectric constant for wood is influenced by moisture content and presence of fuzzy grain. Furthermore, it would appear that the limitations of the pneumatic method also apply to the capacitance method.

The acoustic emission method consists of rubbing two surfaces together to produce acoustic emissions that can be sensed by piezoelectric transducers coupled directly to the specimen. Cyra and Tanaka (2000) and Iskra and Tanaka (2006) used this method to assess the quality of wood surfaces despite the recommendations of Lemaster and Beall (1966), who note that the method when applied to wood surfaces does not give the actual profile, but provides a reading averaged over an area and it is sensitive to individual fibres.

However, the most used measuring instruments were with stylus and by laser and this approach is discussed in the following section.

1.2.2.2.1 Research on wood surface measurements comparing stylus with laser

The first contact stylus roughness measuring instruments appeared at the beginning of the 1930's and the resultant surface texture was exclusively based on 2D profilometry, i.e. (Whitehouse 1994).

Marian et al. (1958) found a stylus was sufficiently sensitive for recording irregularities due to processing and wood anatomy. Some authors, however, have suggested that the contact force and the tip geometry of the stylus may distort the measurements (Schadoffski 2000). However, a Talysurf stylus with 90º pyramid and a spherical tip of 2 μm radius, as described in ISO 3274 (1996), was found unlikely to damage wood (Westkämper and Schadoffski 1995a). Consequently, this setup has been used by many researchers for assessing wood surfaces (Magross 2015) and others have used a 5 μm radius (Westkämper and Schadoffski 1995a , 51. de Moura and Hernandez 2006). Likewise, studies on MDF surfaces have mainly been done using a stylus (Hiziroglu 2005, Prakash et al. 2011).

In the 1980's, 3D measuring instruments appeared, such as the laser techniques based on the reflection of laser light from a measured surface. This non-contact technique has been applied and recommended for wood surfaces (Goli and Sandak 2016). However, Sinn and Sandak (2009) stated that due to the degree of roughness and the variable reflectance characteristics of wood surfaces, laser techniques cannot always accurately measure surface roughness. Similarly, comparing laser triangulation with stylus scanning, Fujiwara et al. (2001) found that the laser detected unusually high amplitude irregularities when scanning a coated wood surface.

Studies of Gurau et al (2001), complemented later by Gurau et al (2005b, 2005c, 2012) *showed that a stylus was better able to detect wood surface irregularities and provided more accurate and repeatable data than a laser triangulation device*. A Taylor Hobson instrument, TALYSCAN 150, was used that could apply two of the most common measuring techniques, laser triangulation and stylus scanning, with a single handling of the specimen. Since only the scanning head was changed, this instrument offered the advantage of inspecting exactly the same area with both methods. Their suitability for wood surfaces was evaluated in terms of their repeatability and their ability to detect peaks and valleys.

The stylus was better able to detect surface irregularities and was more accurate than the laser triangulation device, in spite of the fact that stylus may have its own limitations regarding the accuracy of surface readings because of its size and shape causing some of the smallest features to be overlooked (Sinn and Sandak 2009). The laser has a tendency to smooth the surface profile irregularities (Figure 7). This was in agreement with Sandak and Tanaka (2002), who observed that the laser has a tendency to “average” surface profile irregularities. Consecutive measurements of the same profile showed that stylus is more repeatable than the laser (Figure 8). Those characteristics made the stylus more reliable in meeting the objectives of this research in that it was better able to separate processing and anatomical irregularities (Gurau et al.2012). However, the stylus was significantly slower than the laser triangulation, and so this may preclude it from in-line quality control.

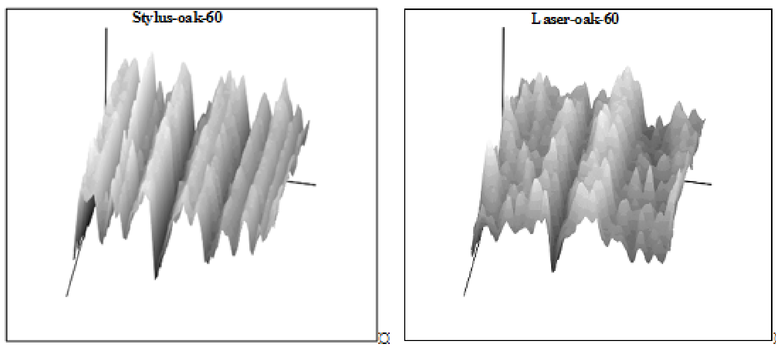


Figure 7 Comparison of stylus and laser surface images on an oak area of 1 mm x 1 mm (Gurau et al. 2012)

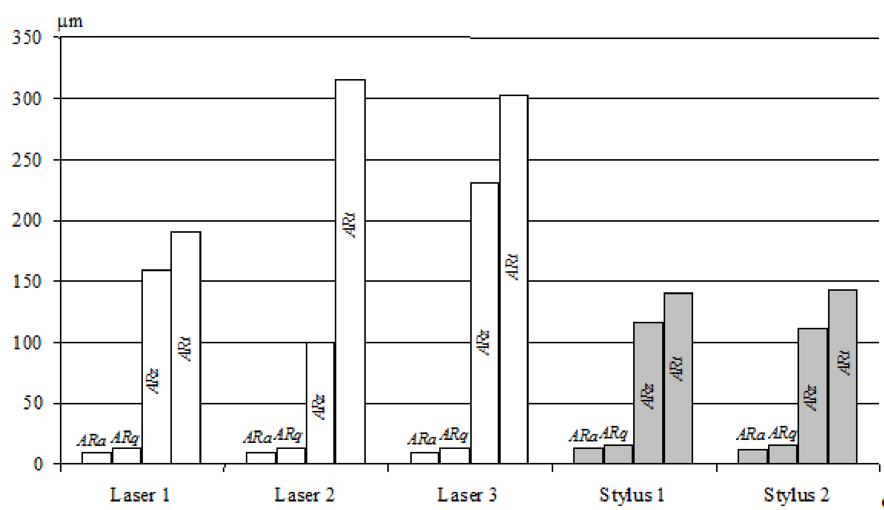


Figure 8 Repeatability of measurements with laser and stylus evaluated with area mean and height parameters (ASME B46.1: 2009) on a spruce surface sanded with P60 (Gurau et al.2012).

Conclusion:

Stylus tracing remains the most accurate measuring technique despite the slow speed of the method compared to the laser technique and the fact that it is only usable in off-line measurements. Both the stylus and laser techniques have the advantage that they provide measured data points for further numerical evaluation.

1.2.3 Which measuring resolution is the most appropriate for wood?

Apart from the selection of a reliable measuring instrument, it is very important to properly select the measuring resolution.

The horizontal or lateral resolution of an instrument is the size of the smallest feature that it can distinguish on a surface and is determined by the sampling interval and the physical characteristics of the mechanical or optical instrument (Morris, 1993). The sampling interval defines the measuring resolution and represents the interval between two consecutive measuring points.

Sometimes, when the surface is very rough, a lower resolution than the maximum possible may be preferable to simplify the reading and parameter interpretation. However, a larger interval means fewer sampling points and increases the chance of missing peaks and valleys, so the peak to valley distance tends to decrease (Carrano, 2000).

A high resolution provides a very detailed data set that can be filtered later, but also increases the time for scanning and data processing. The best resolution is the lowest resolution that still allows an accurate evaluation of roughness parameters.

The sampling resolutions published in the literature vary from 280 μm for the surface of peeled veneer (Faust and Rice 1986), 200 μm for a sawing process (Usenius 1975), and for sanded surfaces: 10 μm (Westkämper and Schadoffski 1995a), 2.5 μm (Carrano 2000) and 2.2 μm (Schadoffsky 2000).

The general standard ISO 3274 (1996) gives a recommendation for selecting the appropriate resolution or sampling interval in relation to the radius of the stylus tip and the filter cut off length. For instance, for a cut off length of 2.5 mm a maximum resolution of 1.5 μm is recommended, while for a length of 8 mm, 5 μm is stipulated. It has been found that these standard recommendations are not applicable to wood.

This observation was the startpoint for the author research on the influence of the measuring resolution on the surface quality results and on the selection of the most appropriate measuring resolution value.

1.2.3.1 Research on the influence of the measuring resolution on the evaluation of wood surface quality

The fact that standard recommendation do not apply for wood, the various measuring resolutions used in the literature and the lack of consensus has inspired the author to focus on this issue and find a solution and acceptable recommendation for wood surfaces.

Therefore, Gurau et al (2013a), **cited 6 times in ISI Web of Science**, *examined the effect of decreasing the resolution on roughness parameters* starting with a resolution of 1 μm, which was taken as a reference.

The effect of varying the resolution was investigated on beech and spruce specimens sanded with P1000 grit size and oak specimens sanded with P1000 and P120 grit size, scanned at 1 μm resolution. It was assumed this resolution captured all the anatomical and processing details, subject to the limitations caused by the geometry of the stylus and the precision of the instrument.

Lower resolutions of 2, 5, 10, 20, 50 and 100 μm were obtained as sub-sets of the original data. A visual comparison of decreasing the resolution and the consequent distortion is given in Figure 9 and Figure 10 for oak sanded with P120.Since the datasets were from the same surfaces and differed only in their resolution, the effect on the roughness parameters of choosing different resolutions could be clearly observed. For resolutions lower than 1 μm the error for each parameter was calculated in percentage terms.

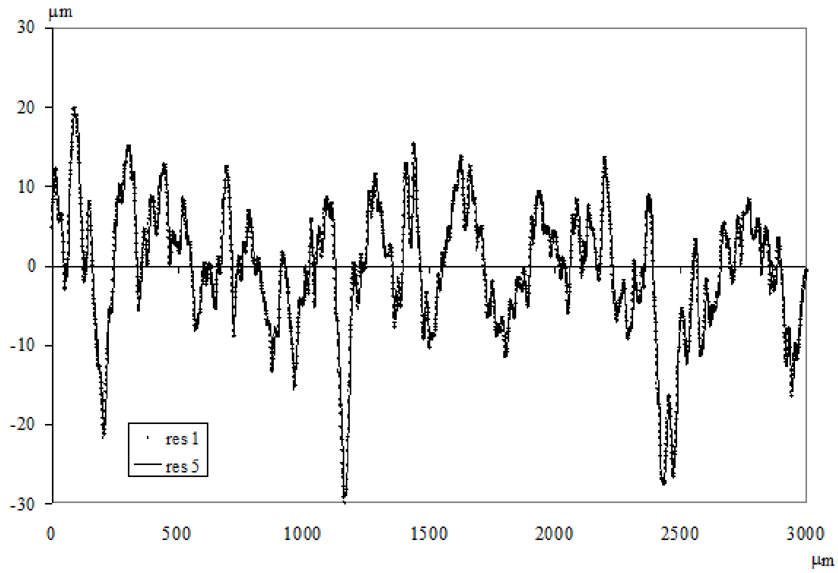


Figure 9. The effect of decreasing the resolution to 5 μm; oak sanded with P120 (dotted line - resolution 1 μm, solid line - resolution 5 μm) (Gurau et al.2013a).

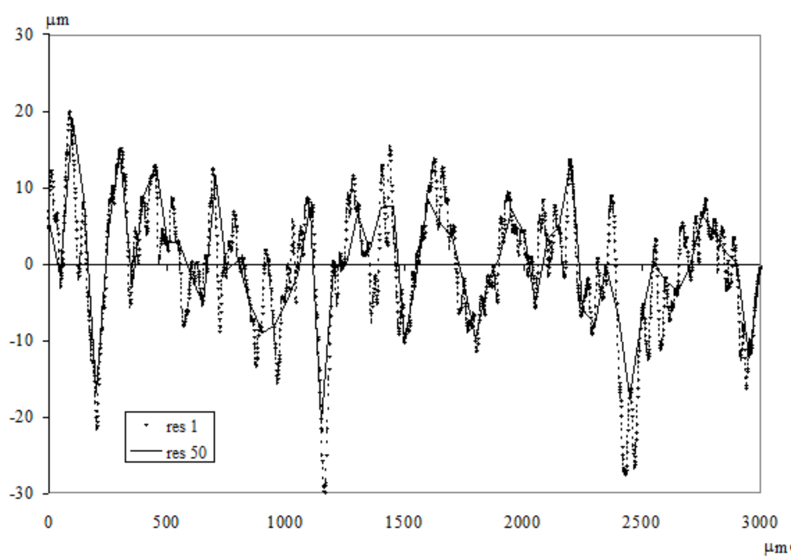


Figure 10 The effect of decreasing the resolution to 50 μm; oak sanded with P120 (dotted line - resolution 1 μm, solid line - resolution 50 μm) (Gurau et al 2013a).

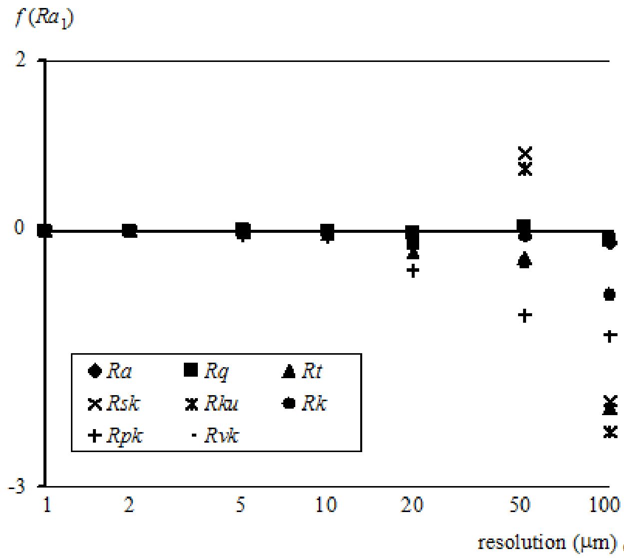


Figure 11 The influence of measuring resolution of an oak surface sanded with P120 on normalised roughness parameters (x-logarithmic scale, y-normalised data; Ra_1-value of *Ra* at resolution 1 µm). All values are in µm (Gurau et al. 2013a).

The parameters *Ra*, *Rq*, *Rsk*, *Rku* were calculated as in ISO 4287:1997, but over the evaluation length. *RSm* from the standard was modified and is renamed *RSmw* in this paper. *RSmw* differs from *RSm* in that the minimum height and spacing requirements for a profile element are disregarded. If they are not, then the width and depth of the anatomical features can obscure the processing features. The other calculated parameters were *Rk*, *Rpk* and *Rvk* from ISO 13565-2: 1996.

The roughness parameters were also presented as figures for each grit and species combination. Figure 11 shows an example of oak sanded with P120. The data have been normalised on the y axis relative to the parameter *Ra* and the x axis has a logarithmic scale.This method of presentation allows an overview of the variation of the parameters (details in Gurau et al.2013a) .

The value of any roughness parameter *R* on the y axis is given in [1] as a function of *Ra* measured at a resolution of 1 µm. **Error! Reference source not found.** shows variation of *RSmw*, the spacing parameter.

$$f(Ra_1) = Ra_1\left(\frac{R_i}{R_1} - 1\right) \qquad [1]$$

Ra_1- *Ra* parameter measured at a resolution of 1 µm.

$f(Ra_1)$- value of a roughness parameter *R* normalised relative to Ra_1.

R_1- roughness parameter *R* measured at a resolution of 1 µm.

i- rank marking the value of resolution

Conclusion:

Results showed that a measuring resolution of 5 µm seems reliable for all species sanded with common grit sizes and for a 2.5 mm filter cut-off length.

1.2.4 Which measuring length and direction of measuring are the most suitable for wood?

Apart from the selection of a reliable measuring instrument and measuring resolution, it is important to select an appropriate measuring length. The measuring length is the total scanning length of the measuring instrument. It can be equal to or greater than the evaluation length, which is the length on which a roughness parameter is calculated (Figure 12). The evaluation length usually comprises five sampling lengths, which correspond to the cut-off length of the filter (see section 1.2.5.5). Some filtering techniques, such as the Gaussian filter, introduce some end-effects, which must be discarded from the ends of the profiles (see section 1.2.5.2). This means, the measuring length should be long enough to allow the standard five sampling lengths in the evaluation (Figure 12). In conjunction with ISO 4287, ISO 4288 makes recommendations regarding the choice of the sampling length and evaluation length as a function of the expected range of variation for some roughness parameters. However, the recommendations are not reliable for a heterogeneous material like wood (Westkämper and Schadoffsky 1995b).

Westkämper and Schadoffsky (1995b) tested the effect of increasing the evaluation length on some parameters of a sanded spruce surface. Rz (DIN 4768: 1990) and Rmax (DIN 4768: 1990) showed a steady increase, while Ra remained constant.

Fujimoto and Takano (1999) tested the effect of increasing the sampling length when evaluating routed wood surface quality. The roughness parameters increased with the sampling length. When the ratio of the evaluation length to the sampling length was greater than five, Ra was nearly constant, but it varied for values less than five. Both Rz "ten point height of irregularities" (ISO 4287 1: 1984) and Rmax increased with the evaluation length.

Various measuring lengths have been applied to wood surfaces (Westkämper and Schadoffski 1995b, Fujimoto and Takano 1999) but there has been no general agreement as to which is the most appropriate. For example, the measuring lengths used on sanded wood surfaces have included: 12 mm (Kilic et al. 2006), 12.5 mm (Thoma et al 2015, Magross 2015), 15 mm (de Moura and Hernandez 2006), 25 mm (Hendarto et al.2005), 30 mm (Javorek et al. 2015) and 50 mm (Gurau 2004). Similarly, the measuring lengths found in the literature for MDF surfaces range from 8 (Sütcü and Karagöz 2012) to 12.5 mm (Ayrilmis et al. 2010). In order to make a reliable measurement of a wood surface a measuring length of 40–50 mm is desirable, because the roughness parameters have been found to stabilize at these lengths (Gurau et al.2011). Generally, researchers did not make distinction between the measuring length and the length on which the software evaluated the roughness parameters, which is the evaluation length. This means, that effectively, the length on which parameters were evaluated might have been shorter than the measured length if a Gaussian filter was used. More recent filters, such as the Gaussian Regression filter (described later) keep the entire measured length in the evaluation and the measured length can equal the evaluation length.

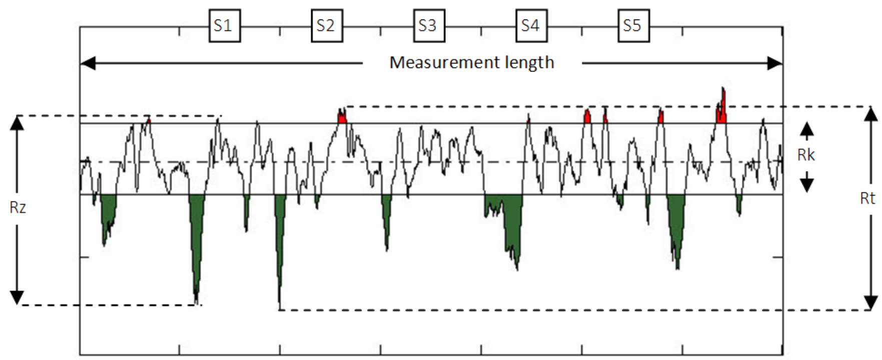


Figure 12 An example of a wood surface profile in which the measurement length is longer than the evaluation length (which is the sum of S1 to S5). The Rz shown is for Sample length 1. The green zones are considered to be caused by anatomy and the red zones represent fuzzy grain (Gurau and Irle, 2017a).

The general standard ISO 4288: 1996 stipulated that the direction of measurement shall correspond to the maximum heights of the roughness parameters. Usually, this direction is normal to the lay of the surface.

Wood surface profiles evaluated across the tool marks are more representative and reproducible than those parallel to the tool marks (Faust and Rice, 1986). Likewise, research by Chen and Huang (1991), on sanded surfaces found higher values for roughness measured across the sanding direction than along it.

1.2.4.1 Research on the influence of the evaluation length and measuring direction on the evaluation of wood surface quality

Gurau *et al*. (2004, 2012a) made studies on the influence of the evaluation length on the values of roughness parameters and implicitly, on the surface quality. *The objective was to find which are the suitable values for wood surfaces regarding the evaluation length and measuring direction.*

A long evaluation length increases the reliability of the roughness parameters (ISO 4288: 1996) since it increases the probability of recording a profile that contains the variation of the surface. The maximum evaluation length depends on the capacity of the measuring instrument.

In the bove studies, it was found that wood does not comply with the evaluation length requirements of the general standard ISO 4288 (1996) because of its variable anatomy. The evaluation length is associated with the cut-off value of the filter, which is the same as the sampling length (ISO 4287: 1997). According to this standard, a minimum of five sampling lengths is required within an evaluation length. Therefore, ISO 4288: 1996 recommends an evaluation length of 12.5 mm for a cut-off length of 2.5 mm. Gurau *et al*. (2006) found 2.5 mm as a suitable cut-off length for common grit sizes, but, the evaluation length of 12.5 mm does not seem to be long enough for wood.

The sensitivity of the roughness parameters *Ra*, *Rk* and *RSmw,* calculated as above, to the evaluation length was investigated on profiles from tangential surfaces of oak and spruce sanded with P120 grit. The roughness parameters were initially calculated over a 5 mm length, taken as the first 5 mm of the profile. The evaluation length was gradually increased to 50 mm.

Figure 13 shows that all roughness parameters for spruce were unstable at the standard evaluation length and tend to stabilize towards a value of 50 mm. Similar observations were made for oak.

Note that the ordinate values for RSmw and Rk are not their real values; to ease the comparison they were normalised relative to Ra. A value of 50 mm seems reasonable for wood because the amount of variation of the roughness parameters stabilised. This value was also recommended by Richter et al. (1995), but without any published justification.

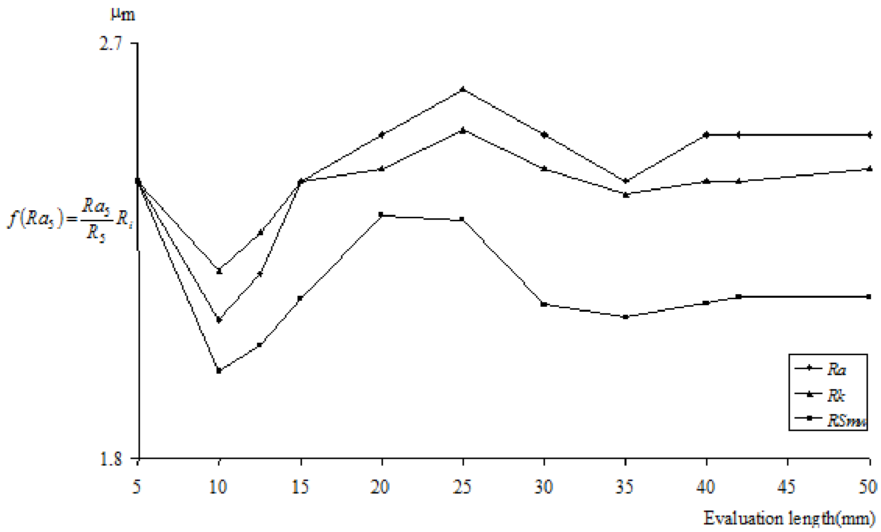


Figure 13 The influence of the evaluation length on the roughness parameters *Ra*, *Rk* and *RSmw*; spruce sanded with P120. In the equation *f* (Ra_5) - the representation of the roughness parameter on the y axis; Ra_5 - value of *Ra* at 5 mm evaluation length; R_5 - value of any roughness parameter *R* at 5 mm evaluation length; *i* - rank marking the length of evaluation (Gurau et al. 2012a).

In Gurau et al. (2012a), the influence of measuring direction was examined on the roughness parameters Ra, Rq, Rz and Rt from ISO 4287: 1997, calculated from an oak surface sanded along the grain with P60 grit. The roughness parameters were adapted for wood in that they were calculated over the entire evaluation length rather than shorter sampling lengths (see section 1.2.7). The evaluation length is restricted by the capacity of the measuring instrument, so its division into sampling lengths, as instructed by ISO 4287, leads to data sets that do not represent the variation of the wood surface (Gurau, 2004).
The surface was measured with sequential scans across the sanding marks, which is more representative and more reproducible than along the marks, (Faust and Rice, 1986, Richter et al.1995) but the roughness parameters were evaluated both along and across the sanding marks (Figure 14).

Wood surfaces should be measured in the direction that gives the maximum values of the irregularities (Triboulot, 1984). Parameters across the grain were higher and had lower standard deviations than those along the grain. In a single factor ANOVA test, the roughness parameters were significantly higher across the grain than along the grain at the 1 % significance level. This is in agreement with the results obtained by Palermo et al. (2014).

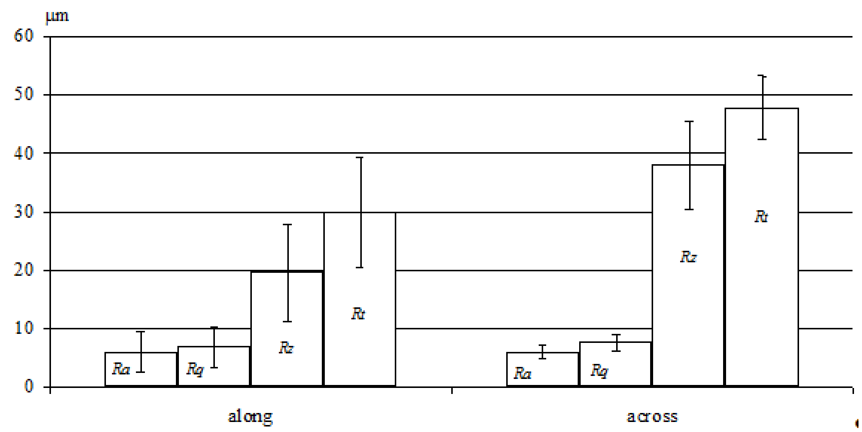


Figure 14. Comparison of roughness parameters for profiles measured along and across the sanding direction, oak sanded with P60 (Gurau et al 2012a).

Conclusions:

A measuring direction across the sanding marks was more meaningful, and it is suitable for further separation of sanding marks from wood anatomy.

As far as the evaluation length is concerned, a value of 50 mm seems reasonable for wood because the amount of variation of the roughness parameters stabilised.

1.2.5 Research on filtering a measured wood surface and associated problems

The previous sections referred to measuring a wood surface, instruments and measuring parameters, which were tested and adapted for wood in various publications of the author.

The standard procedure indicates that after a surface is measured with an instrument and a quantitative information/data is collected from this surface, ususlly in an ASCII format, this information is sent to a dedicated software for evaluation.Usually, the software is attached to the instrument and the user can select some entry data, such as: can opt for form removal, can select the filter for separating the surface roughness, with some limitations can select the cut-off length of the filter (in case is not implicitly correlated with the profile length and imposed by the software), can select the roughness parameters to be calculated. However, these software do not differentiate wood from other more homogeneous materials, apply the same standard procedures and for this reason, the user cannot detect errors occurring during wood surface evaluation. Simply, the software gives a result, but without offering the user the possibility to check if data was biased or not. During a thorough research of the author, complemented with research from other authors, it was found that wood surfaces behave differently than other materials. Wood contains the irregularities/cavities due to own anatomy and it was found that this is a serious source of bias in the process of evaluation. Therefore, the following sections take this procedure of data evaluation, step by step, observing the results when common standards are followed and applied to wood. Specific corrections and evaluation protocol are defined as a result of research on this topic.

The first step, when a surface data is measured is to remove any form errors that were recorded during measuring. This subject is detailed in the next section.

1.2.5.1 Research on removing form error from a measured wood surface

Gurau et al (2009a) has studied the influence of the standard procedure of form removal on the evaluation result of the quality of sanded wood surfaces. *This study had the objective to examine if standard procedure for form removal is applicable to wood or not.*

Data from any processed surface contains inherent form errors, which are slopes or curves that characterise the inaccuracy with which the specimen has been machined. Form errors must be removed to straighten the surface. The standard method of removing form errors for individual profiles is contained in ISO 3274: 1996 and consists of fitting a polynomial regression through the original data. The original profile is called the **total profile** (ASME B46.1: 2009). A **primary profile** can be obtained by subtracting the regression from the total profile (Figure 15).

It is known from the literature that the presence of deep pores under a relatively smooth plateau of processing irregularities affects the shape of the primary profile which is obtained by following ISO 3274: 1996 (Krish and Csiha, 1999). Although this phenomenon also occurs for surfaces that require a higher order polynomial and have deep grouped pores, the disturbance is more visible in linear profiles. The presence of grouped pores can significantly change the slope of the linear regression (Figure 16).

If the surface quality is numerically evaluated with the **primary profile P parameters** defined in the most common standard ISO 4287: 1998, it is important that deep grouped pores do not introduce bias otherwise an incorrect assessment is obtained.

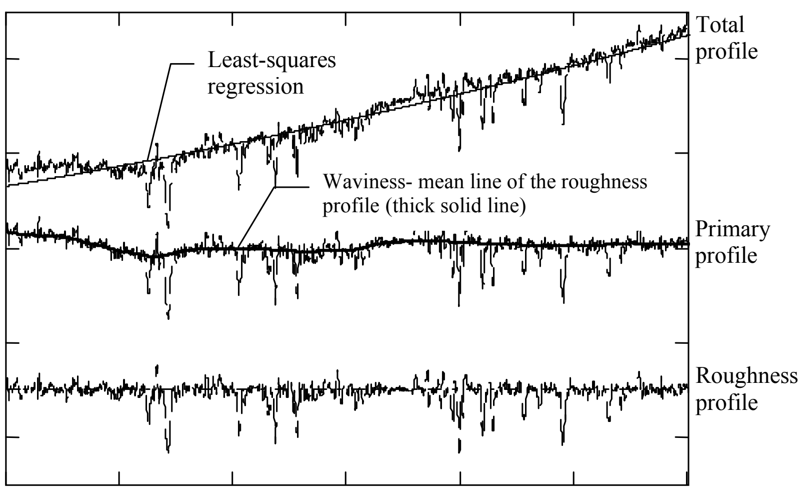


Figure 15 Schematic filtering of profile irregularities shown on an oak profile sanded with P120 Gurau et al, 2009a).

The importance of a non-distorted primary profile results also from the fact that in general, the primary profile is the basis for further digital profile processing. The primary profile contains irregularities with low frequency components, which are the waviness, and high frequency components, which are the roughness (ISO 4287: 1998). The process by which the **roughness profile** is obtained from the primary profile employs more complex filters than those used for the initial removal of form error. This process is generally referred to here as filtering (see section 1.2.5.2). Filtering suppresses the long wave component (waviness) of the primary profile (ISO 4287: 1998). Profile filters are identified by their wavelength cut-off value λ, which determines which wavelength belongs to roughness and which to waviness. The line corresponding to the wavelength suppressed by the profile filter is called **mean line.** The mean line is calculated at each point of the profile by averaging locally weighted values. The roughness profile is calculated by subtracting the mean line (waviness) from the primary profile (Figure 15).

This study contains a method, which was developed by Gurau et al (2009a), that eliminates the influence of wood pores when removing form error. The principle of this method and of the standard method from ISO 3274: 1996 are presented and the results of removing form error are compared.

An oak surface was sanded with a very high grit size P1000. Such highly polished surfaces represent an extreme case of sanding where the height variation due to processing is minimised, while the effect of anatomy and any distorting effects is maximised. Measurements were carried out with a Taylor Hobson instrument TALYSCAN 150 using a stylus with a 2 μm tip radius and a 90° tip angle. The length of the profiles scanned across the grain was 50 mm. A random profile was taken from the surface for further processing.

Another set of data was obtained from an external source[1]. It is a total profile obtained from a back locust (*Robinia pseudoacacia*) surface, 12.5 mm long and sanded with P240 grit. Black locust sanded with P240 is another example of a species with deep pores located under a smoother plateau of irregularities produced by sanding.

Both oak and black locust total profiles were processed with the standard method of form removal from ISO 3274: 1996 and with the method where the pores are removed prior to removing form errors. The principles of both methods and the resulting primary profiles are presented in the following section. The highest density data in a profile is concentrated within a height range that characterizes the sanding irregularities. Any data isolated from the core will bias the location of the regression. The coefficient of determination, r^2, between a regression line and its corresponding profile indicates the degree of fit. Comparisons are made between a regression line according to ISO 3274: 1996 and the total profile and between that of the modified regression line, where the effect of deep pores was previously removed, and the modified profile, that should contain only the sanding data without the biasing effect of deep pores.

Another study investigated whether the shape of the primary profile can affect the shape of the filtered roughness profile. The primary profiles of oak and black locust obtained with the standard method (ISO 3274: 1996) and the method of initial removal of pores were filtered with a Robust Gaussian Regression Filter (see section 1.2.5.2). The oak profile sanded with P1000 required a cut-off length of 8 mm, while the black locust profile sanded with P240 was filtered with a 2.5 mm cut-off length (Gurau *et al*. 2006a).

[1] University of Sopron, Hungary courtesy to Dr. Csiha Csilla

Form removal to the standard method ISO 3274: 1996

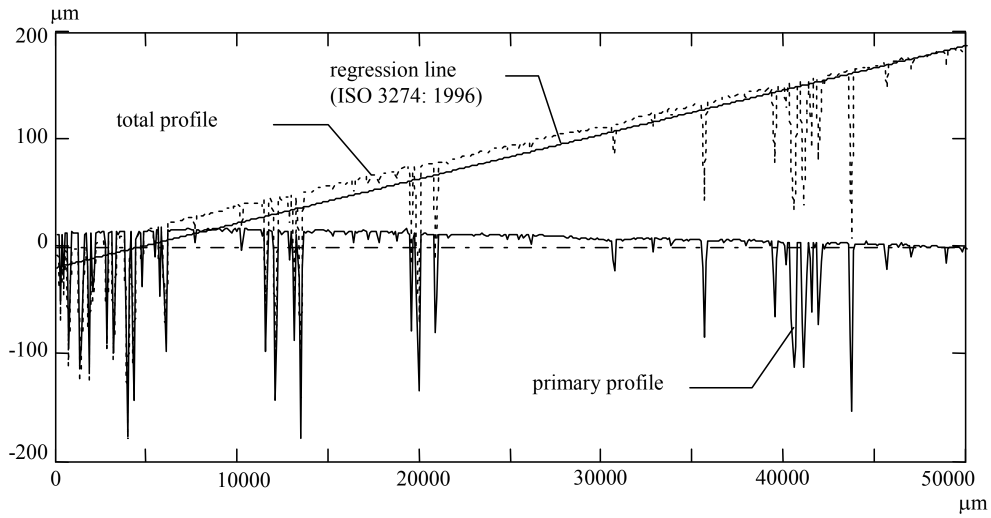


Figure 16 Procedure for removing form errors from an oak surface sanded with P1000 (dotted line - the total profile; solid line - the primary profile) (Gurau *et al*. 2009a)

According to ISO 3274: 1996, the primary profile P is computed from the **total profile T** by excluding the nominal form using **the method of least squares regression** to calculate a line of best fit.

Figure 16 shows the total profile of oak sanded with P1000, where the regression line was distorted by the grouped pores to the left-hand side of the profile.

The primary profile (Figure 16) is obtained as follows $P_i = T_i - f(T_i)$, where $f(T)$ is the regression function and *i* is an index whose length depends on the length of the profile and the measuring resolution. The primary profile suffered from the influence of deep pores and it is inclined relative to the mean line.

The phenomenon of distortion also occurred in the black locust profile. Although this profile required a second polynomial regression, this was also distorted by the presence of deep pores at the end of the profile.

Form removal with the method with initial removal of pores (Gurau *et al*. 2009a)

If the pores are responsible for deviations in the shape of the primary profile then they should be removed completely prior to any form correction.

An algorithm, containing several steps, was designed for this purpose. The first step is to fit a regression line through the total profile. The gradient of the line is used to remove the slope of the total profile, so obtaining the primary profile P as in Figure 16.

The following steps are designed to reduce the influence of pores in the total profile by using a threshold to define data points as being in valleys. First, the Abbot-curve of the primary profile is calculated. The Abbot-curve is a frequency curve in which all the ordinate values are ranked in descending order (Figure 17). Secondly, an algorithm was written to identify the threshold as an abrupt change in the local curvature of the Abbot-curve. The mathematical description of the local curvature can be considered to be the second derivative of a portion of the Abbot-curve (ISO 13565-3: 2000). In the linear regions of the curve the second derivative is near zero, while in the non-linear outer regions the second derivative increases in absolute magnitude. The computation of the derivative at a given point involves a linear regression in a region about the point. The region was taken as 1 % of the length of the profile. This percentage was considered to be small enough to detect the slightest change in the variation of the second derivative.

The computation of the second derivatives starts from the middle index of the regression line that fits the first set of *q* data points considered. The second derivative can be calculated as the difference between the ordinate value of the middle point of this regression window and the corresponding ordinate value in the Abbot-curve. Then the calculation of the second derivative is incremented to the right by a data point, while keeping the same number of data points in the regression window. The last value of the second derivative vector is computed at the middle index of the final window. Compared to the vector of the Abbot-curve the vector of second derivatives contains *q*/2 blank values at each end of the Abbot-curve.

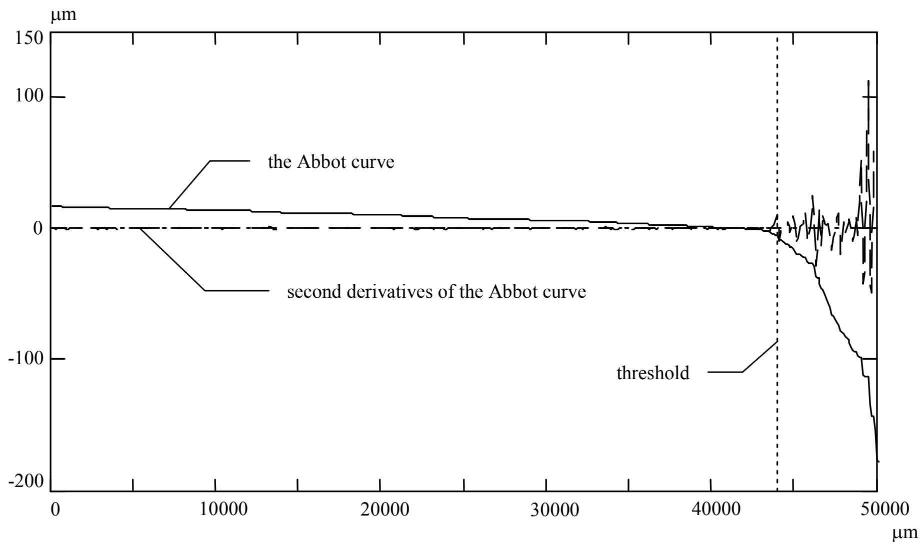


Figure 17 Computation of the second derivative of the Abbot-curve and of the threshold value (Gurau *et al*. 2009a)

The index of the transition point that marks the threshold was identified by finding the first abrupt change in the value of the second derivative. The standard deviation of the first quartile of the derivative values was calculated, then data points were added incrementally to the right. The index of the point where the ratio of the absolute value of the second derivative to the standard deviation of the previous points exceeded a critical value was taken as the index of the transition point. The critical value for the ratio is given in ISO 13565-3: 2000 as 6, but 10 was found to be less likely to cut the profile while it contained some waviness.

The output of this algorithm is an index, which indicates the rank of the value in the Abbot-curve where the transition takes place. Figure 17 shows the Abbot-curve (solid line), the second derivative of the Abbot-curve (dashed line) and the rank (dotted line). The threshold is the value of the Abbot-curve at its intersection with the rank. This threshold is used to separate the deep valleys from the rest of the profile. Values below the threshold were replaced with the value of the threshold itself.

In the next step, the mean line of the profile P is calculated. The calculation of the mean line uses a smoothing function *s*, which is a Gaussian window to compute local weighted averages of the heights and is given in [2] (from MathCAD 2000, Reference Manual - *ksmooth* function).

$$s_{kl} = \frac{1}{\sqrt{2 \cdot \pi} \cdot 0.37} \exp\left(-\frac{(k-l)^2}{2 \cdot (0.37)^2 \cdot b^2 \cdot n^2} \right) \quad [2]$$

s - the smoothing function

n - number of profile data points

k - the index of the location of the smoothing function

l - the index of the profile data points

b - is a proportion of the data points that sets the length of the window for the smoothing process (see [3] from Gurau, 2004).

$$b \cong \frac{\lambda}{2 \cdot \Delta x \cdot n} \quad [3]$$

Δx - the sampling interval

λ - the cut-off wavelength of the profile filter that separates waviness from roughness

The equation for calculating the mean line or waviness *w* is given in [4] (from MathCAD 2000, Reference Manual). The amount of waviness calculated at each point of the profile takes into consideration the equivalent weighted value for every point in the profile.

$$w_k = \frac{\sum_{l=1}^{n} s_{kl} \cdot z_l}{\sum_{l=1}^{n} s_{kl}} \quad [4]$$

w_k - waviness value at index *k*, which is the value of the mean line

z - is a profile height in the unfiltered profile

The deep valleys detected by the threshold level in the previous step are now completely removed from the profile P up to the mean line of the profile P. By reinstating the slope, the total profile may be obtained, but without pores.

The regression line is recalculated from the profile, which is now free of the influence of pores. This new regression line is then subtracted from the total profile that contained the pores and a corrected P profile is obtained (Figure 18). Similar procedure was applied for the black locust, which required a second order polynomial regression.

The new regression line fits the sanding data of the total profile of oak better than the one found with the standard procedure. The improvement is quantified by the r^2 values in **Error! Reference source not found.**. Higher r^2 values for the method with initial removal of pores indicate a better fit. Similar result was found for the black-locust .

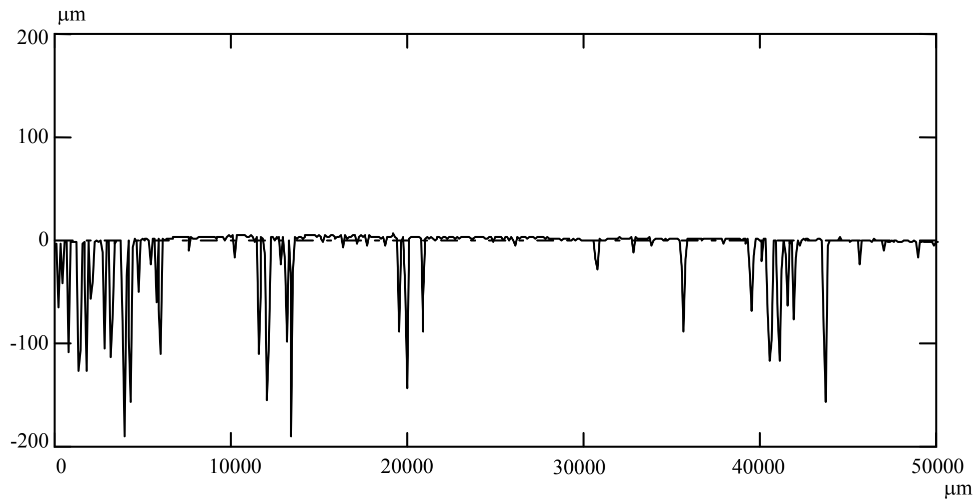


Figure 18 Corrected primary profile with prior and total removal of deep pores (Gurau *et al*. 2009a)

Species	Coefficient of determination r^2 Method from ISO 3274: 1996	Method with initial removal of pores
Oak	0.814	0.997
Black-locust	0.729	0.874

Table 1 Comparison of coefficients of determination r^2 for the standard method and the method with initial removal of pores.

The study, investigated further whether the shape of the primary profile can affect the shape of the filtered roughness profile. For both species, the difference was negligible, except for the first and the last cut-off lengths, where the errors were higher, but still acceptable. This end-effect were probably due to the asymmetry of the smoothing window used by RGRF in the outer areas of the profile (Gurau *et al.* 2005a).

Conclusions

If the surface quality is to be evaluated with the primary profile parameters, P, defined in the most common standard, ISO 4287, the bias caused by deep grouped pores must be excluded. This can be done by mathematically removing pores prior to correcting the form error (Gurau et al. 2009a).

Gurau et al (2009a) showed that, providing the regression line is the best fit of the measured profile, ISO 3274 may be an appropriate method of obtaining the primary profile for further processing in spite of the shortcomings described. Computationally it is less expensive than the method with pores removal, accepting that a small error will remain at the ends of the roughness profile. The rougher the grit size at sanding the smaller the error.

The next step in evaluating the data from a measured surface, after the form error was excluded is to filter the primary profile, in order to get only the roughness profile. This procedure, together with findings of the author are presented in the next section.

1.2.5.2 Research on roughness filters and their suitability for wood

Filtering removes waviness in the primary profile resulting from incidental variations in the machining process, such as vibration, or in the material, such as differential shrinkage within a growth ring.

Filtering suppresses the long wave components (waviness) of the primary profile (ISO 4287:1997). Profile filters are characterised by their wavelength cut off value, λ. The line corresponding to the wavelengths suppressed by the profile filter is called the mean line. It is calculated at each point of the profile by averaging locally weighted values. The roughness profile is obtained by subtracting the mean line from the primary profile (Figure 15).

Compared to metals or similar homogeneous materials, the surface texture of wood depends not only on its processing history, but also on its specific anatomical structure, since it contains cell cavities that are independent of any processing. When this anatomical roughness is greater than the roughness due to processing, standard profile filters, such as those in the standardised filter described in ISO 16610-21 (2011) which was initially presented by the now withdrawn ISO 11562 (1996) as well as ISO 13565-1 (1996) have limitations when applied to wood surfaces. They introduce a type of distortion known as "push-up" (Krish and Csiha 1999, Raja et al. 2002). Its magnitude was analysed for different filters by Gurau et al. (2002 and 2005). Profiles obtained from ring porous species and those where a number of pores are grouped together are particularly susceptible to push-up distortion (Figure 19). The higher the anatomical roughness compared to the processing roughness, the more accentuated the distortion in the roughness profile (Westkämper and Schadoffsky 1995b).

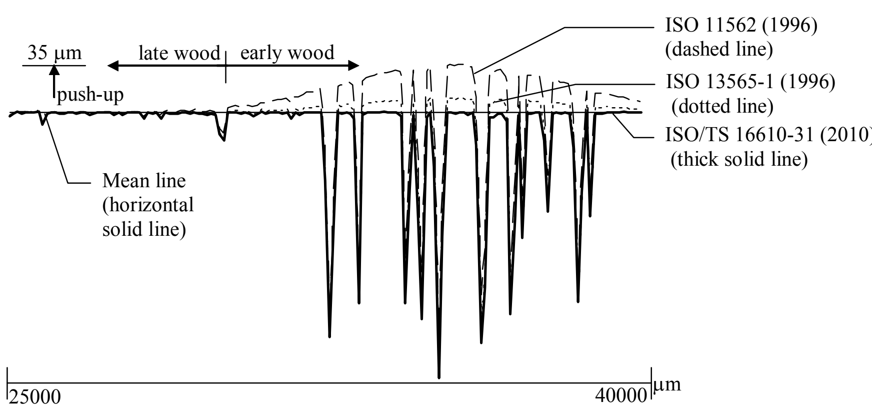


Figure 19 "Push-up" distortion of an oak profile sanded with P1000 when filtering with Gaussian filters from ISO 11562 (1996) and ISO 13565-1 [(1996). The roughness profile filtered with Robust Gaussian Regression filter from ISO/TS 16610 31 (2010) is taken as a reference (Gurau et al.2006a)

Fujiwara et al. (Fujiwara et al.1999) proposed a numerical filtering method to minimize push-up that excluded deep valleys caused by vessels, based on the gradient of the valley sides. The filter was particularly sensitive to the selection of the threshold value of the gradient.

Coelho et al.(2008) proposed a filtering method based on fast Fourier transform (FFT) of image files. The images were generated by 3D laser scanning with light and dark zones corresponding to peaks and valleys respectively.

The filter allows a direct calculation of waviness and roughness criteria from the FFT power spectrum whereby the highest peak is used for waviness and the integral for roughness. The method does not provide for the acquisition of a real roughness profile, the calculation of standard roughness parameters, nor a differentiation between processing roughness and wood anatomical roughness.

The Robust Gaussian Regression Filter (RGRF) is a complex filter that has been tested by Gurau et al (2002) while it was a draft version and found suitable for wood surfaces. The suitability of this filter for wood was also confirmed by studies of Hendarto et al. (2005), Sharif and Tan (2011), Tan et al. (2012) and Piratelli-Filho et al. (2012). The method has been published as ISO/TS 16610-31 (2010). The RGRF filter should produce roughness profiles with no distortion.

The comparison of applying three standard filters to wood surfaces is presented in the following study of Gurau et al. 2005a (**cited 37 times in ISI Web of Science**), which was further detailed in an international book chapter published by Iste-Wiley (Gurau et al.2011).

The objective of the following study was to test the efficacy of a number of standard filters to see if they are suitable for oak, beech and spruce surfaces sanded with P1000 grit. Simple Gaussian filter in most common standards introduced distortions, but a robust Gaussian Regression filter, contained in a draft standard at the moment of testing (now published), appeared to give roughness profiles free of distortions.

Profile filtering with the simple Gaussian filter from ISO 11562 (1996) and ASME B46.1 (2009)

The lack of specific standards for wood surfaces has meant that general standards have been adopted for them. The most widely used profile filter is the Gaussian filter, which is described in ISO 11562 (1996) and ASME B46.1 (2009), and provides the basis for surface parameters in the standards in common use (ISO 4287: 1997, ASME B46.1: 2009, ISO 13565-2: 1996). The filter works by smoothing data points in a sliding Gaussian window, whereby the amount of waviness is calculated at each point of the profile by averaging locally weighted values. The weights are derived from a Gaussian function. The path of the waviness values should represent the mean line of the primary profile.

The averaging function for the mean line calculation is given in digital form in ASME B46.1 (1995) as:

$$w_i = \sum_{k=-n}^{n} s_k \cdot z_{i+k} \qquad [5]$$

w_i -waviness value at index *i*, which is the value of the mean line

z -is a profile height in the unfiltered profile

n and $-n$ -set limits over which the averaging function is calculated.

s -is the weighting function given in [6]

The number of profile heights included in the averaging window is equal to 2n + 1. The first index i is n + 1 data points from the start of the profile, so the filtered profile will lose n data points at either end.

The function for calculating the weights in [6] is as ISO 11562 but without renormalization.

$$s_k = \frac{\sqrt{\pi}\cdot\Delta x}{\sqrt{\ln(2)}\cdot\lambda}\cdot\exp\left(-\frac{\pi^2}{\ln(2)}\cdot\frac{k^2\cdot\Delta x^2}{\lambda^2}\right) \quad [6]$$

s_k - the value of the weighting function at index k

Δx - the sampling interval

λ - the cut-off wavelength of the profile filter that separates waviness from roughness

ISO 4288 recommends specific cut-off lengths depending on the expected values of the roughness parameters. The cut off length, λ, is usually used to set the length of the averaging window, so that λ = 2n + 1. The roughness profile is calculated by subtracting the mean line, w, from the unfiltered profile.

The function can be extended to cover all the data points in the unfiltered profile (ISO/TS 16610-20: 2006). This implies the amount of waviness calculated at each point of the profile takes into consideration the equivalent weighted value for every point in the profile and not only of the 2n + 1 window. The function from [5] becomes:

$$w_k = \sum_{l=1}^{n} z_l \cdot s_{kl} \quad [7]$$

(Gurau et al, 2005a)

n - number of data points in the unfiltered profile

k - the index of the location of the weighting function in the whole profile

The weighting function in [6] becomes :

$$s_{kl} = \frac{\sqrt{\pi}\cdot\Delta x}{\sqrt{\ln(2)}\cdot\lambda}\cdot\exp\left(-\frac{\pi^2}{\ln(2)}\cdot\frac{(k-l)^2\cdot\Delta x^2}{\lambda^2}\right) \quad [8]$$

(*Gurau et al. 2005a*)

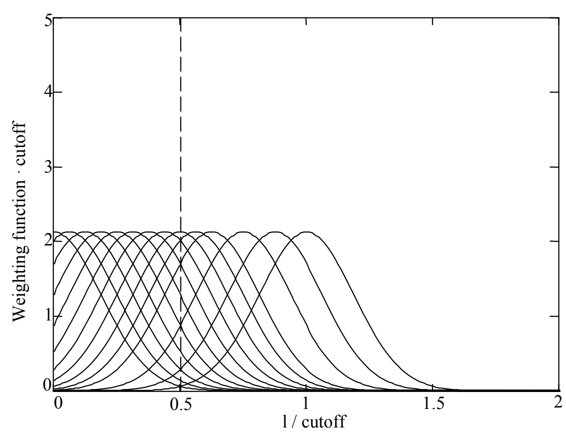


Figure 20 Sliding of the weighting function of a Gaussian filter (Gurau et al. 2005a)

The result of applying [7] and [8] with a cut-off length of 8 mm, to an oak profile sanded with P1000 is shown in Figure 21 and Figure 22. The oak profile was chosen as it had deep pores grouped at both ends, which presents the most difficult case for filtering.

In Figure 21, equations [5] and [6] produce identical results to [7] and [8] within the limits marked by the dashed line. The limits are set at half a cut-off length from the ends. Outside these limits [5] and [6] do not process the data, while [7] and [8] produce a roughness profile that is clearly incorrect. These end effects mean that the data points outside the limits should be discarded (Brinkmann et al.2000, Raja et al. 2002). Although form error was not removed in Figure 21 prior to the application of this filter, this does not affect the errors that are clearly generated at the ends of the profile by this filter.

The loss of data weight in the mean line is a consequence of the variation of the area below the sliding Gaussian bell, as can be seen in Figure 20. Outside the limits, the area decreases from a value of 1, when the window is centred at half a cut off length, down to a value of 0.5, when the window is centred at zero.

The end effects and the distortions of the roughness profile are shown in Figure 21 and Figure 22. Figure 22 shows that the roughness profile contains "pushed-up" valleys, or artificial peaks, when compared with the unfiltered profile in Figure 21. Such highly polished surfaces represent an extreme case of sanding where the height variation due to processing is minimised, while the effect of filtering distortions and anatomy is maximised. These surfaces allow the robustness of a filtering method to be tested with a greater degree of reliability than surfaces prepared with larger grit sizes.

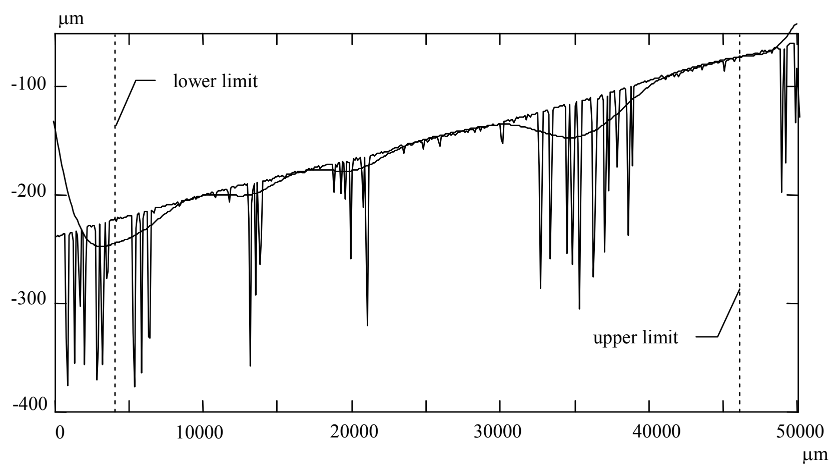


Figure 21 The mean line after Gaussian filtering according to ISO 11652 (1996) with a cut off length of 8 mm, oak sanded with P1000 (Gurau et al.2005a)

Similar results were obtained for surfaces of beech and spruce sanded with P1000 using a cut-off length of 2.5 mm in the filter, although the amount of push-up was smaller than for oak.

The distortion associated with grouped pores means that ISO 11562 is not suitable for sanded wood surfaces. Furthermore, the relatively long cut-off lengths that are suitable for wood mean that a significant amount of otherwise useful data is lost at each end of the profile.

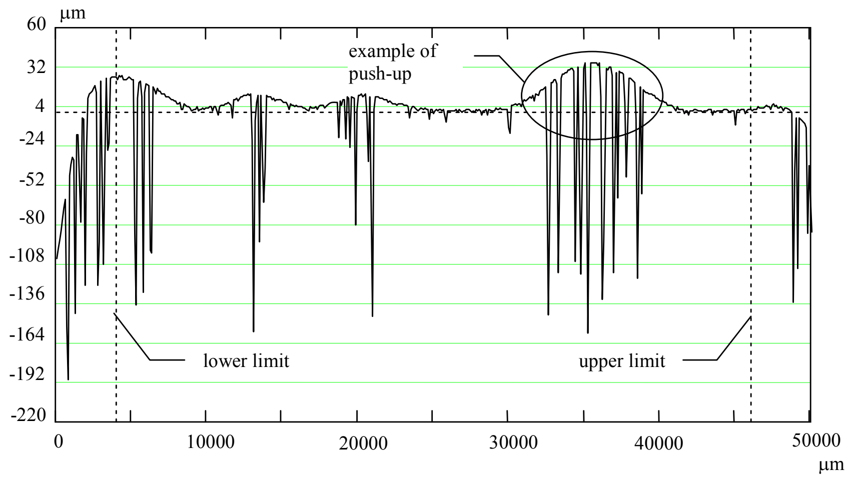


Figure 22 Roughness profile, distortions and end effects introduced by the Gaussian filter in ISO 11652 (1996), oak sanded with P1000 (Gurau et al, 2005a)..

Profile filtering with the Gaussian two step filter from ISO 13565-1 (1996)

ISO 13565-1 (1996) is intended to produce less distortion than ISO 11652 for surfaces that have deep valleys below a finely finished plateau, with a relatively small amount of waviness, by using two-step filter.The first step follows ISO 11652 and establishes the mean line shown in Figure 21. In the second step, all the points in the unfiltered profile that lie below the mean line are replaced by the corresponding value of the mean line, so the valleys are suppressed. The Gaussian filter is applied again, and the new mean line becomes the reference mean line.This approach suffers from the same end-effects mentioned above, and since the filter is applied twice, the useful length of the profile is reduced by the whole cut-off length at both ends (Figure 23). The two-step process is not sufficiently robust against deep valleys (Raja et al. 2002), and a small amount of distortion can still be observed in the roughness profile (Figure 24). The results for beech and spruce sanded with P1000 were similar, but the distortion was less.

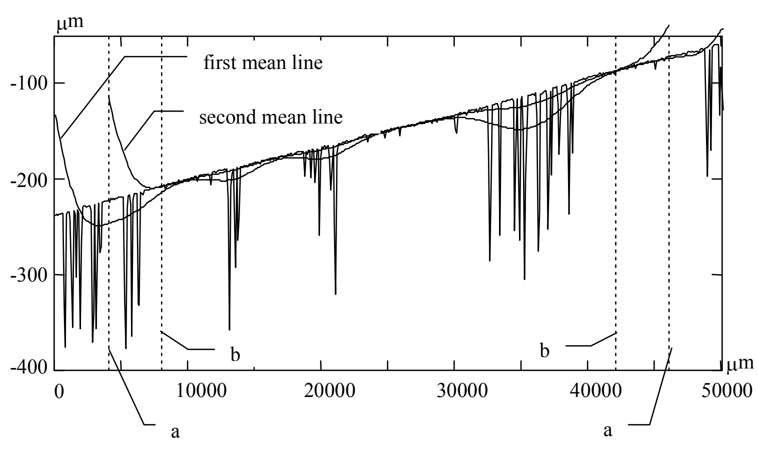


Figure 23 Gaussian filtering according to ISO 13565-1 (1996) with a cut-off length 8 mm. a and b are the limits of the usable profile after first and second filtering respectively, oak sanded with P1000 (Gurau et al., 2005a).

Compared with ISO 11562, ISO 13565-1 reduces distortions in areas with grouped pores, but it does not remove them completely. Furthermore, the double filtering doubles the amount of unusable data at each end of the profile.

The examples above demonstrate that some standard filters contained in existing software are not suitable for wood surfaces. The filters should generate an undistorted roughness profile, irrespective of the presence of pores or other outliers introduced by processing artefacts such as fuzzy grain.

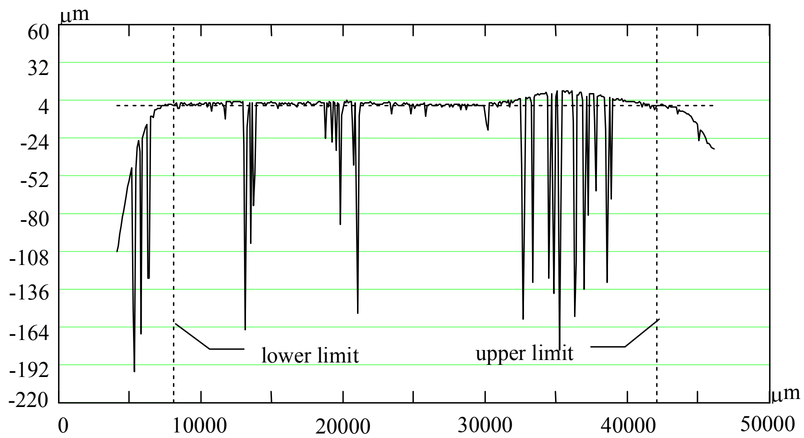


Figure 24 Roughness profile with distortions and end effects introduced by ISO 13565-1 (1996), oak sanded with P1000 (Gurau et al., 2005a).

Profile filtering with the Gaussian Regression Filter from ISO/TS 16610 – 31 (2010)

The algorithms in a new standard, ISO/TS 16610-31 (2010), were tested when the standard was still in draft form, and were found to be suitable for wood surfaces (Gurau et al.2002, Fujiwara et al.2004, Gurau 2004, Gurau et al.2005, Gurau et al. 2011).

ISO/TS 16610-31 is a standard that describes a Robust Gaussian Regression Filter (RGRF) proposed by Brinkmann (Brinkmann 2000). The filter is "robust" when outlying data points do not distort the roughness profile. For wood surfaces, deep valleys caused by wood anatomy or accidental high peaks that do not characterise the processing may be considered as outliers.

Zero Order Gaussian Regression Filter

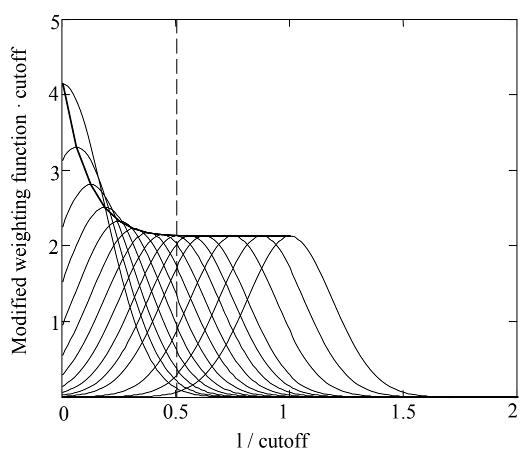


Figure 25 Sliding of the weighting function of the Brinkmann Gaussian regression filter, [GUR 05](Fig.8 © 2004, Springer Science and Business Media)

The Brinkmann filter incorporates a zero order Gaussian regression filter that is a modification of the Gaussian filter from ISO 11562. It is designed to evaluate the entire length of the profile without end effects (Brinkmann et al.2000). The weighting function of the filter is modified in the first and last sections of the profile so that the area below the bell curve remains equal to 1 throughout the profile (Figure 25).

In digital form, the zero order Gaussian regression filter is defined by the general regression arrangement (Raja et al.2002) given in [9]. In this regression approach, the weighting function is calculated for every point on the profile as a result of a minimisation condition. For each position k of the Gaussian bell curve, the mean line value wk is varied so that the sum of the squared weighted deviations of the profile ordinates at each point from the wk is minimised.

$$\sum_{l=1}^{n}(z_l - w_k)^2 \cdot s_{kl} \cdot \Delta x \rightarrow \min_{w_k} \qquad [9]$$

(*Gurau et al. 2005a*)

Specifically, the mean line of a zero order Gaussian regression filter can be given by:

$$w_k = \sum_{l=1}^{n} z_l \cdot s_{reg_{kl}} \qquad [10]$$

(*Gurau et al. 2005a*)

With the adjusted weighting function:

$$s_{reg_{kl}} = \frac{s_{kl}}{\sum_{l=1}^{n} s_{kl}} \qquad [11]$$

where s_{kl} is the weighting function given in [8].

Compared with filters from ISO 11562 and ISO 13565-1, the zero order Gaussian regression filter retains all the data points in the evaluation and causes no end effects. However, push-up distortion still occurs in areas with grouped deep valleys. This is clearly visible with oak and, to a lesser extent, with beech and spruce.

Robust Gaussian Regression Filter (RGRF)

The RGRF reduces distortions by repeatedly applying a zero order Gaussian regression filter to the primary profile, until the mean line is satisfactory.

The robust filter extends [9] by an additional vertical weighting δ at each data point. The generalised regression arrangement in a digital form is taken from ISO/TS 16610-31; Brinkmann et al. (2000) and Raja et al. (2002):

$$\sum_{l=1}^{n}\left(z_l - w_k^{(m+1)}\right)^2 \cdot \delta_l^{(m)} \cdot s_{kl} \cdot \Delta x \rightarrow \min_{w_k^{(m+1)}} \qquad [12]$$

m - index marking the iteration step (this is an index and not a power function).

δ - additional vertical weight

In the first iteration, when $m = 0$, a reference level is calculated by the Gaussian regression filter, and the additional weight $\delta^{(0)} = 1$ is applied to each data point. In subsequent iterations, the value of δ is given by the condition:

$$\delta_l^{(m)} = \begin{cases} \left[1-\left(\dfrac{z_l - w_l^{(m)}}{c_B^{(m)}}\right)^2\right]^2 & \text{for} \quad \left|z_l - w_l^{(m)}\right| \le c_B^{(m)} \\ 0 & \text{otherwise} \end{cases} \qquad [13]$$

(*Gurau et al. 2005a*)

δ can take values of between zero and one. c_B is a threshold value given in [14] and based on a study of Bodschwinna (2000).

$$c_B^{(m)} = 4.4478 \cdot \text{median}\left|z_l - w_l^{(m)}\right| \qquad [14]$$

(*Gurau et al. 2005a*)

Profile heights lying close to the mean line established in the previous iteration are multiplied by values of δ close to one, so almost their full value is included. Profile heights further than c_B from the mean line are multiplied by zero. The value of δ is contained in a modified averaging function in [15].

$$w_k^{(m+1)} = \frac{\sum_{l=1}^{n} s_{kl} \cdot z_l \cdot \delta_l^{(m)}}{\sum_{l=1}^{n} s_{kl} \cdot \delta_l^{(m)}} \qquad [15]$$

(*Gurau et al. 2005a*)

The iterations are repeated until the difference between two consecutive median values is smaller than a given tolerance (Figure 26 and Figure 27).

Figure 27 contains the primary profile obtained after fitting a polynomial regression to the measured data from oak sanded with P1000. The RGRF was applied to this profile. When the tolerance was set to 0.1, a value suggested by Fujiwara et al (2004), the mean lines of consecutive profiles converged after not more than five iterations. However, by investigating several surface and grit size combinations, Gurau (2004) and Gurau et al.(2014) determined that a tolerance of 0.01 was better suited to wood surfaces as this threshold provided stable roughness parameters (see section 1.2.5.4). For the oak profile sanded with P1000, a cut-off length of 8 mm was chosen since it gave reasonable results based on a visual assessment of plotted profiles. A more thorough investigation of the significance of variation in the cut-off length (Gurau, 2004; Gurau *et al*.2006) confirms that the value used here is appropriate.

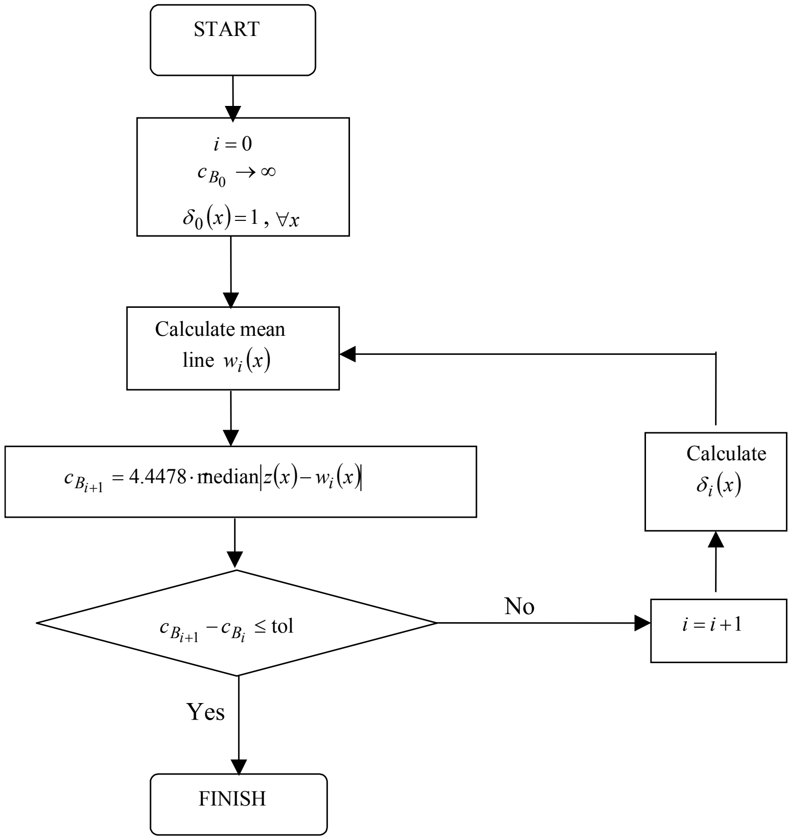


Figure 26 Flowchart of the filtering procedure with the Robust Gaussian Regression Filter (Gurau *et al*. 2011)

$w(x)$- mean line or waviness profile.

$z(x)$- primary profile.

c_{Bi} - threshold value at iteration i.

δ - additional vertical weight.

tol - tolerance.

i - index marking the iteration step

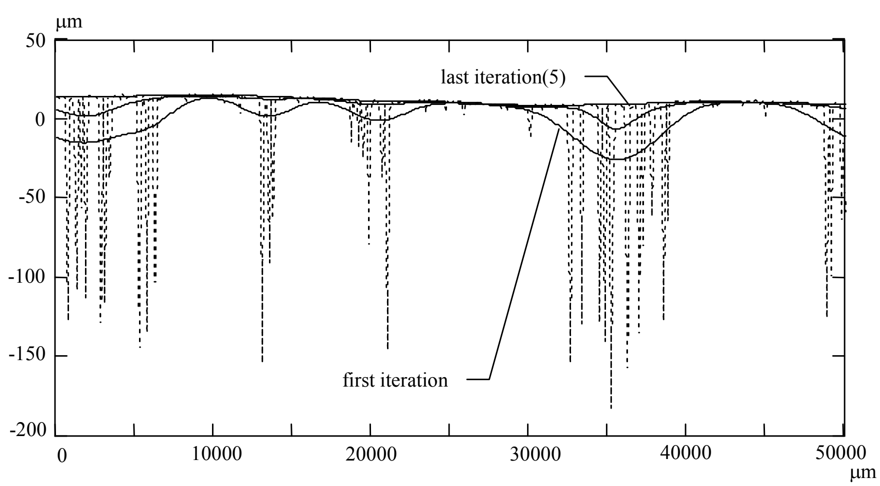


Figure 27 An iterative approach to finding the mean line on oak sanded with P1000 (Gurau *et al.* 2005a)

The effect of applying the RGRF on the same oak profile can be seen in Figure 28.

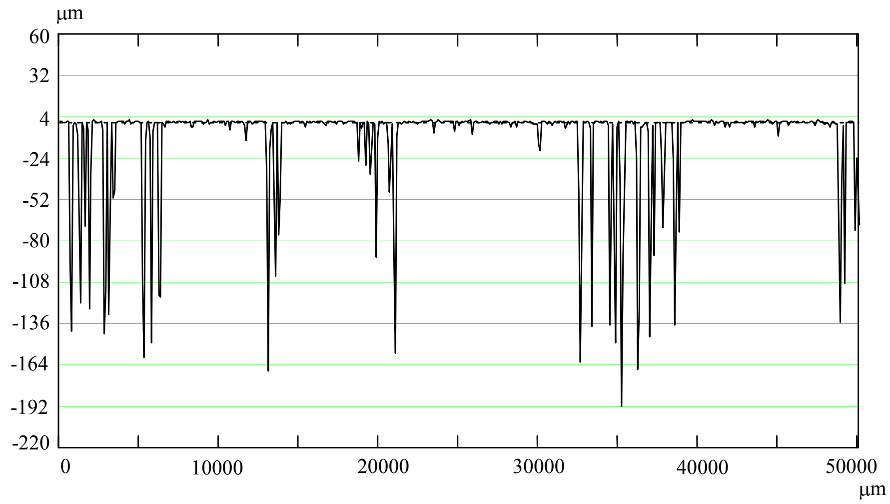


Figure 28 Roughness profile obtained by applying a robust Gaussian regression filter (ISO/TS 16610 31: 2010) with a cut off length 8 mm to a profile obtained from oak sanded with P1000 (Gurau *et al.* 2005a)

The Gaussian regression filter has several advantages: all the data points are retained in the roughness profile, it produces no end effects and there are no distortions in the roughness profile. This method proved to be effective not only for specimens of oak, spruce and beech sanded with P1000, but also for other available specimens sanded with P120 or P60.

The literature agrees that other filtering techniques as robust spline filtering (Muralikrishnan and Raja 2009) or Bayesian smoothness regression models (Zhu et al. 2011) can also overcome the problems of edge distortion and are robust against outliers. Although these filtering techniques may be suitable for wood, only RGRF was yet tested on wood surfaces (Gurau *et al.* 2014).

Conclusions

Standardised filters described in ISO 11562 and ISO 13565-1 have limitations when applied to wood surfaces. The usable length of the filtered profile is shorter than the original data, and they introduce distortions in profiles that have deep valleys below a relatively smooth plateau.

***The robust Gaussian regression filter** from ISO 16610-31 was found appropriate for wood surfaces having deep valleys caused by wood anatomy or presenting accidental high peaks. It avoids limitations from standards using **simple Gaussian filters** and provides a reliable method of obtaining a roughness profile. All the data points are retained in the roughness profile, it produces no end effects and there are no distortions in the roughness profile.*

The following study was performed in order to find a suitable solution of reducing the computational time of the iterative robust filter RGRF, making it easier to be implemented in a metrology software.

1.2.5.3 Research on minimising the computational time for a Robust Gaussian regression Filter

Although highly effective, the RGRF is computationally expensive, since the equation [15] from section 1.2.5.2 calculates a mean line in which each data point in the filtered profile is weighted with the participation of all data points in the unfiltered profile. This means the weighting function has the same length as the unfiltered profile data.

The following study presents the results of a study on a method developed by Gurau *et al*. (2012b) to minimize the computation time of the RGRF using a truncated weighting window.

The objective was to choose an optimum weighting window that gives negligible errors compared to the reference RGRF method, but with a significantly reduced computation time requirement. The algorithm has been verified on profiles of sanded wood surfaces.

a) Truncated RGRF algorithm

Although the weighting function vector of the RGRF filter has the same length as the profile, it contains zeros at each end, so only ordinate values around the centre of the function have a non zero weighting. Data points weighted with zero do not alter the mean line, but they do lengthen the filtering process. This suggests that the weighting window can be truncated without affecting the overall result.

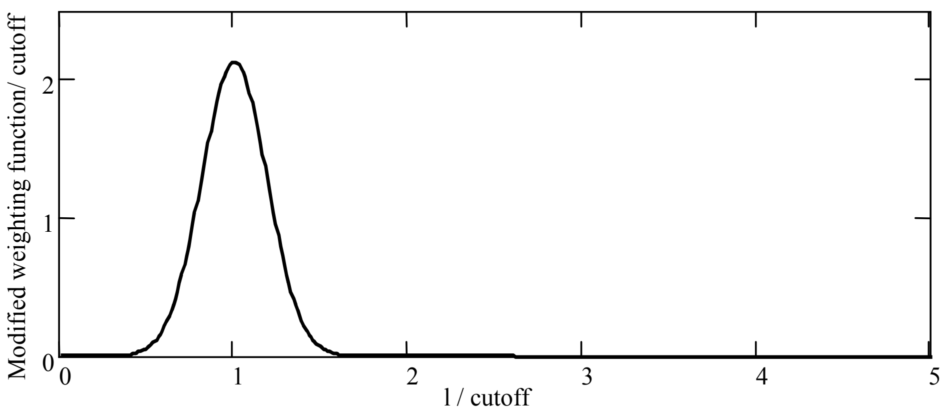


Figure 29 Example of a weighting function vector centred at one cut-off length value and having a length equal to the input profile data. The vector contains zeros at each end (Gurau *et al*. 2012b).

If the length of the truncated window of the weighting function is q intervals, then there are $q + 1$ data points in the window. A profile containing n data points must be divided into three regions, related to the length of the window. The outer regions are $q/2$ intervals long so they each contain $q/2 + 1$ data points. The limits on the summation functions given in equation [15] vary by region.

In the first region, the mean line is calculated according to [16]. The window of the weighting function is not centred on the filtered data point until the final data point because of the margin location.

$$w_k^{(m+1)} = \left. \frac{\sum_{l=1}^{q+1} z_l \cdot s_{kl} \cdot \delta_l^{(m)}}{\sum_{l=1}^{q+1} s_{kl} \cdot \delta_l^{(m)}} \right|_{k=1,2\ldots\frac{q}{2}+1} \qquad [16]$$

(*Gurau et al. 2012b*)

The middle region extends from $q/2 + 2$ to $n - (q/2 + 2)$ and the weighting function is located symmetrical around the filtered data point [17].

$$w_k^{(m+1)} = \left. \frac{\sum_{l=k-\frac{q}{2}}^{k+\frac{q}{2}} z_l \cdot s_{kl} \cdot \delta_l^{(m)}}{\sum_{l=k-\frac{q}{2}}^{k+\frac{q}{2}} s_{kl} \cdot \delta_l^{(m)}} \right|_{k=\frac{q}{2}+2,\frac{q}{2}+3\ldots n-\left(\frac{q}{2}+2\right)} \qquad [17]$$

(*Gurau et al. 2012b*)

The final region is given by [18] and works on the same principle as [16], so the weighting function is only symmetrical around the first data point.

$$w_k^{(m+1)} = \left. \frac{\sum_{l=n-(q+1)}^{n} z_l \cdot s_{kl} \cdot \delta_l^{(m)}}{\sum_{l=n-(q+1)}^{n} s_{kl} \cdot \delta_l^{(m)}} \right|_{k=n-(q+1),n-(q)\ldots n} \qquad [18]$$

(*Gurau et al. 2012b*)

Comparison of the effect of RGRF with and without truncated weighting window on sanded surfaces

Specimens of oak, beech and spruce were sanded by hand parallel to the grain with P1000 grit paper. Such a fine grit size represents an extreme case of sanding. where the height variation due to processing is minimized and the possibility of filtering distortions is maximized. These surfaces allow the robustness of a filtering method to be tested with a greater degree of reliability than surfaces prepared with larger grit sizes. To widen the range of analysis, a surface of oak was sanded with P120, as this grit size is commonly used in industry for sanding prior to finishing applications. Two plastic surfaces sanded with P60 and P120 were added as examples of a homogeneous material. Sanding with P60 and P120 was achieved using a wide-belt sander.

Measurements were carried out with a Taylor Hobson instrument TALYSCAN 150 using a stylus with 2.5 µm tip radius and 90º tip angle, at a speed of 1 mm/s as in Gurau et al (2012b).

The roughness profiles were obtained by filtering the primary profiles with the Robust Gaussian Regression Filter with and without a truncated weighting window. For surfaces sanded with P1000, a cut-off length of 8 mm was used, while for the P60 and P120, a cut-off length of 2.5 mm was preferred.This choice was based on a previous study regarding the selection of cut-off lengths, which do not distort the wood surfaces (Gurau *et al*. 2006a).

To ensure that the truncation of the weighting window to a length of q intervals did not introduce significant errors, roughness profiles obtained with a range of q values were compared with reference roughness profiles obtained without truncation. The length q of the weighting window was set in turn to 0.25λ, 0.5λ, 0.75λ, λ, 1.1λ, 1.2λ, 1.25λ, 1.35λ, 1.5λ, 1.75λ and 2λ. The error for any value of q was taken as a vector of the differences at each point between the profile obtained with that value of q and the reference profile.

Two parameters were calculated to evaluate the error: the peak to valley height *Rt* and the mean of the absolute ordinates *Ra* as from ISO 4287 (1997).

Figure 30 shows the variation of the error Δ*Ra* with the size of the weighting window for oak, beech and spruce sanded with P1000 and measured at a resolution of 10 μm.

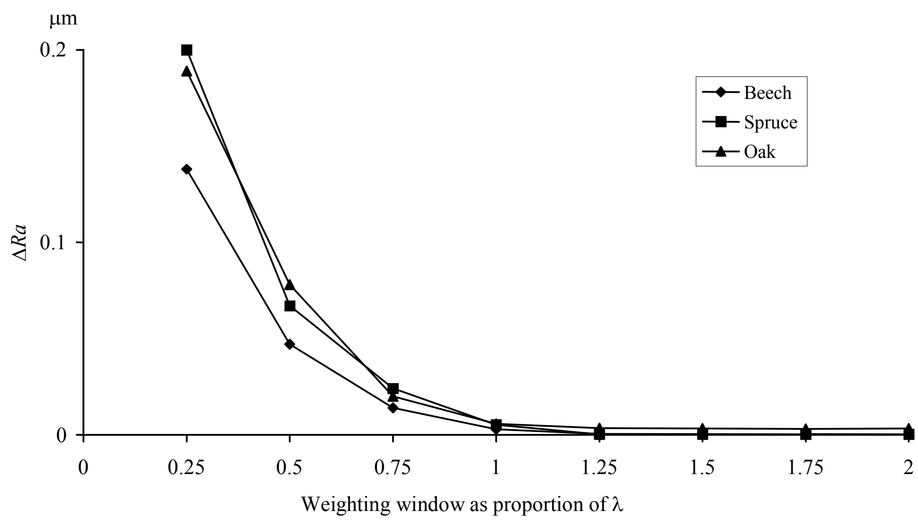


Figure 30 Comparison between RGRF and RGRF with truncation as a variation of *Ra* with the size of the weighting window (Gurau *et al.*2012b)

From Figure 30 it can be seen that for each species the error was negligible from a window length of 1.25λ. Values of ΔRt were calculated for a range of materials, grit sizes and window sizes.

It was seen that the error decreased as the size of the window increased (details in Gurau et al.2012b). The computation time increased with each increase in window length.

The computation time depends on the profile length and the measuring resolution, in other words on the number of data points in the evaluation. When compared with filtering with no truncation, tests performed for profile lengths of 50 mm with a measuring resolution of 10 μm and a cut-off length of 8 mm required only one third of the computation time when using a truncation window of 1.25λ. Note that effective computation time also depends on the computer performance. Such high computation speeds are necessary if the algorithms are to be used for an on-line evaluation tool.

Conclusions

The Robust Gaussian Regression Filter is suitable for wood surfaces, but has the disadvantage that is computationally expensive, as all data points are considered at every iteration in the evaluation. A *modified algorithm of the RGRF was proposed in this study (Gurau et al., 2012b), which reduces the window of datapoints and divides the profile in three regions with specific weighting windows, for central and marginal areas. RGRF with various weighting windows were tested on sanded surfaces of oak, beech, spruce and plastic. A value of 1.25λ of the weighting window introduced negligible errors compared to a RGRF without truncation, but significantly reduced the computation time.*

The following study is also related to the implementation of the robust filter RGRF, which was found suitable for wood surfaces, in order to test the optimal condition, which defines the number of iterations required for obtaining a wood roughness profile without distortions.

1.2.5.4 Research on the convergence of the Robust Gaussian Regression Filter

The quality of a sanded wood surface is represented by its roughness, which can be separated from the original measured data by a procedure of filtering. Past experience has shown that the Robust Gaussian Regression Filter (RGRF) is suitable for wood surfaces because it does not introduce distortions into the roughness profiles (section 1.2.5.2). The filter works iteratively until a user-defined convergence condition is met. The iterations stop when the difference between two consecutive profile median values becomes smaller than a given tolerance (Figure 26).

This study examines the convergence of RGRF when applied to wood surfaces sanded with various grit sizes in order to establish the tolerance value which leads to convergence with the minimum number of iterations (Gurau et al., 2014). This study was based on monitoring the variation of roughness parameters with the number of iterations for a range of tolerance values.

The iterations of a RGRF are repeated until the difference *D* between two consecutive median values, $C_{B,}$ is smaller than a given tolerance (equation [19] and Figure 26):

$$D = \left| C_B^{(m)} - C_B^{(m-1)} \right| \qquad [19]$$

(Gurau, 2004)

c_B - threshold value

m - index marking the iteration step (this is an index and not a power function).

As described in section 1.2.5.2, the algorithm considers all the points in the profile at each step, since the weighting function has the same length as the profile. This is computationally expensive and unnecessary, since only ordinate values near the centre of the function have a non-zero weighting. It was found that the length of the window could be truncated to 1.25λ without introducing errors into the roughness parameters (section 1.2.5.3). The inputs to the algorithm in the implementation of Gurau *et al.* (2012b) are the vector of data points, the cut-off value for the filter, the sampling interval, the value of the tolerance that defines convergence and the maximum number of iterations. If the algorithm converges, the iterations stop and the output is a corrected roughness profile and the required number of iterations. If the algorithm does not converge because the predefined maximum number of iterations was insufficient, the output will be the roughness profile achieved at the last iteration.

For most engineering surfaces that are relatively well-defined with only a limited number of outliers, the robust Gaussian regression filter will practically always converge to a single solution (Friis et al. 2011). According to ISO/DTS 16610 31: 2002(E), the mean line for engineering surfaces will usually converge in not more than 6 iteration steps. However, for wood surfaces it was observed that the difference D oscillated before converging (Gurau 2004). Fujiwara et al. (2004) suggested a tolerance value of 0.1 μm as satisfactory for wood surfaces, but the convergence was estimated only visually. This assessment was based on the variation of values of D over a maximum of 10 iterations. *No other studies were found in the literature about the convergence of the RGRF filter for wood surfaces.*

In the study of Gurau *et al*. (2014), specimens of European oak (*Quercus robur*), beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*) were sanded parallel to the grain with P1000 grit paper. Such a fine grit size represents an extreme case of sanding, where the height variation due to processing is minimized and the possibility of filtering distortions is maximized. A surface of European oak sanded with P60 was also included as an example of coarse sanding as well as one sanded with P120, a grit size commonly used in industry for sanding prior to finishing applications. Data of Japanese oak (*Quercus glabra*), sanded with P180 and P240 provided examples of the finest grit size that are used for finishing (courtesy of Dr. Yuko Fujiwara). The final specimen type was a black filled polyester plastic with an apparently smooth glossy surface and a density of approximately 1500 kg/m^3 (similar to wood cell wall density), which was sanded with P120. The plastic has no surface variation equivalent to wood anatomy and so its roughness should represent only the processing roughness.

After sanding, the surfaces were measured by recording one profile of each surface, 50 mm long, across the grain, with a Taylor Hobson instrument TALYSCAN 150 (as described in detail in Gurau et al. 2014). The roughness profile and the value of *D* were recorded for each iteration.

For each roughness profile the following roughness parameters were calculated over the evaluation length: *Ra*, *Rq*, *Rt*, *Rsk*, *Rku* from ISO 4287 (1997) and Abbot-curve parameters *Rk*, *Rpk* and *Rvk* from ISO 13565-2 (1996). The iterations were continued until the value of each roughness parameter did not change by more than 0.01 μm, a value which was sensitive to even the slightest variation of the parameters. The number of iterations to reach this precision condition and the resulting profile were taken as a reference for the reliable convergence of the roughness parameters.

The iteration number and the difference *D* corresponding to tolerance conditions of less than 0.1 μm and 0.01 μm, were recorded. At each tolerance, the error of the roughness parameters relative to the parameters of the reference profile was calculated as a percentage difference.

$$Percentage\,error = \left| \frac{R_{conv} - R_i}{R_{conv}} \right| \cdot 100 \qquad (1)$$

R_i -roughness parameter *R* measured at iteration *i*.

R_{conv} -roughness parameter *R* measured at the iteration where the reference convergence occurred.

The percentage difference was analyzed in conjunction with the absolute difference between the roughness parameter at iteration *i* and roughness parameter measured at reference convergence.

The variations in the roughness parameters and in *D* were plotted against the number of iterations. The graphs were examined to decide at which iteration all parameters had stopped oscillating and had become relatively stable. This procedure is termed "visual assessment".

One example is presented below: oak sanded with P120. Oak is a ring porous species, which although sanded with a common grit size, has an anatomical structure that can generate greater roughness than sanding and can cause difficulties at filtering. Figure 31 shows the variation of *D* with the number of iterations for oak P120. *D* can only be calculated after a minimum of 2 iterations. 0.1 μm and 0.01 μm tolerances are marked as well as the visual convergence.

In order that the changes in roughness parameters can be seen more clearly, they have been normalised relative to *Ra* in Figure 32. The *y* axis normally indicates the value of the roughness parameter, but because of the normalisation the values are only correct in μm for *Ra*. The value of any roughness parameter *R* on the *y* axis is given in [20] as a function of *Ra* measured at iteration 2.

$$f(Ra_2) = \frac{Ra_2}{R_2} \cdot R_i \qquad [20]$$

Ra_2 -*Ra* parameter measured at iteration 2.

$f(Ra_2)$ -value of a roughness parameter *R* normalised relative to Ra_2.

R_2 -roughness parameter *R* measured at iteration 2.

i -rank marking the iteration.

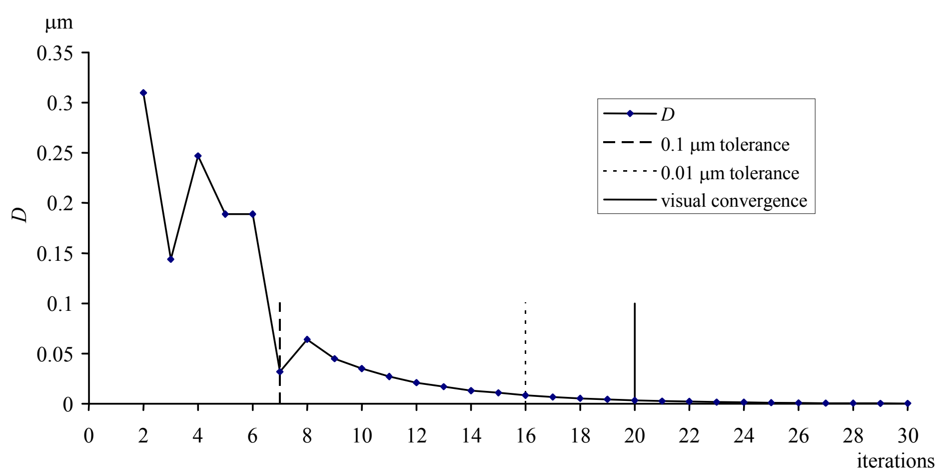


Figure 31 The variation of the parameter D with the number of iterations for an oak profile sanded with P120. The first vertical dashed line corresponds to a 0.1 μm tolerance, the dotted line to a 0.01 μm tolerance and the vertical solid line marks the visual convergence (Gurau *et al.* 2014).

The curve in Figure 31 has an asymptotic shape in which *D* oscillates at the start. In this example, the 0.1 μm tolerance is in the unstable region, which confirms the need for further iterations. However, after 8 iterations, the curve tends to smooth and visually converge after 20 iterations. The tolerance condition of 0.01μm occurs at 16 iterations in a region where the curve is smooth.

The parameters variation in Figure 32 was not the same. Some parameters, like those from ISO 4287 changed smoothly, while the family of *Rk* parameters exhibited sudden jumps. *Rpk* is very sensitive to profile outliers, like isolated peaks, and likewise *Rvk* is affected by valleys. *Rk* measures the core data.

The fact they fluctuated before becoming stable is an indication of the variation in the profile, where datapoints have pushed up and down after consecutive iterations. Less sensitive, in this respect, were the mean parameters *Ra* and *Rq*, which are not affected to the same extent by such fluctuations in the profile, as well as the skewness and kurtosis, which are non-dimensional parameters.

For spruce, a tolerance of 0.1 μm is found in a region of curve instability. Compared to oak sanded with P120, at spruce sanded with P1000, the convergence occurs earlier, after 14 iterations, according to a visual assessment (details in Gurau et al.2014).

Tolerance values and the number of iterations where they were achieved were calculated for all species and grit sizes examined. However, it is difficult to speculate a connection between the convergence of the parameter *D* and species or grit size. Compared to plastic sanded with P120, which stabilized after 7 iterations, wood needs more iterations, perhaps due to its inherent anatomy, which introduces a degree of variation in the measured data.

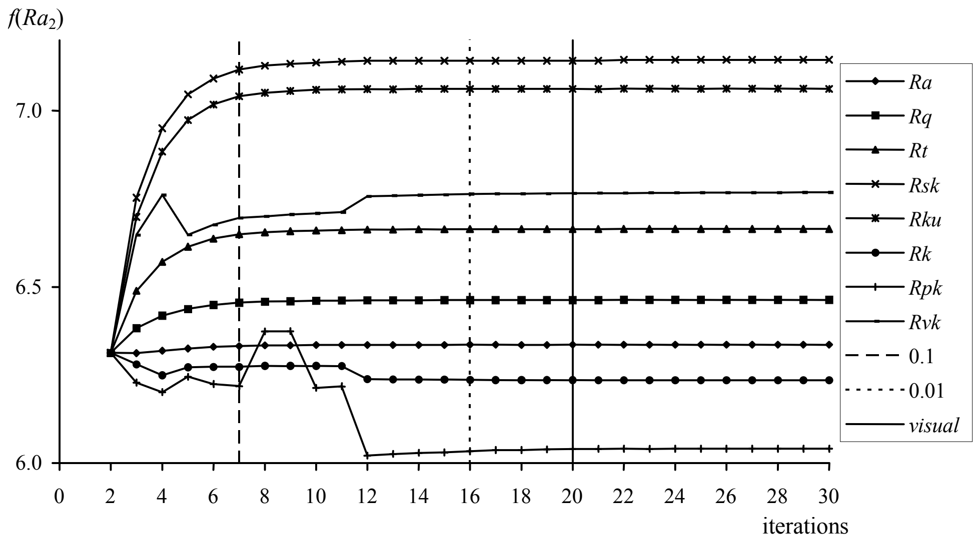


Figure 32 The variation of roughness parameters with the number of iterations for an oak profile sanded with P120. The dashed line corresponds to a 0.1 μm tolerance, the dotted line to a 0.01 μm tolerance and the vertical solid line marks the visual convergence. Data are normalised (*y*-normalised data; Ra_2 -value of *Ra* at iteration 2) (Gurau *et al*. 2014)

The variation of *D* with the number of iterations for all the profiles studied can be seen in Figure 33. The level of a 0.1 μm tolerance is marked with a dotted line.

Tables regarding the influence of tolerance condition on roughness parameters can be found in detail in Gurau *et al.* (2014).

The effect of filtering with RGRF was visually observed on an oak profile sanded with P1000, for the first, second and nine-th iteration, which ultimately led to reference convergence.The “push-up” appears clearly in areas with grouped pores in the first two iterations with a tendency to attenuate at following iterations, but the profile eventually straightened at convergence. The other species and grit sizes showed similar “push-up” behaviour, but this was more pronounced in oak sanded with P1000.

It can be concluded that all the roughness parameters do converge given a sufficient number of iterations. The number of iterations required differs from parameter to parameter and species to species.

In most cases, the parameters *Ra*, *Rq*, *Rt*, *Rsk* and *Rku* varied asymptotically, whereas the Abbot-curve parameters: *Rk*, *Rpk* and *Rvk* oscillated although eventually they converged as well.

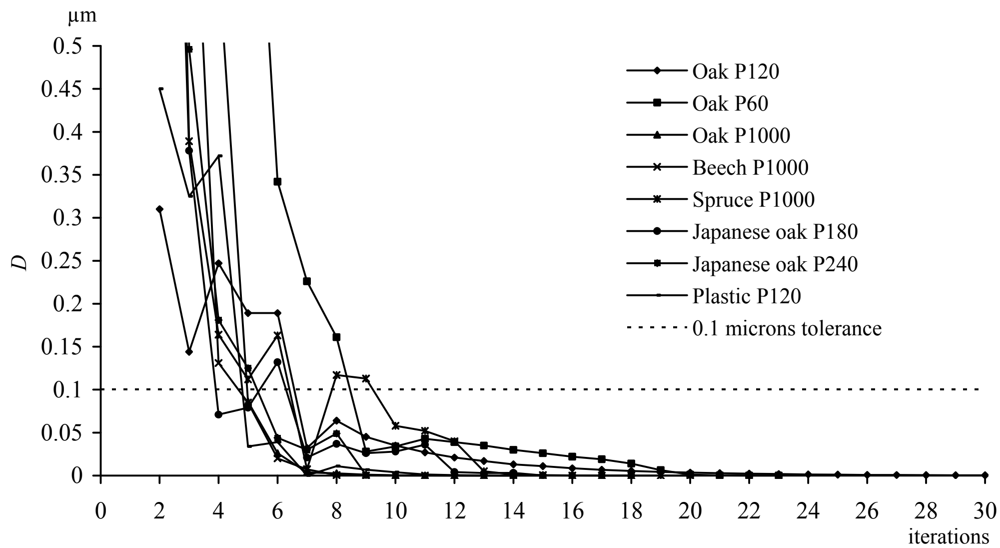


Figure 33 Variation of *D* parameter with the number of iterations for all 8 profiles studied. With dotted line is represented the level of tolerance 0.1 µm (Gurau *et al*.2014)

By analysing the data it can be concluded (details in Gurau et al.2014):

- The tolerance condition D < 0.01 µm produced small but acceptable errors. The number of iterations is still very large, the maximum was 19 for oak P60.
- The tolerance condition D < 0.1 µm introduces errors in some profiles. The advantage of this tolerance condition is that a smaller number of iterations are required and, generally, less than 10.
- There were very small errors at the iteration deemed "accurate" after visual assessment. The results of the visual examination were very close to those of the tolerance condition 0.01 µm.

It may be, given the wood anatomical variety, that other profiles from the same species studied and sanded with the same grit sizes converge after a different number of iterations than those in this study. However, the variety of wood materials, in terms of their anatomy, the homogeneous plastic, together with various grit sizes from coarse to very fine tested in this study indicate a tolerance condition of 0.01µm. This tolerance condition is more restrictive than 0.1µm, which is given in literature by one bibliographic reference, and therefore, more likely to lead to an acceptable convergence.

Conclusions

This study (Gurau et al. 2014) examined the convergence of the RGRF by monitoring the effect of some predefined tolerances (0.1 µm and 0.01 µm) on the variation of roughness parameters of wood profiles from various sanded surfaces. The results were compared to a reference where the roughness parameters have stabilized. This study shows that unlike a tolerance condition of 0.1 µm, recommended by one bibliographic reference, the roughness parameters converge at a tolerance of 0.01 µm. This makes 0.01 µm the preferred level of tolerance.

The following study is investigating the influence of selecting the value of the filter cut-off length on the evaluation of surface quality by roughness parameters.

1.2.5.5 Research on the influence of the cut-off length of the filter on the evaluation of surface roughness

A very important condition in filtering the roughness from longer wavelength irregularities is the correct selection of the cut-off length of the roughness filter. The general standard ISO 4288 contains recommendations for selecting the cut off length in conjunction with the estimated values of the roughness parameters *Ra* and *Rz*, defined in ISO 4287 Table 2.

Ra (μm)	*Rz* (μm)	λ (mm)
$0.1 < Ra \leq 2$	$0.5 < Rz \leq 10$	0.8
$2 < Ra \leq 10$	$10 < Rz \leq 50$	2.5
$10 < Ra \leq 80$	$50 < Rz \leq 200$	8

Table 2 Selection of the filter cut-off length as a function of expected *Ra* and *Rz* parameters (from ISO 4288: 1996) (Gurau *et al.* 2006a)

Since it uses *Ra* and *Rz* in this way, ISO 4288 (1996) implies that they are a direct measure of the processing roughness, and so assumes that the surface is otherwise homogenous. For a wood surface, this method of selecting the cut-off length is probably not suitable, because the processing roughness is often obscured by larger anatomical irregularities. Krisch and Csiha (1999) observed that, when filtering with a Gaussian filter, the selection of the cut-off length of the filter is critical. The distortion in the filtered roughness profile increased when the roughness profile was obtained with a short cut-off length Krisch and Csiha (1999). Lemaster and Dornfeld (1982) also noted that the incorrect choice of cut-off length would lead to distortion in the roughness profile.

The range of cut-off length values used by various researchers is wide and often given without justification for its selection. The values used for sanded wood surfaces range from 0.8 mm (Javorek et al. 2015), 2.5 mm (Hendarto et al.2005, Thoma et al.2015) and 3 mm (Kilic et al.2006). Likewise for MDF surfaces, some authors used 0.8 mm (Pinkowski et al.2011), while others used 2.5 mm (Ayrilmis et al.2010). This makes any comparison between measurements from different authors problematic (Gurau and Irle, 2017).

The only study to date on the impact of cut-off length on filtering profiles of wood surfaces is that by Gurau *et al.* (2006a) who examined 43 cut-off values ranging from 0.025 mm to 40 mm for oak and spruce surfaces sanded with various grit sizes.

The objective of this study was to investigate the influence of the cut off length on roughness parameters calculated from a variety of roughness profiles. The robust Gaussian Regression filter was used because it is less likely to produce distortion than the standard Gaussian filter.

Specimens of European oak and Norway spruce were chosen for this investigation because sanded surfaces of these species are difficult to filter. The total roughness profile in oak contains grouped deep pores, while spruce surfaces are prone to fuzziness, whereby individual fibres or groups of fibres are not cleanly removed by the machining process and remain attached at one end to the surface. Spruce has finer anatomical features than oak and an irregular pattern of waviness due to density variation within the growth ring.

The oak and spruce surfaces were sanded with P120, as this grit size is commonly used in industry for sanding prior to finishing applications. The surfaces were all tangential faced and were sanded parallel to the grain.

Two other types of surface were included in the investigation. Data of Japanese oak sanded with P180 provided an example of the finest grit size that is commonly used for finishing. In addition, an oak surface sanded with P1000 was included in the study, although such a fine grit size is not used on wood in industry. Such a highly polished surface represents an extreme case of sanding where the height variation due to processing is minimised, so the effect of filtering distortions and anatomy is maximised.

Individual profiles were measured perpendicular to the sanding marks according to the procedure described in Gurau et al. (2006a).

The roughness profiles were obtained by filtering the primary profiles with the Robust Gaussian Regression Filter. The cut-off values that were tested were (in mm): 0.025, 0.05, 0.1, 0.25, 0.5, 0.8, 1, 1.5, 2, 2.5, 3 to 35 in 1 mm increments, and 40. Additional values between 35 and 40 were occasionally calculated, when the trend of the parameter in this region was not linear. Although the total roughness profile does not provide a good measure of the effect of processing, it must be free of distortion and waviness prior to any separation of anatomical irregularities and processing roughness, so this study concentrates on the total roughness profiles.

To examine if the processing roughness parameters of wood comply with the recommendations of ISO 4288: 1996 in Table 2, the processing roughness was separated from the wood anatomical irregularities. The method of separation was described in Gurau *et al*. (2007)- see section 1.2.6. The separation was performed after the analysis of the cut-off results, so only one cut-off length was applied for each species-grit combination (Table 3)

The total roughness, which contains both processing and anatomical roughness, was evaluated with the roughness parameters *Ra*, *Rq*, *Rz, Rsk, Rku* and *RSm* from ISO 4287: 1998 but calculated over the whole evaluation length rather than sampling lengths (see section 1.2.7). (The parameter *Rz* calculated over the evaluation length is equivalent to another standard parameter *Rt*, but will be referred to here as *Rz*.) Only the parameters *Ra* and *Rz* were calculated for the processing roughness.

In addition to the standard *RSm* parameter a derivation of *RSm* was used, named *RSmw* in this study. *RSmw* differs from *RSm* in that the minimum height and spacing requirements for a profile element are disregarded. If they are not, then the width and depth of the anatomical features can obscure the processing features. Compared with *RSmw*, *RSm* is strongly influenced by the presence of grouped large valleys in the profile. The values of *RSm* should differ substantially from those of *RSmw* for profiles where the irregularities due to anatomy are greater than those due to processing. *RSm* is also sensitive to any waviness retained in the roughness profile. The parameters *Rk*, *Rpk* and *Rvk* were calculated from ISO 13565-2: 1996 (as in section 1.2.7).

An examination of the data profiles shows that the cut-off length has a significant effect on the roughness profile. A primary profile from an oak surface sanded with P120 (Figure 34) may be compared with the same profile filtered with the extreme cut-off values of 0.025 and 40 mm (Figure 35 and Figure 36 respectively). The 40 mm cut-off value has retained all the waviness, while 0.025 mm has attenuated not only the waviness, but most of the roughness and anatomical irregularities as well.

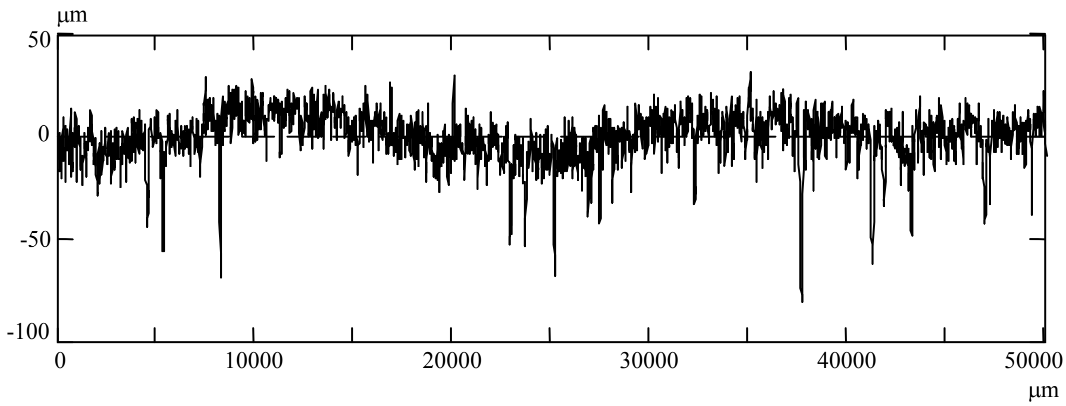


Figure 34 Primary profile of an oak surface sanded with P120 (Gurau *et al.* 2006a)

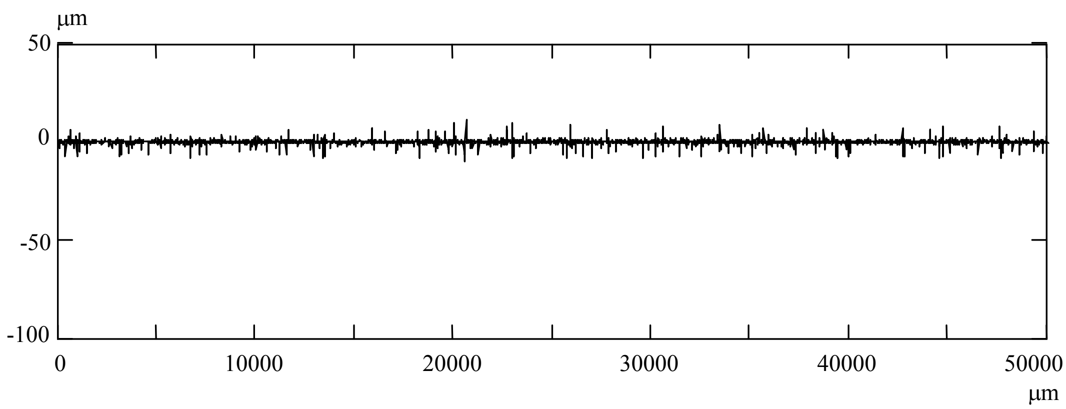


Figure 35 Roughness profile of an oak surface sanded with P120 when a cut-off λ = 0.025 mm was used(Gurau *et al*. 2006a)

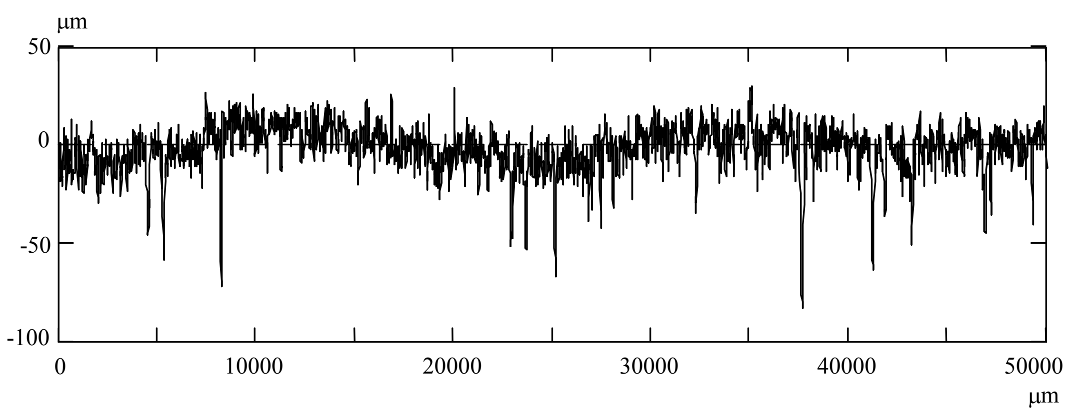


Figure 36 Roughness profile of an oak surface sanded with P120 when a cut-off λ = 40 mm was used (Gurau *et al.* 2006a).

The effect of varying the cut-off length on the total roughness parameters is presented in Figure 37 (all profiles in Gurau et al. 2006a). The values on the *y*-axis were normalised relative to *Ra* so they do not represent the real values of the parameters. This adjustment was preferred because it showed the trend of variation for all the parameters in one figure. The value of any roughness parameter R on the y-axis is given in [21 as a function of Ra, measured when a 0.025 mm cut-off was used.

$$f(Ra_1) = \frac{Ra_1}{R_1} \cdot R_i \qquad [21]$$

Ra_1 -Ra parameter measured when a 0.025 mm cut-off was used

$f(Ra_1)$ -value of a roughness parameter R normalised relative to Ra_1.

R_1 -roughness parameter R measured when a 0.025 mm cut-off was used

R_i -roughness parameter R measured when a cut-off corresponding to a rank i was used

i -rank corresponding to cut-off values of 0.025 to 40 mm

Figure 37 shows the variation of roughness parameters with the cut-off length for European oak sanded with P120.

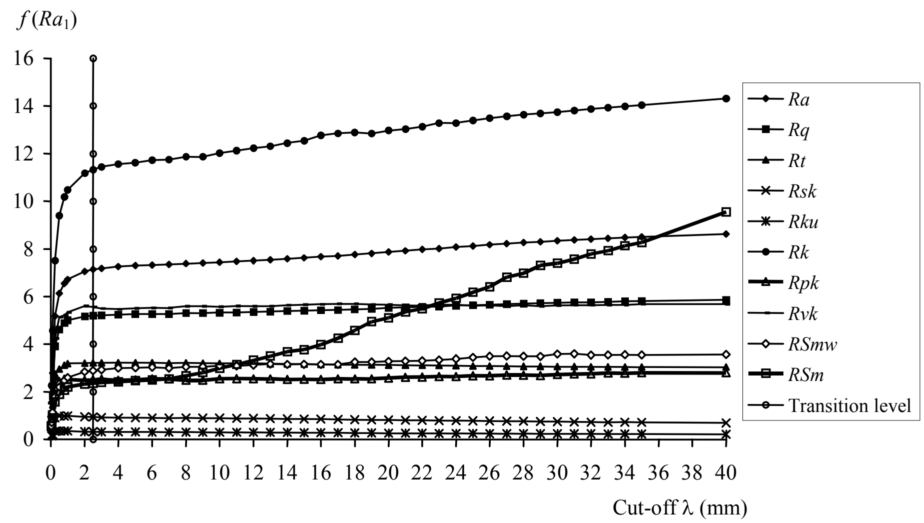


Figure 37 The influence of the filter cut-off on roughness parameters of an oak surface sanded with P120 (y-normalised data; Ra_1-value of Ra when a cut-off length 0.025 mm was used) (Gurau *et al.* 2006a)

All the roughness parameters in Figure 37 show an abrupt change in the first sector followed by more stable behaviour. The transition point appears to be around a cut-off value of 2.5 mm.

Within the stable region, all the roughness parameters increased slightly with the cut-off length, except *Rz* and *Rku*, which slightly decreased with cut-off lengths. In Figure 37 this increase is most clearly observed in *Rk* and *RSm*. The increasing amount of waviness included in the profile has probably attenuated the extreme values caused by the wood anatomy or fuzziness. This observation is supported by the decreasing kurtosis *Rku* (see significance of parameters in section 1.2.7).

The spacing parameter *RSm*, which is very sensitive to waviness, follows a kind of plateau from a value of 2.5 to a value of 8, and then increases steadily. The plateau may correspond to the cut-off range where the mean width of the irregularities corresponds to the mean width of the sanding grits. The area to the left of the plateau could correspond to values of *RSm* that measure only anatomical irregularities, while the upward slope to the right may be due to the increasing amount of waviness included in the roughness profile.

Similar results were found for Japanese oak sanded with P180 and spruce sanded with P120. For these species-grit combinations, the trend of the roughness parameters was the same as for oak sanded with P120, but *Rz* increased slightly, while the plateau region of *RSm* was shorter.

For every surface tested*, RSm* and *Rk* showed the greatest increase with the cut-off length, demonstrating that they are the most sensitive parameters to changes in the cut-off length.

Spruce showed an increase in *Rpk* with cut-off lengths higher than 2.5 – 3 mm, when waviness was included in the profile. *Rpk* seems to be an important parameter that, together with *RSm,* can indicate the best choice of cut-off length.

Since a cut-off length of 2.5 mm marks the start of a region of stability for surfaces sanded with P120 and P180, it seems a reasonable value for obtaining a roughness profile free of distortions and of waviness.

Processing roughness profiles were obtained by removing the anatomical irregularities from total roughness profiles that had been filtered with a 2.5 mm cut-off length. For both species the processing roughness parameters for P120 grit (Table 3) complied with the recommendations of ISO 4288: 1996 (Table 2), where for values $2 < Ra \leq 10$ μm and values $10 < Rz \leq 50$ μm a cut-off length of 2.5 mm is recommended. However, the parameters for Japanese oak sanded with P180 were at the upper limit of the interval where the standard recommends a choice of 0.8 mm cut-off length, although results showed that 2.5 mm was more appropriate (Gurau et al.2006a).

For oak sanded with P120 and P180, when *Ra* and *Rz* where calculated from the total roughness profile obtained with any one of the standard cut-off lengths, they did not both fall within the range of values recommended for that cut-off length. For spruce, as with the processing roughness parameters, the total roughness parameters *Ra* and *Rz* complied with ISO 4288: 1996. However, although both values of *Rz* are within the recommended interval, it should be noted that they are towards opposite ends of its limits. It appears that the total roughness parameters of species that have relatively large anatomical irregularities are less likely to comply with ISO 4288: 1996 than those with smaller irregularities, when they are sanded with normal finishing grit sizes.

Species and grit size	Roughness parameter (μm) *Ra*		*Rz*		Cut-off length λ (mm)
	Processing roughness	**Total roughness**	**Processing roughness**	**Total roughness**	
European oak P120	2.2	4.77	10.8	115.5	2.5
Japanese oak P180	1.85	4.73	8.8	120.8	2.5
European oak P1000	0.5	10.9	2.3	234	8
Norway spruce P120	3.02	3.89	16.28	45.33	2.5

Table 3 Processing and total roughness parameters of oak sanded with grit sizes of P120, P180 and P1000. The total roughness includes the anatomical irregularities (Gurau *et al.* 2006a)

The oak surface sanded with P1000 produced processing roughness parameters (Table 3) in the range where ISO 4288: 1996 recommends a cut-off value of 0.8 mm (Table 2). However, for oak sanded with P1000, a much greater cut-off length was necessary to overcome the effect of large pores in oak. The roughness profile at cut-off lengths less than 3 mm contains push-up distortion, which affects *Rpk* in particular. Most of the roughness parameters were unstable at these cut-off lengths. It is worth noting that with this species-grit combination, the total roughness parameters did fit the ISO 4288: 1996 recommendation for a cut-off length of 8 mm, but this is a reflection of the anatomy, not the grit size.
For all of the species-grit combinations investigated there was a significant difference between the values of the total roughness parameters and the processing roughness parameters. This confirms the importance of separating the anatomical irregularities from the processing roughness if a proper measure of the sanding process is required (see next section 1.2.6).

Conclusions

The cut-off length has a significant effect on the roughness parameters of sanded wood surfaces, so it is important to choose the correct cut-off length, which may vary with grit size and species.

A cut-off length of 2.5 mm would minimise waviness without introducing distortions or significantly affecting the various roughness parameters. This value was suitable for surfaces sanded with grit sizes P120 to P180, which commonly precede finishing applications. However, finer processing may require larger cut-off lengths to overcome the distorting effect of deep pores.

The recommendations in ISO 4288: 1996 for selecting the filtering cut-off length were more often reliable when they were based on the processing roughness parameters than the total roughness parameters, which contained wood anatomy.
After filtering a wood surface, the next step in surface metrology consists in evaluating the surface roughness usually caused by a mechanical process like sanding, planing or other processes. In such cases, it is important to be able to quantify only the effect of process parameters on wood disregarding wood anatomical irregularities, which are a source of bias. The next section is dedicated to studies from the literature on this topic finalized with a research study of the author.

1.2.6 Research on the evaluation of processing roughness and separation from wood anatomy

A proper evaluation of the quality of a sanding operation requires that roughness due to wood anatomy is excluded from the numerical characterization of the processing roughness (Kilic et al.2006, Magross 2015). The literature contains various approaches in this respect. Sometimes measurements have been made in areas less affected by wood anatomy, such as latewood (Cotta et al.1982, Costes and Larricq 2001). Mechanical methods of minimizing the effects of anatomical roughness have concentrated on the stylus of the measuring device. Workers have used non-standard radii for the stylus, (Pohl 1999); or have otherwise modified the stylus geometry (Heisel and Krondorfer 1995). Given the variety of anatomical features among species and the range of possible grit sizes it does not appear feasible to use a specific tip for each species or region of a wood specimen.

Schadoffsky (2000) used an image analysis technique for surface evaluation. Values below a certain threshold were considered anatomical and were excluded, so that standard roughness parameters could be calculated from the modified profile. He found the procedure to be less reliable for softwoods and diffuse-porous species than for hardwoods with large vessels.

Fujiwara et al. (1999) proposed a numerical filtering method to minimize push-up by excluding deep valleys, caused by vessels, based on the gradient of the valley sides. The filter was particularly sensitive to the selection of the threshold value of the gradient.

Goli and Sandak (2016) used a laser triangulation method to obtain the 3D surface topography and wavelet filtering for detection of surface defects and comparison of different tool-grain interactions. Wavelets locate and identify outliers, can filter individual features, but are difficult to interpret (ISO 16610-1:2015). Although the method has potential and can be useful for characterising different surface processing qualities of the same species, the question of separating the wood anatomical features from processing species with different anatomies still remains.

A numerical approach that has been applied by a number of workers employs the Abbot-curve (Westkämper amd Schadoffski 1995a, Sharif and Tan 2011). The curve allows the characteristic parameters *Rk, Rvk* and *Rpk* (see 1.2.7) to be calculated, by dividing the profile into three sections: the peaks, a middle plateau and the valleys. The parameters *Rk*, *Rvk* and *Rpk* may be interpreted as measuring particular aspects of a wood surface. For instance, for a specimen with deep pores and a fine grit size, the *Rk* parameter may be understood as the processing roughness (Westkämper and Riegel 1993a), *Rvk* as the anatomical roughness, and *Rpk* as fuzzy grain. However, according to Riegel (1993), standard Abbot-curve parameters are only approximate indicators of the processing roughness, fuzziness and wood anatomy.

Gurau et al.(2005a, 2007) proposed a method to determine the boundaries of the outlying peaks and valleys by monitoring the variation of the second derivative of the Abbot-curve of the roughness profile.

The objective of the following study was to separate the processing roughness from the wood anatomy and the fuzziness using a method based on thresholds defined in the Abbot-curve and to investigate the effect of grit size on the processing roughness of sanded European oak (*Quercus robur*) after this separation.

1.2.6.1 Principles of the method to separate processing roughness from wood anatomy

Once a roughness profile is free of any distortions, the Abbot-curve is the most appropriate starting point for devising a separation method since it is a straightforward tool for calculating the distribution of the profile heights (Gurau *et al*. 2005a, 2007, 2011). The Abbot-curve is constructed by sorting the data points in descending order. It allows the profile to be divided into three sections: the peaks, a middle plateau and the valleys (Figure 38).

Outlying peaks and valleys appear as non-linear regions in the Abbot-curve, and can be excluded. The following method determines the boundaries of these regions with greater precision than the standard

Abbot-curve parameters, so that they can be used to identify the processing roughness (Gurau *et al*. 2007).

The boundaries between the central plateau and the outer regions are marked by transition points in the Abbot-curve (Figure 38). The indexes of the transition points can be found by monitoring the variation of the second derivative of the Abbot-curve near the boundary. The index where the ratio of the absolute value of the second derivative to the standard deviation of the previous points exceeds a critical value [22] may be taken as the index of the transition point. ISO 13565-3 (1998) recommends a critical value of 6 for this ratio. Other critical values have been investigated for wood, but 6 was found to be the most suitable value (Gurau 2004).

$$criticalvalue = \frac{|SD_{i+1}|}{stdev_{1..i}} \qquad [22]$$

(Gurau et al.2011)

SD_{i+1} - second derivative of the "*i*+1"data point in the Abbot-curve

$stdev_{1..i}$ - standard deviations of the previous "*i*" second derivatives data points

The vector of second derivative values is calculated from a moving window that is short enough to be sensitive to slight variations in the gradient of the Abbot-curve. A window length of 1% of the data profile is appropriate, so the second derivative vector is 0.5% shorter than the data profile at each end. Since there are generally fewer peak values than valley values, and their absolute deviation from the mean line is less, it is convenient to determine the upper boundary before the lower boundary. To find the upper transition point, the standard deviation of the third quartile of the derivative values is calculated (assuming that this excludes all valley values) then data points are added incrementally to the left until the critical value is exceeded.

The lower transition point should be calculated from a modified second derivative vector where the peak values have been replaced by zeroes. If the peaks are not excluded, they can lower the location of the valley threshold by an unpredictable amount. The search for the lower transition point begins with the first quartile of the modified data then data points are added incrementally to the right until the critical value is exceeded.

The core data between the two transition points is assumed to represent the height variation caused by sanding, but inevitably includes some anatomical features located within the thresholds that cannot be separately identified, such as shallow valleys or the upper limits of deep valleys. Data points above the upper threshold represent the fuzziness, which is mainly dependent on wood characteristics: species, density and moisture content, and to a lesser extent on the grit size. Data points below the lower threshold represent the anatomical features that exist on the surface independently of the sanding process. The thresholds are shown for the oak profile sanded with P1000 as vertical dashed lines in Figure 38 and solid lines in Figure 39.

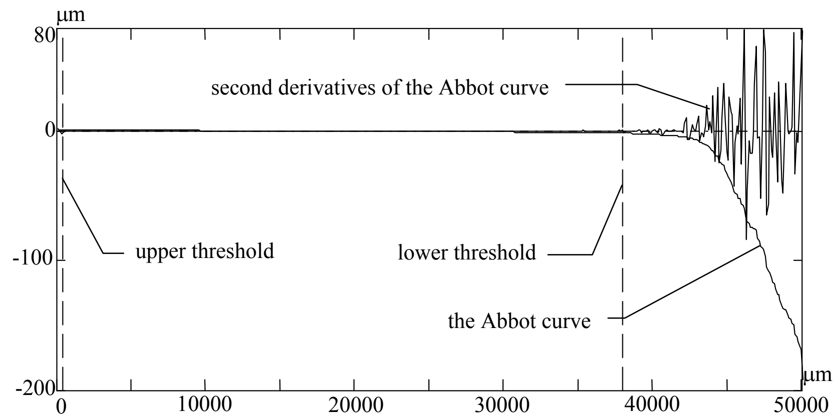


Figure 38. Use of the Abbot-curve to find threshold values to delimit the processing for oak sanded with P1000 (Gurau et al. 2005a)

Figure 40 shows a detail of a roughness profile represented as data points, where upper and lower thresholds delimit the core data, which is of a much higher frequency than the remaining data. The core data may be used to characterize the processing roughness whereby data points outside the upper and lower thresholds can be replaced with zeroes that are subsequently excluded from the calculation of roughness parameters. Figure 41 and Figure 42 show the processing roughness and the anatomical roughness respectively of the oak profile sanded with P1000 after the separation.

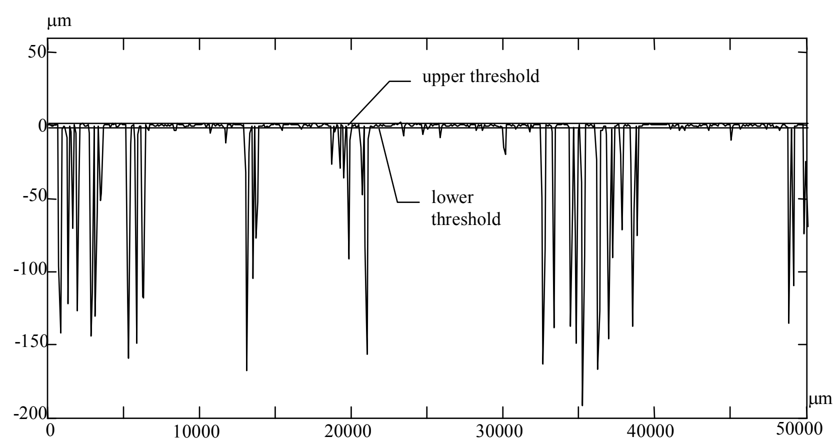


Figure 39. Location of the upper and lower thresholds as boundaries for the processing roughness, oak sanded with P1000 (Gurau *et al.* 2011).

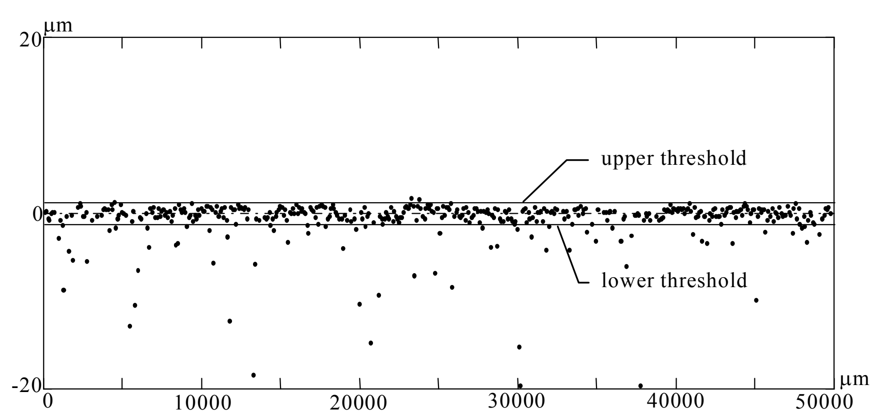


Figure 40. Core roughness data delimited by thresholds for oak sanded with P1000 (Gurau *et al.* 2005a)

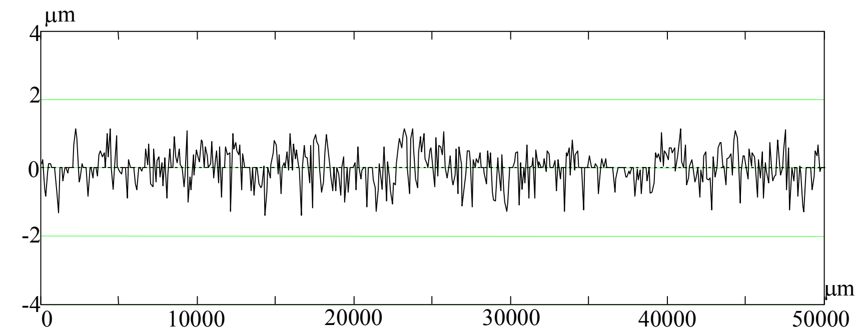


Figure 41. Processing roughness of an oak surface sanded with P1000 (Gurau *et al.* 2005a)

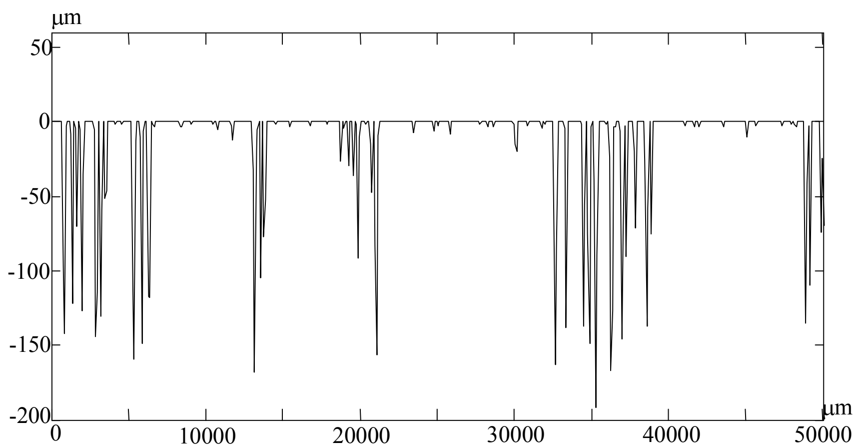


Figure 42. Anatomical roughness of an oak surface sanded with P1000 (Gurau *et al*. 2005a)

1.2.6.2 First case study: the processing roughness of oak surfaces sanded with various grit sizes

This is a study published in a book chapter edited by Iste-Willey (Gurau *et al*.2011) and *it was meant to demonstrate the negative effect of wood anatomy on the evaluation of the surface quality of oak surfaces sanded with a large range of grit sizes, from very rough to very fine. Oak is an example of a ring porous species with deep pores, which often are deeper than the irregularities caused by sanding.*

European oak (*Quercus robur*) was chosen, as it is a common commercial species with large earlywood pores. Oak surfaces are inherently difficult to analyze since they contain groups of deep pores that must be separated from the recorded profile if the processing roughness is to be properly evaluated. Tangential surfaces of earlywood bands were prepared, to give the greatest variation in the surface features. The specimens were conditioned to a uniform moisture content of approximately 12% by storage in a climate-controlled environment of 65% relative humidity at 20 °C. For each grit size to be tested, one specimen was prepared from each of two boards and cut to surface dimensions of 100 × 90 mm, suitable for sanding on a Makita 9402 portable belt sander. The sander was inverted and mounted on a solid base, and a stiff frame was constructed around the equipment. The specimen was held rigidly at all times on top of the belt.

The sanding was performed with aluminium oxide closed-coated cloth belts measuring 600 × 100 mm. Fresh belts result in high roughness values, which are not representative of the process, so before the specimens were sanded, the new sanding belts were worn by continuous sanding for 30 minutes to remove the initial sharpness of the abrasive grits. The processing was conducted at a constant contact pressure of 3.2 kN/m^2 and a nominal belt speed of 5 m/s, the fastest speed on this machine.

The grit sizes used were P60, P120, P150, P180, P240 and P1000. Sizes P120, P150 and P180 are commonly used in the furniture industry for the final sanding before coating. New finishing techniques can require even finer grit sizes from P220 to P280, so P240 was included as an example of such fine commercial sanding. P60 is too coarse for final sanding and P1000 is too fine for commercial applications, but they were included for the sake of comparison and to test the effectiveness of the separation algorithm to the extreme grit sizes.

The surface measurements were carried out as described in Gurau et al. (2011). The total roughness profiles, were obtained by filtering the surface with the Robust Gaussian Regression Filter from ISO/TS 16610-31. A cut-off length of 2.5 mm for surfaces sanded with grits P60 to P240 and 8 mm for grit P1000 produced undistorted profiles (Gurau *et al*.2006- section 1.2.5.5).

The separation of processing roughness from the other irregularities of the surface followed the method described above, in which outlying peaks and valleys were replaced with zeros that were neglected when the roughness parameters were calculated (see also section1.2.6.2).

The processing roughness and the total roughness were evaluated with the roughness parameters *Ra* (arithmetical mean deviation), *Rq* (root mean square deviation), *Rt* (total height of profile), *Rsk* (skewness) and *RSm* (mean width of the profile elements) from ISO 4287. The parameters were adapted for wood in that they were calculated over the entire evaluation length rather than shorter sampling lengths (see also section 1.2.7 for more explanation about roughness parameters). The evaluation length is restricted by the capacity of a measuring instrument, so its division into sampling lengths, as instructed by ISO 4287, leads to data sets that do not represent the variation of the wood surface. *RSm* from the standard was modified for calculating the processing roughness in that the minimum height and spacing requirements for a profile element were disregarded. If they are not, then the width and depth of the anatomical features can obscure the processing features. Other calculated parameters were *Rk*, *Rpk* and *Rvk* from ISO 13565-2. Each roughness parameter was calculated as a mean of the mean values obtained from each individual area. Similarly the coefficients of variation were calculated as means from the area values.

The mean processing roughness parameters and their corresponding mean percentage coefficients of variation and total roughness values are shown in Table 4 and Table 5.

Parameter/grit size	***Ra***	***Rq***	***Rk***	***Rpk***	***Rvk***	***Rsk***	***Rt***	***RSm***
P60								
Processing (P)	12.1 (8.4)	14.3 (7.4)	40.6 (4.7)	6.58 (21.5)	9.7 (16.7)	-0.18	58.1 (7.6)	154.8 (4.8)
Processing + anatomy (P +A)	17.1	23.3	48.8	20.7	37.3	-1.12	200.8	244
(P + A)/P	**1.41**	**1.63**	**1.2**	**3.15**	**3.85**	**-**	**3.46**	**1.58**
P120								
Processing (P)	2.24	2.65	7.60	1.24	1.86	-0.15	10.8	78.4

	(8.3)	(7.1)	(4.7)	(20)	(13.3)		(7.6)	(5.2)
Processing + anatomy (P + A)	4.78	9.1	9.96	7.28	19.8	-4.05	115.5	213.7
(P + A)/P	**2.1**	**3.4**	**1.3**	**5.9**	**10.6**	**-**	**10.7**	**2.7**
P150								
Processing (P)	2.03 (8.1)	2.4 (7.3)	6.52 (4.2)	1.22 (18.2)	1.89 (20.4)	0.05	9.89 (8.7)	74.4 (4.1)
Processing + anatomy (P + A)	6.13	13.19	9.02	6.66	31.3	-4	129.3	283.4
(P + A)/P	**3.02**	**5.5**	**1.38**	**5.46**	**16.6**	**-**	**13.1**	**3.8**

Table 4. Processing and total roughness parameters in μm for oak sanded with P60, P120 and P150. The values in brackets are mean percentage coefficients of variation (Gurau *et al*. 2011)

Parameter/grit size	*Ra*	*Rq*	*Rk*	*Rpk*	*Rvk*	*Rsk*	*Rt*	*RSm*
P180								
Processing (P)	1.86 (9.5)	2.19 (8.5)	5.96 (4.9)	1.01 (16.1)	1.62 (21.9)	-0.07	8.85 (9.3)	65.2 (5.1)
Processing + anatomy (P +A)	4.73	10.5	7.98	4.64	24.8	-4.97	120.8	251
(P + A)/P	**2.54**	**4.79**	**1.34**	**4.59**	**15.3**	**-**	**13.6**	**3.8**
P240								
Processing (P)	1.34 (6.4)	1.6 (5.6)	4.5 (3.1)	0.71 (18.8)	1.08 (16.7)	-0.14	6.5 (6.8)	47.6 (3.3)
Processing + anatomy (P + A)	4.76	12.6	6.03	3.89	34.1	-5.13	136.2	262.1
(P + A)/P	**3.55**	**7.88**	**1.34**	**5.48**	**31.6**	**-**	**21.0**	**5.5**
P1000								
Processing (P)	0.44 (9.3)	0.52 (9.8)	1.37 (7.3)	0.22 (24.2)	0.49 (20.0)	-0.17	2.16 (12.4)	38.4 (8.6)
Processing + anatomy (P + A)	10.9	33.8	1.95	0.51	78.5	-3.99	233.9	468.8
(P + A)/P	**24.8**	**65**	**1.42**	**2.32**	**160.2**	**-**	**108.3**	**12.2**

Table 5. Processing and total roughness parameters in μm for oak sanded with P180, P240 and P1000. The values in brackets are mean percentage coefficients of variation (Gurau *et al*.2011)

The results in Table 4 and Table 5 demonstrate that all the processing roughness parameters were sensitive to the grit size, whereas for total roughness parameters the variation was random. In general, processing roughness values were highest with P60, similar with P120, P150 and P180 and much smaller with P240 and P1000. Although sanding is almost always performed in a sequence of grit sizes from coarse to fine, the close roughness values obtained for the commercial grit sizes P120, P150 and P180, which are normally used for final sanding, indicate that, at least for oak, it is not necessary to have a sequence of sanding operations within this range of fine grit sizes.

As was expected, given the anatomy of oak, there were considerable differences between the processing and total roughness parameters.

Rpk and *Rvk*, which were much smaller in absolute terms than *Rk*, are parameters that define isolated peaks or valleys in the profile. They are sensitive to any change in the thresholds that separate the processing roughness from wood anatomy and that can add or remove a few peaks or valleys. Such changes do not affect the core data to any great extent so the coefficients of variation in Table 4 and Table 5 are much smaller for *Rk* than for *Rpk* and *Rvk*. *Rk* measures the core roughness depth, and it is the parameter least affected by the presence of anatomy. Furthermore, *Rk* had the smallest coefficient of variation of all parameters, so it is the most reliable parameter for characterising the processing roughness. The low variability in *Rk* indicates that the core data is well defined for all the profiles.

The height parameter *Rt* and the reduced valley depth *Rvk* were strongly influenced by the presence of wood anatomy, since they have the highest ratio values between total roughness and processing roughness in Table 4 and Table 5.

The parameters *Ra* and *Rq* were higher when calculated from the total roughness than from the processing roughness since the wood anatomy of oak creates greater variation of the data around the mean.

Rsk is a parameter that can be strongly influenced by isolated peaks or isolated valleys. When calculated from the total roughness data, surfaces with a positive skewness, *Rsk* > 0, have fairly high peaks that protrude above a smoother plateau, while surfaces with a negative skewness, *Rsk* < 0, have fairly deep valleys in a smoother plateau. In the total roughness data, *Rsk* indicates the presence of deep pores in the oak surface, whereas the near-zero values of *Rsk* in the processing roughness data indicates that the distribution of the marks left by the grit particles on the surface is symmetrical around the mean line.

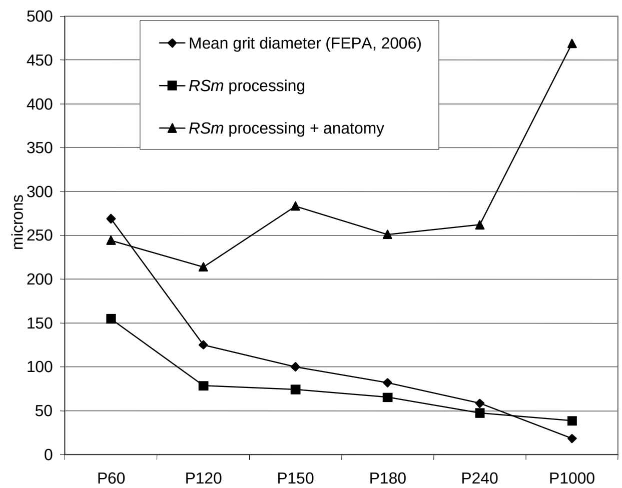


Figure 43. Comparison of the spacing parameter *RSm* measured from processing and total roughness data of oak sanded with various grit sizes with the mean grit diameter as given in FEPA (2006a, 2006b) (Gurau *et al*. 2011)

In contrast to the above parameters, which are measures of the height of the irregularities, *RSm* is a measure of their width. To calculate *RSm* for the processing roughness, the profile was compacted in areas where the outliers had been replaced with zeros. The coefficient of variation for *RSm* in Table 4 and Table 5 was as low as for *Rk*, which shows that *RSm* is virtually unaffected by fluctuations in the threshold locations within individual profiles. Such fluctuations can be expected with a material as heterogeneous as wood, due to the variation in the depth of grit marks. This makes *RSm* a reliable measure of the widths of the sanding mark irregularities when the anatomical variation is excluded. *RSm* should be a measure of the grit print width and should, decrease with the grit size (Table 4, Table 5 and Figure 43). As expected, it was, smaller than the mean grit diameter (FEPA 2006a, 2006b) except for P1000, where the processing width of such fine grits may have been obscured by the anatomical openings.

The higher values of *RSm* for the total roughness data than for the processing roughness indicates the influence of anatomy, in this case the large diameters of cell lumena. The parameter was certainly biased by the oak anatomy since all *RSm* values for the total roughness were higher than the mean grit diameter, which logically is not possible (Figure 43).

Conclusions

All the processing roughness parameters, for sanded oak, were sensitive to the grit size, whereas for total roughness parameters, which included wood anatomy, the variation was random. The comparison of processing and total roughness parameters further demonstrates that the wood anatomy must be removed from the roughness profile if a proper measure of the processing roughness is required.

1.2.6.3 Second case study: the processing roughness of beech surfaces sanded with various grit sizes

This is another case study, published in Gurau *et al.* (2015) and *it was meant to demonstrate the negative effect of wood anatomy on the evaluation of the surface quality of beech surfaces sanded with a large range of grit sizes, from very rough to very fine. The effect of wood anatomy on the processing roughness of diffuse porous species is less well reported.*

This study (Gurau *et al*. 2015) examines the processing roughness of beech surfaces sanded with 13 grit sizes from P60 to P600 after the separation from wood anatomy and quantifies the biasing effect of wood anatomy when it is not removed.

In the majority of studies regarding the influence of grit size on the surface roughness, the anatomical roughness has not been removed (de Moura and Hernandez 2006; Kilic *et al.* 2006; Ratnasingam 2006; Marthy and Cismaru 2009; Sulaiman *et al*. 2009; Salca and Hiziroglu 2012; Varasquim *et al* 2012; Vitosyte *et al.* 2012; de Moura Palermo *et al.* 2014; Miao and Li 2014). Even though a trend of decreasing roughness with increasing grit number was unanimously reported, the exact quantification of the processing roughness produced by each grit size was not performed, nor was there a thorough analysis by means of roughness parameters of the effect of retaining the anatomical roughness.

Beech (*Fagus sylvatica*) was chosen for the study, as it is a common commercial species. The diffuse distribution of its pores and their negligible size in comparison with ring porous species are reasons why researchers have not determined the biasing effect of its anatomy on the evaluation of sanding roughness (Kilic *et al.* 2006). Therefore, for this study, its anatomy was included in the surface roughness data. The same judgement has been made in the assessment of the processing roughness of other diffuse porous species (de Moura and Hernandez 2006; Kilic *et al.* 2006; Ratnasingam 2006; Sulaiman *et al.* 2009; Salca and Hiziroglu 2012; Vitosyte *et al.* 2012). However, since wood anatomy should be considered regardless of anatomical type, this study aims to examine the processing roughness of beech surfaces sanded with a wide range of grit sizes and to quantify the effect of wood anatomical irregularities if they are retained in the measured surface data.

A number of 39 beech boards with semi-radial faces were randomly taken from the stock of a furniture factory in Hungary. From these boards, 39 specimens were cut, one per each board, which were then planned on four sides and had the following dimensions: 300 × 100 × 27 mm. The specimens were taken to the laboratory and conditioned in an environment of 65% relative humidity and 20 °C. Their mean density after conditioning was of 722 kg/m³. The specimens, three for each grit size, were sanded with 13 different grit sizes selected to cover the complete range of final sanding grit sizes: P60, P80, P100, P120, P150, P180, P220, P240, P280, P320, P400, P500 and P600 (grading system by FEPA). P120, P150 and P180 are commonly used in the furniture industry for the final sanding before coating. New finishing techniques can require even finer grit sizes from P220 to P280, so they were also included (Ratnasingam 2006; Landry and Blanchet 2012; Vitosyte et al. 2012). The grit sizes from P320 to P600 are not used in the common practice but were included in the analysis to provide examples of a very fine grit size compared to wood anatomy and to make the presence of wood anatomy visible with no uncertainty. The sanding was performed so that a constant layer of material, 0.4±0,05 mm thick, was removed for each grit size and this condition was monitored by sequential specimen thickness measurements with a digital micrometer. This layer thickness was considered sufficient to remove any previous irregularities from planning, leaving on the surface just the roughness caused by sanding with that particular grit size.

Sanding was performed with a Makita portable sander 9902, with Toptech Siawood 2920 closed system belts 76 ×533 mm, working at a belt speed of 440 m/min. The sanding machine was kept parallel to a height adjustable belt conveyor, which fed the material at a feed speed of 7 m/min. As the belts were new, an initial wearing was performed prior to tests, so that the "working sharpness", which is characterized by a slow, but constant rate of decrease in the sanding capacity, was achieved.

The number of sanding sequences increased with increasing grit number. Between each step of sanding, both the sample surface and the belt were cleaned from dust by means of a vacuum cleaner adjusted with a smooth, dense brush. The direction of sanding was parallel to the grain.

Two random roughness measurements were performed on each surface of the three specimens that had been prepared with the same grit size. The measurements were performed perpendicular to the sanding direction, by means of a Mahr Perthen SP3 instrument fitted with a stylus tip with 5 µm radius. The profiles were 12.5 mm long and were measured at a lateral resolution of 2.17µm, so that 5760 datapoints were collected from each profile.

Data were stored in ASCII format and processed with algorithms written in MathCad™. Form errors were removed according to the profile method of ISO 3274 (1996) by using a second order polynomial regression, which proved to be the best fit for the initial data after trials with polynomials of order one, two and three.

The total roughness profiles containing both the processing and the anatomical irregularities were obtained by filtering the surface with the Robust Gaussian Regression Filter (RGRF) described by ISO/TS 16610-31 (2010). As said in previous sections (1.2.5.2), this filter is intended to be "robust" against outliers (Lou et al. 2013), which in wood are represented by deep anatomical features or accidental high peaks that do not characterize the processing. For filtering the roughness profiles, a cut-off length of 2.5 mm was used because it had been previously tested and found useful to produce undistorted profiles in wood (Gurau *et al.* 2006a)- see section 1.2.5.5.

Another set of data was obtained by separating the processing roughness from the other irregularities of the surface by using the method based on the Abbot curve. The core data is assumed to represent the height variation caused by sanding, but inevitably includes the portions of anatomical features located within the thresholds, which cannot be separately identified. Data points above the upper threshold represent the fuzziness, while data points below the lower threshold represent the anatomical features that exist on the surface independently of the sanding process. To separate the data points outside the thresholds from the core data, they were replaced with zeroes, which were excluded from the calculation of roughness parameters (see section 1.2.6.1).

The processing roughness and the total roughness were evaluated with the roughness parameters *Ra* (arithmetical mean deviation), *Rq* (root mean square deviation), *Rt* (total height of profile), *Rsk* (skewness), *Rku* (kurtosis) and *RSm* (mean width of the profile elements) as defined in ISO 4287 (1998). Other calculated parameters were *Rk* (the core roughness depth), *Rpk* (the reduced peak height) and *Rvk* (the reduced valley depth) from ISO 13565-2 (1996). As noted above, *Rk* is a measure of the core roughness data. *Rpk* and *Rvk* are parameters that define isolated peaks or valleys in the profile.

The ratio of any total roughness parameter to the equivalent processing roughness parameter was calculated to give a quantification of the biasing effect of other irregularities present on the surface together with the processing.

An analysis of the influence of wood anatomy on the evaluation of surface roughness sanded with grit sizes from P60 to P600 was made based on each type of roughness parameter.

The ratio total/processing parameters, increased with the grit number, which is a clear indication that anatomical irregularities have to be removed from the surface data in order to have only an evaluation of the processing. The most biased parameter was *Rt*, for which the ratio increased from 2.53 for P60 to 8.96 for P600 (Figure 44). From both sets of data it is clear that wood anatomy tends to bias the evaluation of the processing quality and this phenomenon occurs even for rough sanding with P60.

The influence of wood anatomy can be visualized in Figure 44 with help of the non dimensional shape parameters *Rsk* and *Rku* from the total roughness data.

The total skewness parameter, *Rsk*, decreases with the grit number. The negative values indicate the presence of deep valleys below the core data increasing in influence as the grit particles become finer. In other words, wood anatomy is obscuring the processing roughness with a magnitude that increases with the grit number.

The kurtosis parameter *Rku*, is strongly influenced by isolated peaks or valleys, which can lead to values of kurtosis greater than 3, which is the value for normally distributed data. The total *Rku* increased with the grit number indicating the same trend of wood anatomy obscuring the processing (Figure 44) as noted for *Rsk*.

It can be seen that from grit sizes P60 to P100, the variation in these parameters was very small, but beginning with P120 the anatomy became a factor of bias, with the parameters gradually increasing (*Rku*), or decreasing (*Rsk*) up to P320. Any further decrease of the grit size above P320 seems to cause a pronounced change in the parameters, most probably as a predominat effect of wood anatomy.

The influence of anatomy in Figure 44 is also illustrated by the ratio of (*Rpktotal*+*Rvktotal*), as approximate descriptors of wood anatomical peaks and valleys, to *Rktotal*, as an approximation of the processing roughness. Furthermore, Figure 44 shows the ratio of *Rttotal*, as a height parameter quantifying the data which includes the processing and anatomy, to *Rtprocessing*, as the height parameter that evaluates only the processing. Both ratios had a similar trend as the shape parameters.

The conclusion from this analysis is that a reliable assessment of the final sanding before applying the finishing layer, which normally begins with P120, should separate the wood anatomy from the processing roughness.

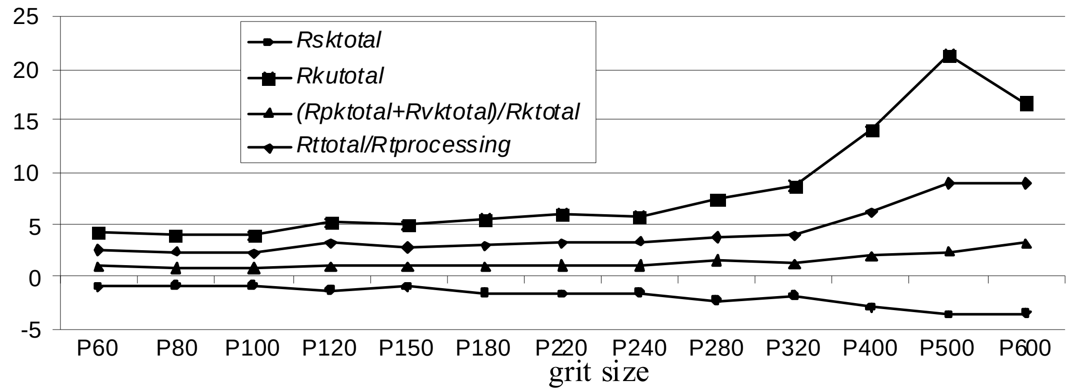


Figure 44 The influence of wood anatomy reflected by the variation of some key roughness parameters with the grit size for sanded beech surfaces (Gurau *et al.* 2015)

A logarithmic variation with the grit size was observed for all the processing roughness parameters examined. The *Rvk* parameter determined from the total roughness set of data includes the wood anatomical variation and it approximates the wood anatomical depths to a certain degree. When anatomical irregularities are removed, *Rvk* remains a measure of isolated processing depths, so it should show an improved correlation with the grit size. Figure 45 confirms this judgment by showing the logarithmic correlations of *Rvk* from both sets of data with a clearly better correlation for the case where wood anatomy was removed.

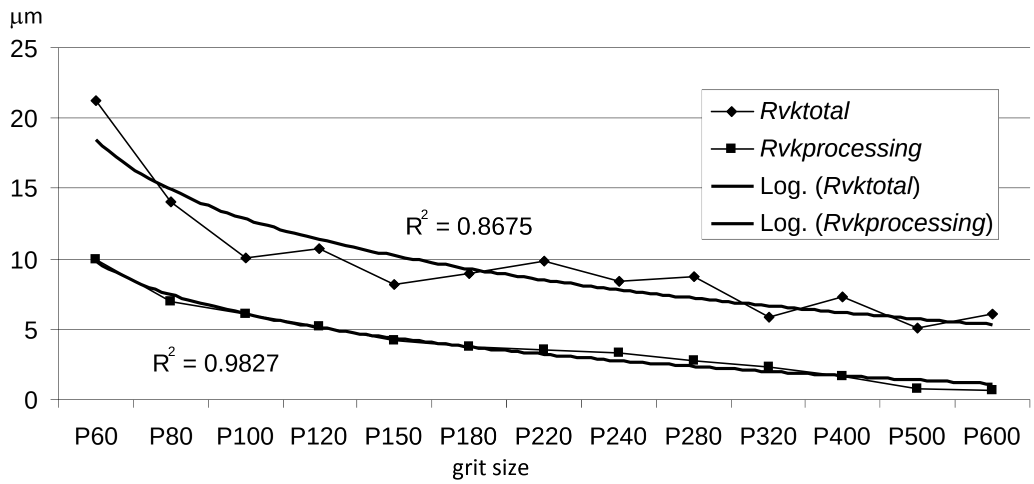


Figure 45 The variation with the grit size of the valley depth *Rvk* parameter when anatomy was removed (*Rvk processing*) and when it was not (*Rvk total*) (Gurau *et al*. 2015)

These observations are particularly interesting because were made on beech, a diffuse porous species where the effect of the anatomy might be considered negligible in comparison with ring porous species. However, it appears that the heterogeneity of wood should be taken into consideration regardless of species and measurements should always exclude wood anatomy if the processing roughness is to be properly evaluated.

Conclusions

In general, the processing roughness parameters, for sanded beech surfaces, had a strongly correlated logarithmic variation with the grit size. The roughness parameters from the total roughness data were biased by the presence of wood anatomical irregularities. The bias was smaller for grit sizes from P60 to P100, gradually increased from P120 to P280 and increased sharply from P320 onwards.

Although beech is a diffuse porous species and considered more homogeneous than ring porous species, wood anatomical irregularities should be excluded from roughness data for a reliable assessment of the processing roughness.

1.2.6.4 The third case study- comparing the processing roughness with total roughness for sanded oak and spruce

The study published in Gurau *et al*. (2005d), *investigated the effect of wood anatomy on surface roughness parameters of oak and spruce wood after sanding with P120 sandpaper. The wood anatomy was excluded from the roughness profile using the method developed and described in section 1.2.6.1. Total roughness parameters, which contain both the processing irregularities and the wood anatomy, were compared with processing roughness parameters.*

Tangential faced specimens of oak and spruce were conditioned to a constant moisture content of about 12%, in a climate-controlled environment. Oak was chosen, as it is a common commercial species and because it has large earlywood vessels, which make it inherently difficult to analyse roughness data. These large pores must be separated from the recorded profile if the processing roughness is to be properly evaluated. Spruce contains fuzziness and irregular waviness due to density variation within the growth ring, both of which do not characterise the processing.

The test material was pre-sanded in a wide belt sander to remove the irregularities from sawing and planing operations. It was sanded parallel to the grain, firstly with a P60 grit size followed by P80. The specimens were cut for the test material to surface dimensions of 100 mm × 90 mm, suitable for final sanding.

The final sanding was performed with cloth belts, 600 mm × 100 mm, closed coated with aluminium oxide of P120 grit size, with a MAKITA sander. The sanding was conducted at a constant contact pressure of 0.0032 N/mm^2 and at a belt speed of 5 m/s, the fastest available with this machine. Before the specimens were sanded, the new sanding belts were dulled by continuous sanding for 30 minutes, to remove the initial sharpness of the abrasive grits.

The surface measurements were carried out at the Technical Centre of the 3M manufacturing company in Atherstone, on a Taylor Hobson scanning instrument Talyscan 150, which is a 3D surface profiler. The scanning head was a stylus with 2.5 μm tip radius and 90° tip angle, which moved across the surface perpendicular to the sanding marks at a speed of 1000 μm/s. A detailed description of the measurements and evaluation with roughness parameters is given in Gurau et al. (2005d).

A comparison of roughness parameters calculated from processing and total roughness in Table 6 shows considerable differences for oak and smaller differences for spruce. This pattern is as might be expected given the anatomy of the two species.

For both species the parameter with the greatest difference between total and processing roughness was the shape parameter *Rsk*, which measures skewness. The near-zero values of *Rsk* in Table 6 indicate that the distribution of the processing roughness data as marks left by the grit particles on the surface is symmetrical around the mean line, whereas the skewness of -4.05 from the total roughness profile indicates the presence of deep pores in the oak surface.

The other shape parameter *Rku* measures kurtosis, which describes whether a distribution is flat or peaked. *Rku* from the processing roughness of oak was 2.2, which indicates that the shape of the distribution function tended to have a flat top around the mean. *Rku* from the total roughness profile was strongly influenced by isolated valleys and increased to 30.5, which indicated that the density function had a distinct peak around the mean, and was spread over a greater range. The equivalent values for spruce show a much weaker influence of anatomy.

The height parameter *Rz* and the reduced valley depth *Rvk* were strongly influenced by the presence of wood anatomy. For oak, the total roughness values for these parameters were both 10.7 times greater than processing roughness values (Table 6).

The reduced peak height *Rpk* is an indication of surface fuzziness when it is calculated from the total roughness profile. Contrary to expectations, the oak surface appeared be fuzzier than the spruce surface.

However the core roughness *Rk* of spruce was higher than oak, which implies that the fuzziness was so frequent that it was partially included in the core roughness.

Parameter	Oak P120			Spruce P120		
	Processing	Total	Total / Processing	Processing	Total	Total / Processing
Rsk	-0.15	-4.05	26.2	-0.06	-0.42	7.1
Rku	2.18 (4.30)	30.5 (21.2)	14.0	2.13 (3.48)	4.17 (10.0)	2.0
Ra	2.24 (8.32)	4.78 (3.52)	2.1	2.85 (9.70)	3.80 (1.38)	1.3
Rq	2.65 (7.14)	9.10 (7.64)	3.4	3.36 (8.34)	4.99 (1.87)	1.5
Rz	10.8 (7.55)	115.5 (9.77)	10.7	13.5 (9.04)	46.4 (11.2)	3.4
Rk	7.60 (4.65)	9.95 (1.60)	1.3	9.56 (5.26)	11.3 (2.32)	1.2
Rpk	1.24 (20.0)	7.28 (11.8)	5.9	1.60 (20.5)	5.08 (7.18)	3.2
Rvk	1.86 (13.3)	19.9 (9.98)	10.7	2.06 (15.7)	6.57 (4.68)	3.2

Table 6 Comparison between processing and total roughness parameters of oak and spruce surfaces sanded with P120. Values represent mean roughness parameters (μm). The values in brackets are mean percentage coefficients of variation (Gurau *et al.* 2005d)

Rk measures the core roughness depth, and for both species it is the parameter least affected by the presence of anatomy. It is also has a low coefficient of variation, and as such is perhaps the best single measure of surface roughness. Comparing *Rk* from the processing roughness, the values for spruce were higher than those for oak. Since oak is the denser species, it is reasonable that spruce has a higher processing roughness when sanded with the same grit and pressure.

The parameters *Ra* and *Rq* for oak were more than two and three times greater respectively when calculated from the total roughness than from the processing roughness. Higher values for these parameters indicate that there is greater variation of the data around the mean. The differences were smaller for spruce.

Conclusions

A comparison of roughness parameters calculated from processing and total roughness showed considerable differences for oak and smaller differences for spruce. All roughness parameters were greater when calculated from the total roughness as opposed to those calculated just from the processing *roughness. Rk measures the core roughness depth, and for both species it is the parameter least affected by the presence of anatomy. Its lowest coefficient of variation renders it the best single measure of surface roughness*

1.2.6.5 The fourth case study- comparing the processing roughness with total roughness for sanded oak and beech

Another paper, published by Gurau (2013) *investigated surface roughness and the effect of wood anatomy on roughness parameters of oak and beech sanded with various grit sizes. The wood anatomy was excluded from the roughness profiles using the method based on the Abbot-curve (section 1.2.6.1). Total roughness parameters, which contain both the processing irregularities and the wood anatomy, were compared with processing roughness parameters for both species.*

One set of species was European oak (*Quercus robur*), as a common ring porous commercial species with large earlywood pores. Tangential surfaces were prepared, to give the greatest variation in the surface features. The other set of species for analysis was beech (*Fagus Sylvatica*) as a commercial diffuse-porous wood species, with relatively homogeneous anatomic structure, which was prepared by sanding courtesy to Dr. Csilla Csiha from Sopron. The preparation of specimens is detailed in Gurau (2013).

Before the specimens were sanded, the new sanding belts were worn by continuous sanding for 30 min to remove the initial sharpness of the abrasive grits. The grit sizes were P120, P150, P180, P240. P120, P150 and P180 are commonly used in the furniture industry for the final sanding before coating. New finishing techniques can require even finer grit sizes from P220 to P280, so P240 was included as an example of such fine commercial sanding.

The surface measurements and evaluation were carried out as in Gurau (2013). The separation of processing roughness from the other irregularities of the surface followed the method that uses the Abbot-curve (Gurau et al. 2005a), in which outlying peaks and valleys were replaced with zeros, which were neglected when the roughness parameters were calculated.

The processing roughness and the total roughness were evaluated with the roughness parameters *Ra, Rq, Rt, Rsk, Rku* and *RSm* from ISO 4287 (1998). Other parameters used were: the modified *RSmw* (*RSm* modified for wood- see section 1.2.7) and *Rk*, *Rpk* and *Rvk* from ISO 13565-2 (1996). Each roughness parameter was calculated as a mean of all values obtained from each individual profile.

Height processing roughness parameters were higher for beech than for oak (Table 7).

If not removed from the evaluation, the wood anatomy increases the roughness parameters indicating a surface rougher than in reality. The ratios total roughness/processing roughness show that *Rt* was the most affected parameter, greater in case of oak 10-20 times for total roughness compared to processing roughness and app. 3 times in case of beech (Table 9). The influence of wood anatomy on the total roughness parameters is clearly shown by skewness and was greater for oak than for beech. *Rsk* for the total roughness data indicates the presence of deep pores in the surface, whereas the near-zero values of

Rsk in the processing roughness data indicate that the distribution of the processing roughness data as marks left by the grit particles on the surface is symmetrical around the mean line.

Parameter/ grit size	**OAK**				**BEECH**			
	P120	P150	P180	P240	P120	P150	P180	P240
Ra	2.24 (8.32)	2.03 (8.05)	1.86 (9.56)	1.34 (6.36)	3.09 (8.43)	2.69 (13.44)	2.41 (11.76)	1.91 (9.64)
Rq	2.65 (7.14)	2.4 (7.33)	2.19 (8.44)	1.6 (5.63)	4.07 (7.99)	3.52 (11.96)	3.16 (10.78)	2.53 (7.89)
Rsk	-0.15	0.05	-0.07	-0.14	0.06	-0.11	-0.22	-0.20
Rku	2.18	2.22	2.17	2.18	2.67	2.72	2.67	2.67
Rt	10.8 (7.55)	9.89 (8.71)	8.85 (9.32)	6.5 (6.74)	18.16 (8.36)	15.88 (13.36)	14.02 (11.78)	11.28 (7.30)
Rk	7.60 (4.65)	6.52 (4.23)	5.96 (4.92)	4.50 (3.12)	7.29 (11.43)	6.83 (17.15)	6.16 (30.54)	4.54 (14.84)
Rpk	1.24 (20.02)	1.22 (18.23)	1.01 (16.12)	0.71 (18.78)	3.94 (22.22)	3.49 (8.51)	2.81 (20.46)	2.49 (5.64)
Rvk	1.86 (13.32)	1.89 (20.36)	1.62 (21.89)	1.08 (16.67)	5.16 (7.72)	4.17 (26.28)	4.00 (10.04)	3.29 (3.55)
RSmw	78.4 (5.18)	74.4 (4.04)	65.2 (5.07)	47.6 (3.31)	61.37 (9.32)	61.14 (5.80)	57.81 (11.53)	47.21 (7.45)
RSm	81.5 (5.06)	77.66 (4.13)	69.16 (4.98)	51.39 (3.62)	70.57 (7.75)	69.34 (4.38)	67.38 (8.51)	59.34 (4.70)

Table 7 Processing roughness parameters of sanded oak and beech (in µm) (in brackets mean percentage coefficients of variation) (Gurau, 2013)

Parameter/ grit size	**OAK**				**BEECH**			
	P120	P150	P180	P240	P120	P150	P180	P240
Ra	4.78	6.13	4.73	4.76	5.33	4.33	4.10	3.63
Rq	9.1	13.19	10.5	12.6	7.13	5.73	5.50	5.00
Rsk	-4.05	-4	-4.97	-5.13	-1.16	-0.95	-1.40	-1.50
Rku	30.5	21.13	35.3	33.3	5.30	4.90	4.77	5.78
Rt	115.5	129.3	120.8	136.2	59.39	45.56	38.22	38.49
Rk	9.96	9.02	7.98	6.03	15.45	12.83	11.72	10.02
Rpk	7.28	6.66	4.64	3.89	5.70	4.72	3.09	3.42
Rvk	19.8	31.3	24.8	34.1	2.68	7.26	13.22	10.88
RSmw	104.2	106.9	87.9	64.9	78.83	78.52	71.81	65.81
RSm	213.7	283.4	251	262.1	93.60	93.85	84.74	76.90

Table 8 Total roughness parameters of sanded oak and beech(in µm) (Gurau, 2013)

Similarly, kurtosis was influenced by wood anatomy and had high positive values indicating the presence of deep valleys below a smoother plateau, greater for oak than for beech (Table 7 and Table 8).

Species	Grit size	Ratio total roughness parameter/processing roughness				
		Ra	*Rq*	*Rt*	*RSmw*	*RSm*
oak	P120	2.13	3.43	10.69	1.33	2.62
beech		1.73	1.75	3.27	1.28	1.33
oak	P150	3.02	5.50	13.07	1.44	3.65
beech		1.61	1.63	2.87	1.28	1.35
oak	P180	2.54	4.79	13.65	1.35	3.63
beech		1.70	1.74	2.73	1.24	1.26
oak	P240	3.55	7.88	20.95	1.36	5.10
beech		1.90	1.98	3.41	1.39	1.30

Table 9 The influence of wood anatomy on roughness parameters of sanded oak and beech surfaces measured by ratios total/processing (Gurau, 2013)

The biasing effect of wood anatomy on the evaluation of processing roughness is illustrated also by the ratio between *Rvk* total and *Rk* total, which increases with the grit size (Gurau 2013). This shows that as the grit size becomes finer, the biasing effect of wood anatomy is stronger, especially in the case of a ring porous species as oak and is less in case of a diffuse porous species as beech.

While processing roughness parameters were consistently greater for beech than for oak, the total roughness parameters had unpredictable trends because of the variable anatomy.

Conclusions

The comparison of processing and total roughness parameters demonstrates that the wood anatomy must be removed from the roughness profile if a proper measure of the processing roughness is required. Although the total roughness parameters can be useful indicators for further finishing operations, particularly for the calculation of lacquer consumption, they cannot assess the quality of sanding. An evaluation of sanding quality would be unreliable using the total roughness parameters.

In spite of acknowledging the biasing effect of wood anatomy on roughness parameters, the majority of studies in the literature do not remove wood anatomy, perhaps because it is time consuming if not automated in the software. However, for a reliable assessment of the surface quality, it is advisable to remove wood anatomy, especially in case of fine processing of ring porous species, since the sources of roughness variation apart from processing cannot be predicted (Krisch and Csiha 1999, Gurau *et al*. 2011, Piratelli-Filho *et al*. 2012).

1.2.6.6 Study on replacing outlying wood anatomy data in the evaluation of processing roughness

The previous case studies have confirmed opinion in the literature regarding the need to separate the roughness attributed to processing from roughness due to wood anatomical irregularities. Now, the next question is: how to replace the wood anatomical data in the evaluation without introducing more bias in the results?

The following study (Gurau 2015) *aimed to compare, by means of roughness parameters, the effect of replacing wood anatomical data in the processing roughness profiles using three methods: replacing outliers with zero values which are disregarded in calculations, replacing outliers with predicted values and total removal of outlying data up to the profile meanline. The reliability of calculating the roughness parameters on sampling lengths as instructed by ISO 4287 (1998) was also examined.*

a).Replacing with zeroes – Zero method

This method consists of replacing outlying data points with zeroes, which will be disregarded in the calculation of roughness parameters. Figure 46 shows the roughness profile of an oak surface sanded with P1000, where outliers caused by wood anatomy, deeper than the sanding marks, lie below the lower threshold. In Figure 47, the anatomical data crossed by the lower threshold is replaced by zero values in the processing roughness profile resulted after the separation. This method has the advantage that every data point is kept in its original place so that a visual examination of the real surface by image analysis remains possible. However, it maybe that replacing outliers with zeroes will create less data points in the evaluation and that might affect the values of some roughness parameters within the processing roughness, especially when calculating them on sampling lengths, too short for wood surfaces. This assumption is investigated in this study, roughness parameters calculated when outliers are replaced with zeroes will be compared with parameters obtained with a method where they are replaced with predicted values.

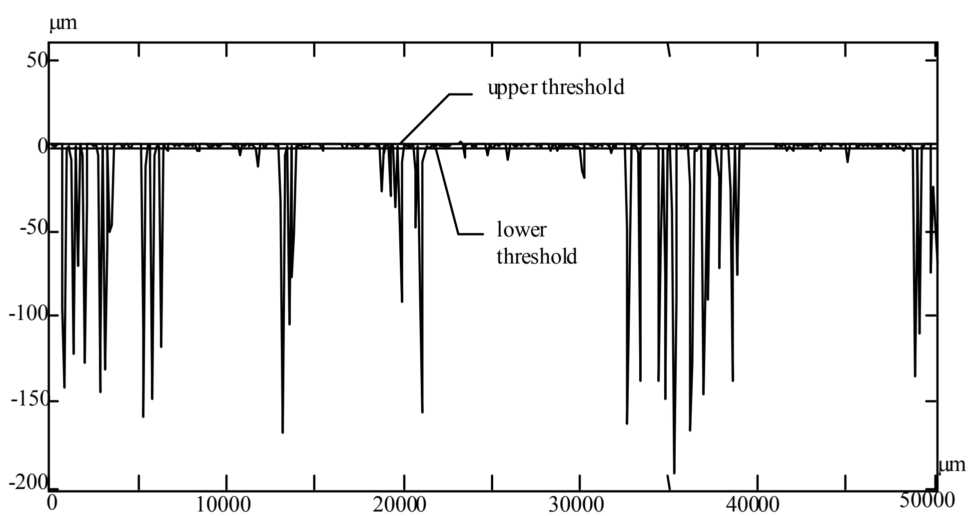


Figure 46 Core roughness data delimited by thresholds at oak sanded with P1000. Outlying anatomical data appears below the lower threshold (Gurau 2015)

An alternative to the Zero method is to replace the outliers with mean or median of values between the mean line and the lower or upper threshold respectively.or even to replace them with the value of the threshold itself (Hendarto *et al*. 2005). The advantage is that it maintains the same number of data points in the profile (compared with the Zero method). However, they do not introduce real data, can artificially increase some roughness parameters, as *Ra* and *Rq* in the study of Hendarto *et al.* (2005) and therefore, affect the reliability of the results.

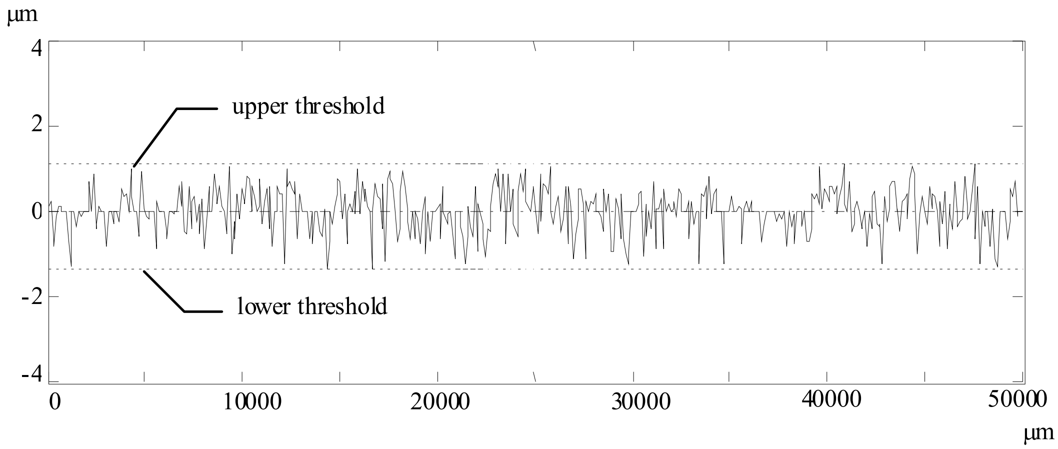


Figure 47 Processing roughness of an oak surface sanded with P1000 obtained by replacing outlying anatomy with zero values (Zero method) (Gurau 2015)

b).Compacting the profile

In this method the outliers are not replaced with values; instead the profile is shortened. This method, called here the Compacting method, does not introduce bias by replacing the outliers with some unreal value, but it does produce different length profiles from a single measured area (Figure 48). Roughness parameters calculated on the evaluation length should have identical values for Compacting method and Zero method. However, the calculation of roughness parameters on sampling lengths is more difficult and since data points move from their original location, an image analysis becomes impossible.

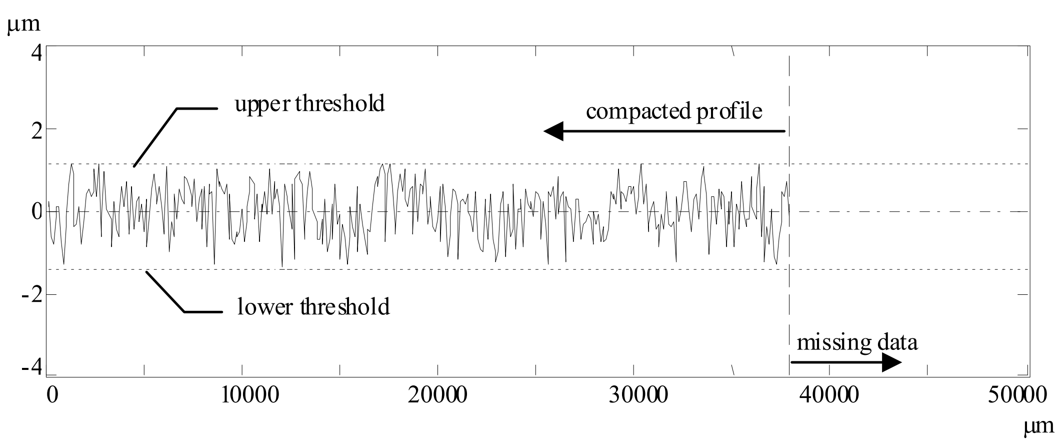


Figure 48 Processing roughness of an oak surface sanded with P1000 obtained by compacting the profile where anatomical outliers were removed (Compacting method) (Gurau 2015)

c).Replacing with predicted values – Predicted method

To avoid the limitations of the Compacting method a modification can be sought to keep the same length for all measured profiles. MathCAD 2000- Reference Manual provides a prediction function, which can use coefficients calculated from the last *m* data points of the original profile to compute coordinates of the missing data points. Having the prediction coefficients, the function uses the last *m* points to predict the coordinates of the *m* + 1 point, in effect creating a moving window that is *m* points wide. The prediction algorithm is based on Burg's method (Press *et al.* 1992). If there are *n* missing data points, then the prediction equation can be given by [23].

$$P = predict(C, m, n) \quad [23]$$

P- predicted vector of data points

C- compacted vector of data points

m- length of vector C

n- number of data points to be predicted

The results for the Predicting method for oak can be seen in Figure 49. The first part is identical to the Compacting method (Figure 48), but predicted data has been added to the ends of the profiles to restore the original profile length. Although this modified method allows the analysis of sampling lengths, any image analysis remains impossible.

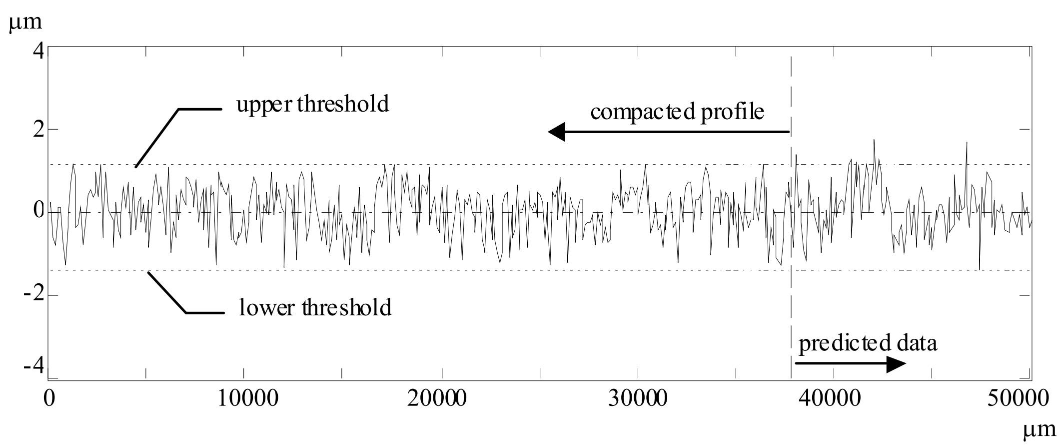


Figure 49 Processing roughness of an oak surface sanded with P1000, compacted in areas where the anatomical outliers were removed and completed with predicted datapoints (Gurau 2015)

To make image analysis possible there is an alternative to the Predicted method. Instead of adding predicted values to the end of a compacted profile, and so changing the real location of original data points, the predicted values can be located in place of outlying data (Figure 50). MathCAD provides a function, which returns the vector of coefficients of a cubic spline with cubic ends. Cubic spline passes a curve through a set of three adjacent points so that the first and second derivatives of the curve are continuous across each point.

$$F = cspline(vx, vy) \quad [24]$$

F- vector of spline coefficients.

vx- vector of indices in ascending order, which indicates the length of the processing roughness profile without outliers.

vy- ordinate values of processing roughness data with no values in place of the outliers

The cubic spline coefficients are further used as arguments of an interpolation function, which interpolates the values from the spline coefficients.

$$I = interp(vs, vx, vy, x) \qquad [25]$$

I- vector of processing roughness with outliers replaced by cubic spline interpolation.

vs- vector of spline coefficients supplied by cspline function.

vx- vector of indices in ascending order, which indicates the length of the processing roughness profile without outliers.

vy- ordinate values of processing roughness data with no values in place of the outliers

x- vector of indices in ascending order, which indicates the length of the processing roughness with outlying values replaced by interpolated values ($x > vx$).

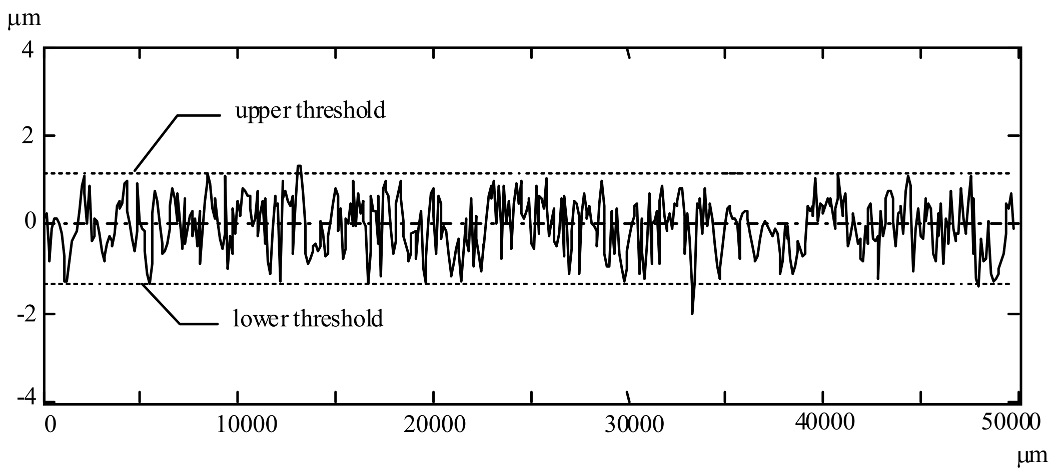


Figure 50 Processing roughness of an oak surface sanded with P1000 when outlying anatomical values are replaced with data predicted with cubic spline interpolation (Predicted method) (Gurau 2015)

From Figure 49 and Figure 50 it can be seen that both predicting methods have introduced some isolated values, which are outside the threshold limits. This can influence some roughness parameters sensitive to isolated peaks or valleys, such as the skewness, *Rsk* and the height paraleter *Rt* as will be seen in the analysis that follows. This leads to a general assumption that predicting values is less reliable than using existing real data.

d)Total removal of outlying features – Total removal method

The separation method presented in section 1.2.6.1, does not completely remove the data points associated with the pores. Data points in the sides of the pores that are between the mean line and the lower threshold are retained. An algorithm was developed to remove these points completely by replacing them with zeroes up to the mean line, so that their influence on some roughness parameters could be compared with the Zero method. The location of data points in the profile is checked in relation to the lower threshold. Anatomical features intersecting the lower threshold are identified, their shape is reconstructed up to the mean line (shaded areas in Figure 51) and corresponding values replaced with zeros, which are disregarded in further calculation of roughness parameters.

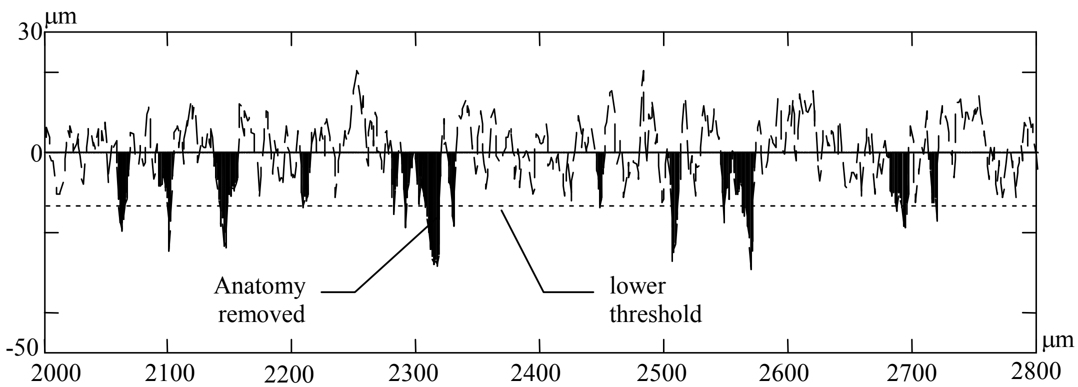


Figure 51Identification of the anatomical roughness (black areas), when the roughness profile (dashed line) is intersected by the lower threshold (dotted line), at an oak surface sanded with P120 (Gurau 2015)

From Figure 51 it appears that the number of peaks remained in the processing roughness profile is much greater than the number of valleys and this method reduces the number of data points left in the profile for evaluating roughness parameters even more than the Zero method. Large wood pores obscure the grit marks to such an extent that few valleys are left in the roughness profile after the total removal of outlying features.

The following study contains a **comparison of roughness parameters calculated on sampling lengths and evaluation lengths** from profiles obtained with the Zero method. Although the Predicted method with cubic spline interpolation is based on predicted data added to the original profile, it is used in comparisons because the number of data points within the profile is the same as in the total roughness profile. The difference between roughness parameters calculated on sampling lengths and on evaluation lengths with the Predicted method can be taken as a reference for the same parameters, calculated with Zero method, although slight differences are inevitable due to the additional predicted data in the Predicted method. The comparison includes the Total removal method, in order to evaluate the impact on roughness parameters of a much lower number of real data in comparison with the other two methods.

Specimens of oak, beech and spruce were sanded parallel to the grain with P1000 grit paper. Measurements were carried out as in Gurau (2015).

The total roughness profiles, which contain both processing roughness and wood anatomy, were obtained by filtering the surface with the Robust Gaussian Regression Filter from ISO/TS 16610-31 (2010). A cut-off length of 2.5mm was used for beech and spruce and 8 mm for oak in order to produce undistorted profiles (Gurau *et al.* 2006a).

The separation of processing roughness from the other irregularities of the surface followed the method that uses the Abbot-curve (section 1.2.6.1). In a first set of data, the outlying peaks and valleys were replaced with zeros, which were neglected when the roughness parameters were calculated. The method is known here as **Zero method.** Another set of data replaced the outlying values with predicted data by using a cubic spline as described in the **Predicted method**. Finally, a third set of data removed outlying data completely up to the mean line as described in the **Total removal method.**

For each set of data, roughness parameters were calculated: *Ra*, *Rq*, *Rt*, *Rsk*, *Rku* from ISO 4287 (1998) and *Rk*, *Rpk* and *Rvk* from ISO 13565-2 (1996). Their calculation was performed on sampling lengths and evaluation lengths for Zero method and Predicted method and only on the evaluation length for Total removal method. The reduced number of datapoints remained in the profile with Total removal method, makes calculation on sampling lengths unreliable.

The sampling length is numerically equal to the characteristic cut-off length of the profile filter. Therefore, for oak, a cut-off length of 8 mm was used, that allowed 6 sampling lengths to be evaluated. For beech and spruce, a 2.5 mm cut-off length, divided the length of profile in 20 sampling lengths. An average parameter value was calculated by taking the arithmetic mean of the parameters from all the individual sampling lengths. Further, a mean value was calculated for all profiles measured for each species. Mean values were calculated also for the set of parameters calculated on evaluation lengths.

Processing roughness parameters calculated when outlying data was replaced with the three methods are evaluated on sampling lengths and evaluation lengths and are contained in Table 10.

		Replacement with zero values		Replacement with predicted data		Total removal of outliers
		SL	EVL	SL	EVL	EVL
Ra	Oak	0.586	0.493	0.500	0.500	0.261
	Beech	0.468	0.345	0.352	0.349	0.174
	Spruce	1.647	1.05	1.004	1.005	0.655
Rq	Oak	0.680	0.588	0.601	0.603	0.412
	Beech	0.482	0.424	0.431	0.430	0.292
	Spruce	1.600	1.325	1.233	1.273	1.013
Rsk	Oak	-0.259	-0.247	-0.103	-0.042	0.362
	Beech	0.305	0.368	0.470	0.450	1.250
	Spruce	-0.650	-0.831	-0.721	-0.740	0.756
Rku	Oak	1.738	2.309	2.439	2.463	3.972
	Beech	1.773	2.474	2.568	2,698	4.631
	Spruce	2.128	3.038	2.987	3.035	4.765
Rk	Oak	1.455	1.492	1.455	1.532	0
	Beech	0.755	1.061	-	1.042	0
	Spruce	-	2.821	-	2.800	0.374
Rpk	Oak	0.304	0.304	0.345	0.391	0.422
	Beech	0.299	0.357	-	0.402	0.308
	Spruce	-	0.670	-	0.765	1.406
Rvk	Oak	0.585	0.526	0.562	0.517	1.045
	Beech	0.495	0.373	-	0.384	0.645
	Spruce	-	1.838	-	1.623	2.312
Rt	Oak	-	2.526	-	3.14	2.423
	Beech	-	1.759	-	2.468	1.754
	Spruce	-	5.953	-	6.071	5.894

Table 10 Processing roughness of three species sanded with P1000 after removal of wood anatomy with three methods: replacement of data with zero values, with predicted data or total data removal with no replacement. Processing parameters are mean values (in μm) calculated on sampling lengths (SL) and evaluation lengths (EVL) (Gurau 2015)

More details and figures are given in Gurau (2015). In the Zero method, the number of data points left for evaluation in each sampling length will vary within the same profile and between profiles. As expected, this variation caused very different results between parameters calculated on sampling lengths as compared with those calculated on evaluation lengths (Table 10). The *Ra* and *Rq* values when calculation was on sampling lengths was greater 16-36%, respectively 12-17% than the value of the same parameters calculated on evaluation length. Fewer data in the roughness profile divided by sampling lengths led also to a 33-43% lower kurtosis, *Rku*, which indicates a flattened data distribution around the mean of the density function. This is because the amount of data retained in each sampling length varied in non-zero datapoints from the neighboring sampling lengths and demonstrates that processing roughness parameters calculated with the Zero method are not reliably evaluated on sampling lengths as ISO 4287 (1998) recommends.

In contrast, parameters calculated using the Predicted method on sampling lengths, which had a constant number of data points, had very similar results to those calculated on the evaluation length: values were almost identical for *Ra* and *Rq* and differed by only 1-5% for *Rku*. This suggests that differences between parameters calculated on sampling lengths and evaluation lengths with the Zero method are caused solely by the variation in the number of data points in the sampling lengths.

The parameters calculated on the evaluation length with the Predicted method were in general close to those calculated with the Zero method differing by 1-4% for *Ra*, *Rq* and *Rk* (Table 10). This means that, although the profile length was shortened by removing the zero values, this did not affect the reliability of the parameters calculated on the evaluation length with the Zero method and therefore, a more reliable calculation of roughness parameters should refer to the evaluation length.

Exception in this comparison made the shape parameter *Rsk* and the height parameter *Rt*, which were different for predicting method compared to Zero method. It appears that the artificial predicted datapoints (valleys or peaks) may introduce features outside the thresholds which are sensitive for some roughness parameters in an impredictible way.

From Table 10 it can be seen that calculation of *Rk* parameters becomes unlikely for division of roughness profile into sampling lengths. Data included in a sampling length does not contain enough variation for such stratified parameters.

The method with Total removal of outliers worsened the roughness parameters results, which were influenced by the unbalanced ratio peaks-valleys reflected in very different values for the skewness, *Rsk*, kurtosis, *Rku* and shape parameters, *Rk*, *Rpk* and *Rvk* . Total removal method caused little influence on *Rt*, which measures the peak to valley distance over the evaluation length, but a great impact on *Ra* and *Rq*, which were smaller by 38-50%, respectively 24-31%. The positive skewness, *Rsk*, is a clear indication of a higher peak occurrence, supported by an *Rku* greater than 3, which is an indication that the distribution has a peak around the mean. A data distribution containing more peaks than valleys, introduced errors in the calculation of *Rk* parameters, *Rk* was zero for oak and beech, which is clearly incorrect. It is clear from this, that Total removal is not a good option for replacing the outlying wood anatomy. Compared to Total removal method, the Zero method has the advantage of keeping more real datapoints in the evaluation and allows calculation of roughness parameters with no bias when the evaluation length is considered.

From the three methods tested, the Zero method proves to be a better choice if calculation of roughness parameters is made on the evaluation length.

Conclusions

Wood anatomical irregularities can be separated from processing irregularities with an Abbot-curve, whose inflexions define a lower and an upper threshold. The core data should represent the processing roughness, while the outlying data must be removed or replaced..

Compared with other methods of replacing values outside the threshold limits, the Zero method seems the most reliable because it is based on real data. Even though this method reduces the number of data points in the profile, the parameters calculated on the evaluation length appear reliable.

The calculation of processing roughness parameters was more reliable on the evaluation length than on sampling lengths.

1.2.7 Quantitative evaluation of wood surface quality by roughness parameters

Previous sections of this chapter indicated a sequence of steps required in surface metrology. ***Data measured and evaluated from a surface is further used for numerical evaluation of the surface quality***. A numerical evaluation of the surface quality implies the calculation of standard roughness parameters that allow comparisons to be made between different surface textures. The common standard parameters usually found in the software included with most measuring instruments have been successfully used for metals and other homogeneous materials. These can be unreliable for wood because of its inherent anatomical variation, consequently, they may indicate processing roughness to be greater than it really is. This is especially so when the irregularities due to wood anatomy exceed those caused by the processing, which is often the case after sanding with a fine grit size and especially for ring porous species (Huang and Chen 1992, Gurau et al. 2011). As was shown in section 1.2.6 , for wood, processing roughness should be separated from anatomical roughness if the effect of processing is to be properly evaluated.

The most common standards, ISO 4287 (1997) and ISO 13565-2 (1996), give a variety of quantitative measures of surface roughness. A single value of these parameters is defined on a nominal interval called the sampling length. The length used for assessing the profile is called the evaluation length, which in general should contain five sampling lengths (Figure 12). Given the variability in wood anatomy, however, roughness parameters calculated over the evaluation length are more reliable than those defined on sampling lengths, according to studies of Gurau (2004 and 2015)- see also section 1.2.6.6. **No other studies were found in the literature with regard to the calculation of roughness parameters on sampling or evaluation length**. Considering the large wood variability, in studies of the author of this habilitation thesis, calculation of roughness parameters on evaluation length rather than sampling lengths was considered more appropriate for wood. The evaluation length is restricted by the capacity of the measuring instrument, so its division into sampling lengths, as instructed by ISO 4287: 1997, leads to data sets that do not represent the variation of the wood surface (Gurau, 2004). In particular, the total roughness, which comprises the processing and anatomical roughness, would seem to be best described by evaluation length parameters.

Profile roughness parameters from ISO 4287: 1998 and their adaptation to wood surfaces

The following parameters are calculated from digitised profiles. A profile is represented by a vector of length *n* of ordinate values Z_i.

$$Ra = \frac{1}{n}\sum_{i=1}^{n}|Z_i|$$

The arithmetical mean deviation of the assessed profile is the arithmetic mean of the absolute ordinate values Z(*x*) within a sampling length. *For wood surfaces, the calculation of this parameter should be on the evaluation length.*

$$Rq = \sqrt{\frac{1}{n}\sum_{i=1}^{n}Z_i^2}$$

The root mean square deviation of the profile is the root mean square value of the ordinate values Z(*x*) within a sampling length. *For wood surfaces, the calculation of this parameter should be on the evaluation length.*

$$Rt = |\max Zp| + |\max Zv|$$

The total height of profile is the sum of the largest peak height Zp and the largest valley depth Zv within an evaluation length.

$$Rz = |\max Zp| + |\max Zv|$$

The maximum height of profile is the sum of the largest peak height *Zp* and the largest valley depth *Zv* within a sampling length. *For wood surfaces, the calculation of this parameter should be on the evaluation length.In this case Rz=Rt*

$$Rsk = \frac{1}{Rq^3}\left[\frac{1}{n}\sum_{i=1}^{n}Z_i^3\right]$$

The skewness of the profile is the quotient of the mean cube value of the ordinate values Z(*x*) and the cube of *Rq* respectively, within a sampling length. *For wood surfaces, the calculation of this parameter should be on the evaluation length.*

$$Rku = \frac{1}{Rq^4}\left[\frac{1}{n}\sum_{i=1}^{n}Z_i^4\right]$$

The kurtosis of the profile is the quotient of the mean quadratic value of the ordinate values Z(*x*) and the fourth power of *Rq* within a sampling length. *For wood surfaces, the calculation of this parameter should be on the evaluation length.*

$$RSm = \frac{1}{m}\sum_{i=1}^{m}Xs_i$$

The mean width of the profile elements represents the mean value of the profile element widths *Xs* within a sampling length. A profile element comprises a profile peak and the adjacent profile valley.

In determining the size of the profile elements, the parameter *RSm* makes specific requirements of their height and spacing. The default minimum profile height within a profile element is 10% of *Rz* (the sum of height of the largest peak height *Zp* and the largest valley absolute depth *Zv* within a sampling length) and the default minimum spacing of the profile element is 1% of the sampling length. Both conditions shall be met.

RSmw *This parameter was modified from the standard in that the minimum height and spacing requirements for a profile element were disregarded. .*

If they are not, then the width and depth of the anatomical features can obscure the processing features

Mean parameters *Ra* and *Rq* are common roughness indicators, but alone, they do not provide sufficient information about wood surface topography. Height parameter *Rt* and shape parameters *Rsk* and *Rku* are instead very sensitive to isolated extreme irregularities (Gurau 2013).

Rsk is a parameter that can be strongly influenced by isolated peaks or isolated valleys. Surfaces with a positive skewness, *Rsk*>0 have fairly high peaks that protrude above a smoother plateau, while surfaces with a negative skewness, *Rsk*<0 have fairly deep valleys in a smoother plateau.

Rku is also a parameter that can be strongly influenced by isolated peaks or valleys, which lead to high kurtosis (Rku>3).

In contrast to the previous parameters, which are measures of the height of the irregularities, the parameter *RSm* is a measure of their width.

Abbot-curve parameters from ISO 13565-2: 1996

Rk	The core roughness depth is the depth of the core profile within an evaluation length, excluding the height of the protruding peaks and deep valleys.
Rpk	The reduced peak height is the average height of the protruding peaks above the roughness core profile.
Rvk	The reduced valley depth is the average depth of the valleys projecting through the roughness core profile

All roughness parameters are useful, because they describe a certain aspect of a surface, their interpretation must be correlated with the material that is measured. If anatomy is not removed for wood surfaces, then *Rk* (core roughness depth) appears to be the most useful indicator of the processing roughness because *Rk* is the parameter least affected by the presence of wood anatomy (Gurau 2004, Sharif and Tan 2011, Tan *et al.* 2012, Magross 2015).

Rk is a parameter defined in ISO 13565-2 (1996), a standard intended for profiles containing deep valleys below a finely finished plateau. An Abbot-curve is obtained by ranking all the ordinate values of the roughness profile in descending order (Figure 52). The curve allows the characteristic parameters *Rk* (core roughness depth), *Rvk* (reduced valley depth) and *Rpk* (reduced peak height) to be calculated, by dividing the profile into three sections: the peaks, a middle plateau and the valleys (Figure 53). The central region is defined as the 40% of the curve whose secant has the smallest gradient. The indices of the upper and lower boundaries of the central region correspond to their rank and are shown as dotted lines in Figure 52. A line following the gradient of the central region is extended to intersect with the upper and lower boundaries of the ranked data. The roughness core profile *Rk* is the difference between the y-values at these intersections, and is marked by the horizontal dashed lines.

The dashed lines of Figure 52 are solid in Figure 53 and intersect the Abbot-curve to establish the boundaries of the material portions Mr1 and Mr2 (Figure 53). The areas of protruding peaks and valleys outside the core profile are diagonally hatched in Figure 52 and Figure 53. The parameters *Rpk* and *Rvk* are set by the heights of right-angle triangles that have the same area as the "peak area" and "valley area" respectively (also diagonally hatched in Figure 53).

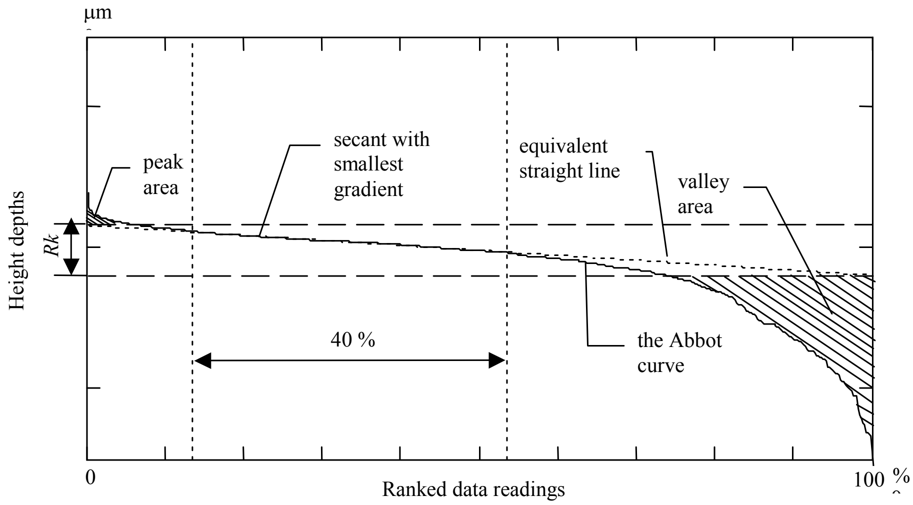


Figure 52 Determination of the central region of the Abbot-curve based on the minimum gradient, and the definition of the peak and valley areas (Gurau *et al.* 2011).

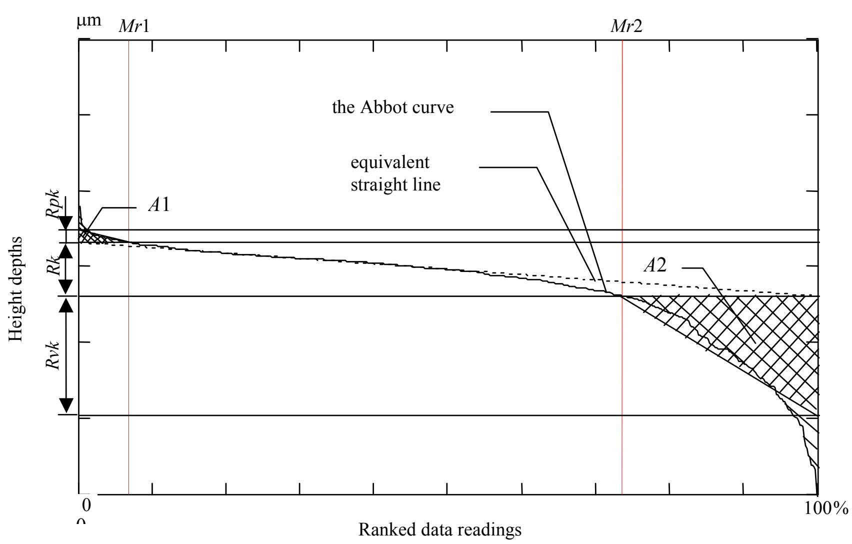


Figure 53. The determination of right angle triangles with equivalent areas as the peak area *A*1 and the valley area *A*2, as shown by opposing hatching (Gurau *et al.* 2011).

The parameters *Rk*, *Rvk* and *Rpk* may be interpreted as measuring particular aspects of a wood surface. For instance, for a specimen with deep pores and a fine grit size, the *Rk* parameter may be understood as the processing roughness (Westkämper and Riegel 1993a and 1993b), *Rvk* as the anatomical roughness and *Rpk* as fuzzy grain. For sanded wood surfaces, the most used parameters have been Ra and Rz to which Rt was occasionally added. In addition to these common parameters, other parameters have been used, for example, Rsk and Rku (de Moura and Hernandez 2006); Rk, Rpk, Rvk (Kilic et al. 2006); Rk, Rpk, Rvk, Rz (Magross 2015).

Although ISO 4287 (1997) and ISO 13565-2 (1996) provide a comprehensive range of parameters, only a few have been applied to wood based materials. The most used parameter was Ra (Hiziroglu 2005, Gaitonde *et al.* 2008b, Davim *et al.* 2009, Pinkowski *et al*. 2011, Sütcü and Karagöz 2012, Prakash *et al*. 2014) followed by Rz (Hiziroglu 2005, Aguilera 2008, Davim *et al.* 2009, Prakash *et al*. 2014) and Rt (Hiziroglu 2005, Davim *et al.* 2009).

Conclusions

A numerical evaluation of the surface quality implies the calculation of standard roughness parameters that allow comparisons to be made between different surface textures. All roughness parameters are useful, because they describe a certain aspect of a surface and their interpretation must be correlated with the material that is measured. In spite of a large range of roughness parameters offered by standards, only a few were used in the literature. A larger range of parameters is recommended in order to have a complete view over the topography of a surface heterogeneous as wood.

Given its variability, calculation of roughness parameters on evaluation length rather than sampling lengths is more appropriate for wood.

1.3 Conclusions and original contributions regarding the metrology applicable to wood surfaces

The literature reviewed showed a lack of general consensus regarding the metrology of wood surfaces. Existing standards do not contain specific recommendations for the metrology of wood surfaces. Simply applying existent general standards proved to be unreliable because wood is heterogeneous and contains a characteristic anatomy, which makes surface metrology difficult and is a source of bias in the measurement results. Specific recommendations for the metrology of processed wood surfaces, tested for wood, would be useful for monitoring the quality of processing, while reducing the finishing costs.

Author studies in this chapter aimed to investigate various aspects of wood surface metrology and to provide a set of recommendations that can give an accurate method for measuring and evaluating the quality of wood surfaces. The recommendations are based on dedicated studies and intensive research, which were published and acknowledged by several citations (**138 citations in ISI Web of Science**).

These recommendations were developed in studies contained in sections of this chapter, they were published in a review paper in ***Current Forestry Reports*** (Gurau and Irle 2017**- cited 11 times in ISI Web of Science)** and are briefly reviewed below for clarity. For a better understanding of the steps in the metrology of wood surfaces two diagrams are provided below. The recommended method is bolded (Figure 54 and Figure 55).

SET OF RECOMMENDATIONS FOR THE METROLOGY OF WOOD SURFACES:

MEASURING

- **MEASURING INSTRUMENT**: The **standard stylus scanning method** (ISO 3274: 1996), with stylus having 2.5 μm tip radius, a 90° tip angle and 0.001 N pressing force, is able to detect surface irregularities with an acceptable degree of accuracy and it has a high repeatability, so it is suitable for research (section 1.2.2)

- **MEASURING DIRECTION**: A measuring direction across the sanding marks is more informative than along the grain (section 1.2.4).
- **MEASURING LENGTH:** Wood does not comply with the evaluation length requirements of the general standard ISO 4288: 1996 because of the variability of the surface. An evaluation length of 50 mm proves to be suitable (section 1.2.4).
- **MEASURING RESOLUTION:** A resolution of 5 μm is reliable for measuring wood surfaces sanded with commercial grit sizes (section 1.2.3)

DATA EVALUATION

- **FORM ERROR REMOVAL**: The standard method of form removal contained in ISO 3274: 1996, which employs a regression fit to obtain the primary profile can be used for removing form errors of wood surfaces, providing the best regression fit is used
- **FORM ERROR REMOVAL:** The wood anatomy distorts the primary profile obtained with ISO 3274: 1996. When it is necessary to obtain a primary profile free of distortion and to analyse primary profile parameters, the deep pores should be removed from the total profile prior to applying the regression (section 1.2.5.1)
- **FILTERING THE ROUGHNESS PROFILE:** Standardised filters described in ISO 11562: 1996 and ISO 13565 1: 1996 have marked limitations when applied to wood. A robust Gaussian regression filter (RGRF), introduced by the standard ISO/DTS 16610 31: 2010, avoids limitations of standard filters, keeps the same length of data in the filtered profile, causes no end-effects and no distortions (section 1.2.5.2)
    - **A derivation of RGRF called by the author "RGRF with truncation"** reduces the size of the weighting window to 1.25λ (where λ is the filter cut-off). and substantially reduces the computation time (section 1.2.5.3)
    - **Convergence condition of the RGRF:** The iterative process of the filter RGRF ends when a tolerance condition is met. The value found suitable for wood surfaces was 0.01 (section 1.2.5.4)
    - **The filter cut-off value:** A cut off length of 2.5 mm was found suitable for filtering surfaces sanded with commercial finishing grit sizes with RGRF (section 1.2.5.5)
- **SEPARATION OF PROCESSING ROUGHNESS FROM WOOD ANATOMY**: Anatomical irregularities distort the measured results so that a surface appears rougher than it really is. Abbot curve can be a straightforward tool to separate the anatomical from the processing roughness, once a roughness profile free of any distortion has been obtained.

  - This method, proposed by the author, is loosely based on a recommendation in ISO 13565 3: 2000. The influence of statistically outlying anatomical valleys or high isolated peaks can be excluded by monitoring the variation of the second derivative of the Abbot curve The index of the transition points is the index of the point where the ratio of the absolute value of the second derivative to the standard deviation of the previous points just exceeds a critical value of six (1.2.6.1)
  - **Processing roughness** is defined as the core roughness of a profile where the outlying peaks and valleys are replaced with zeros that are ignored in further calculations of roughness parameters. This method is called the "Zero method" (section 1.2.6.6)
  - The **anatomical roughness** is defined as the outlying valleys of a profile, while the outlying peaks represent the **fuzziness** (section 1.2.6.6)
- **ROUGHNESS PARAMETERS**: The numerical characterization of roughness produces roughness parameters that allow comparisons to be made between different surface textures (section 1.2.7)
  - **Processing parameters must exclude the influence of wood anatomy** in order to represent objective references for the surface quality.
  - **Roughness parameters calculated over the evaluation length** are more reliable for a wood surface than those defined on sampling lengths.

The metrology method proposed in chapter 1 offers comprehensive guidelines as to how to measure and evaluate reliably a sanded wood surface. Distortions in data evaluation are avoided and the roughness caused solely by the processing can be robustly evaluated by eliminating the bias of a very instable and independent of any machining factor: wood anatomy. Although this method was derived from studying sanded surfaces, it can be used:

- to evaluate the surface roughness for other types of processing with the purpose of understanding the influence of process variables on the surface quality or for processing optimisation (eg. milling, planing, sawing, tuning, others)
- to evaluate the surface roughness for different types of materials based on wood (chipboard, MDF, other wood based composites)
- to evaluate the surface roughness of wood after various treatments (superficial or in depth), in order to see the effect they have on the surface quality
- to identify the surface quality after surface coating
- to identify improper selection of tool and technological parameters for the species being machined
- to identify the moment when the tool needs to be replaced
- to identify the presence of wood defects (tension wood, grain deviations such as curly grain, spiral grain or wavy grain, which are a source of fuzziness)

SURFACE DATA ANALYSIS

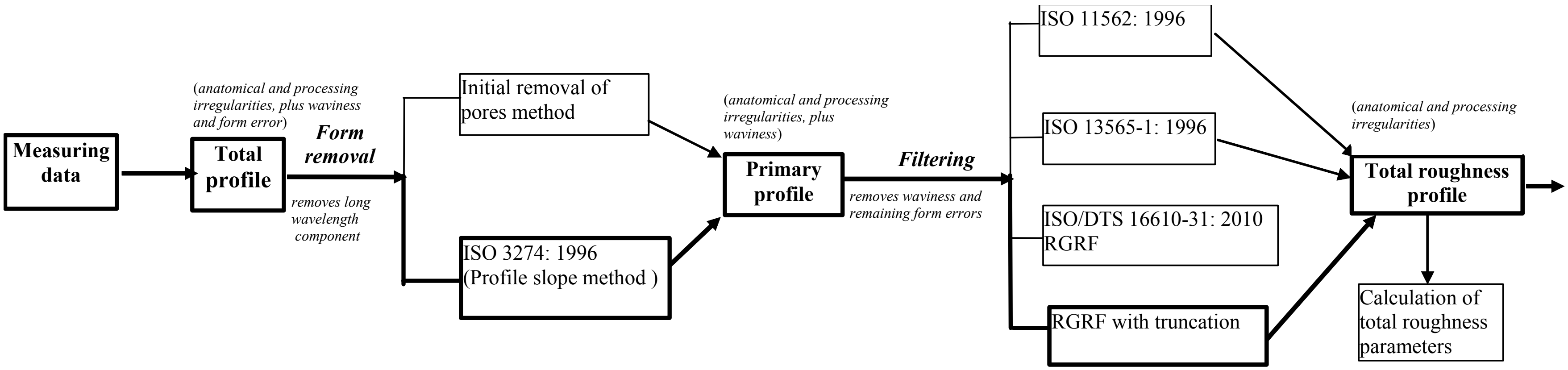


Figure 54 Metrology of wood surfaces, part 1.

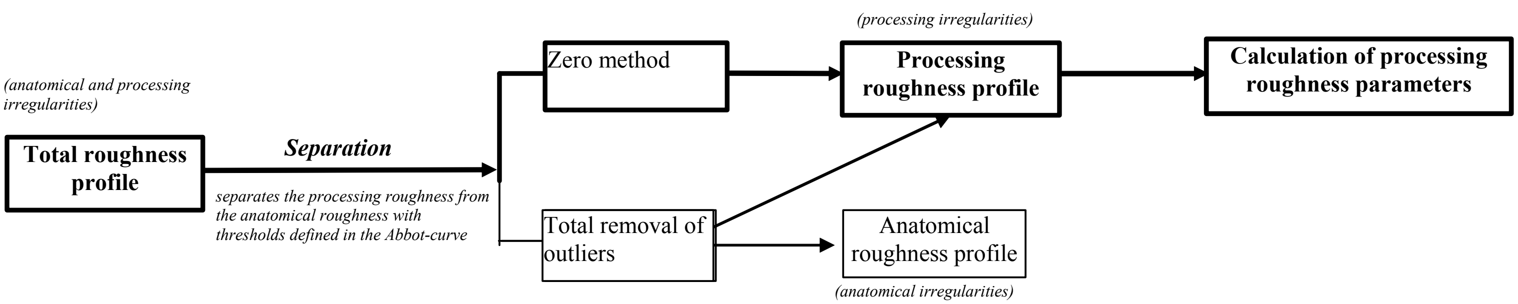


Figure 55 Metrology of wood surfaces, part 2

The above, only show the multiple research directions and further work, which can be approached, once a methodology for the metrology of wood surface quality was defined.The studies in this chapter have outlined the fact that wood surfaces require specific metrological protocol, since general standards are not entirely applicable to wood.

The research results from chapter 1 were disseminated, as first author, in 28 publications, among which:

- 1 Book- in English: Gurau (2007). "*Quantitative Evaluation of the Sanding Quality in Furniture Manufacturing*" pp. 261.Publishing house:Transilvania University Brasov,ISBN 978-973-598-126-6
- 2 Book chapters in international publishing houses:
  - Gurau et al.(2011)"*Evaluating the Roughness of Sanded Wood Surfaces*". Book Chapter 6., 51 pages, pp.217-267. In: **Wood Machining**. Edited by J. Paulo Davim, University of Aveiro, Portugal. ISBN: 9781848213159. May 2011, pp.288, Publishing house: ISTE-Wiley (UK). DOI: 10.1002/9781118602713.ch6
  - Gurau et al.(2012a) "*A quantitative method to measure the surface roughness of sanded wood products*". Book Chapter pp.1-23 In: **Wood and Wood Products**. Series: Materials and Manufacturing Technology, Edited by J. Paulo Davim, University of Aveiro, Portugal. ISBN: 978-1-62081-973-9, pp 140., Publishing house: NOVA Science Publishers, Inc., Hauppauge, New York, USA
- 7 papers in ISI Web of knowledge top journals, **ranked in the red zone** according to UEFISCDI hierachy. The most cited in ISI web of Science were:
  - Gurau *et al*.(2005a). Processing Roughness of Sanded Wood Surfaces. *Holz als Roh und Werkstoff*. 63(1), DOI 10.1007/s00107-004-0524-8. At the moment of writing, this paper has **58 citations (in ISI Web of Science)** and 98 in Google Scholar)
  - Gurau et al. (2006a). Filtering the Roughness of a Sanded Wood Surface. *Holz als Roh und Werkstoff.* 64(5).DOI 10.1007/s00107-005-0089-1, with **37 citations (in ISI Web of Science)**
  - Gurau et al.(2007). Separation of Processing Roughness from Anatomical Irregularities and Fuzziness to Evaluate the Effect of Grit Size on Sanded European Oak. *Forest Products Journal.* 57 (1-2). pg. 110-116. Publisher: Forest Products Society, USA. ISSN 0015-7473, with **13 citations (in ISI Web of Science)**
  - Gurau et al.(2013a). The influence of measuring resolution on the subsequent roughness parameters of sanded wood surfaces. *European Journal of Wood and Wood Products*: 71(1), pp.5-11, ISSN 0018-3768 (Print) 1436-736X (Online), Ed. Springer DOI: 10.1007/s00107-012-0645-4, with **6 citations (in ISI Web of Science)**
  - Gurau et al. (2015). Processing roughness of sanded beech surfaces. *European Journal of Wood and Wood Products* 73(3): 395-398. ISSN 0018-3768 (Print) Ed. Springer. DOI: 10.1007/s00107-015-0899-8, with **7 citations (in ISI Web of Science)**
- 1 review paper in ISI Web of knowledge top journal. This paper contains the state of the art regarding the metrology of wood surfaces and the above proposed method for wood:
  - Gurau and Irle (2017). Surface Roughness Evaluation Methods for Wood Products: a Review. *Current Forestry Reports* 3(2), DOI 10.1007/s40725-017-0053-4 with **11 citations (in ISI Web of Science). Journal impact factor in 2017: 3.548**
- 2 ISI web of knowledge conference papers
- 6 Journal papers in other international databases
- 9 International conference papers

2. CHAPTER 2. APPLICATIONS OF THE METROLOGY METHOD TO WOOD AND WOOD BASED MATERIALS FOR SURFACE QUALITY EVALUATION

While studies in chapter 1, pursued intensively before 2014, had the purpose to define a set of reccomendations for wood surface metrology, the studies in chapter 2, carried out intensively after 2014 till present, have used the knowledge and experience gathered in previous studies and **have evaluated the surface quality of wood and wood based composites by applying,** and in this way testing, **the metrology method-** proposed by the author in chapter 1.

2.1 Research on the influence of earlywood and latewood upon the processing roughness parameters at sanding

Tho objective of the following study (Gurau, 2014), paper in international databases, ***cited by 5 in Google Scholar****, was to investigate the effect of earlywood and latewood on the surface quality of sanded wood, when wood anatomy was excluded from the evaluation of the processing roughness.*

A sanded surface contains irregularities caused by the abrasive grit particles, which plough the material, creating scratches in the surface. Such irregularities of the surface are inherent in a machining process like sanding and are known as the processing roughness.

Compared to processed homogeneous materials, wood surface roughness data contains not only processing irregularities, but also a specific anatomical structure. This is specially the case of earlywood areas which may locally cause large surface irregularities which have nothing to do with the machining process (Magoss 2008). It was acknowledged that surface roughness of wood can be affected by the latewood/earlywood ratio (Goli et al. 2001, Kilic et al. 2006; Dundar et al. 2008; Wilkowski et al. 2010).

Earlywood is comprised of cells with thin walls and large lumen, which have a low resistance to processing, while latewood has cells that are more mechanical resistant to stresses, with thicker walls and narrow lumens (Pescarus 1982). The ratio of the latewood to the earlywood density is ρ_0 (LW)/ ρ_0 (EW)= 1.96- 3.1 for softwoods, ρ_0 (LW)/ ρ_0 (EW) = 1.55-2.8 for ring porous hardwoods and ρ_0 (LW)/ ρ_0 (EW) = 1.21-1.76 for diffuse porous hardwoods (Kollmann and Côté 1968). Large differences between earlywood and latewood in softwoods and ring porous species can be explained by the high difference in cell lumen volume, while diffused pores species are more homogenous.

Differences between earlywood and latewood affect the smoothness of softwood surfaces more than of hardwoods (Lutz 1956, Wilkowski et al. 2010). Spruce is known as a species that is difficult to sand smoothly (Cotta et al. 1982). The particles may compress the earlywood elastically, but the latewood prevents proper cutting. After sanding the earlywood may recover and form ridges on the surface. Follrich et al. (2010) found that wood machining particularly affects earlywood tracheids of softwoods. Abrasively planed surfaces and saw-cut surfaces suffer from crushed and fractured surface cells and this is occuring to the earlywood cells, which have thin walls that are easily split. Vitosite et al. (2012) stated that surface sanding causes damage to the walls of wood cells, which are particularly weak in the earlywood area.

Sieminski and Skarzynska (1987) found that the roughness of earlywood surfaces was much higher than of the latewood surfaces. Similar result was found by Laiveniece and Morozovs (2014). However, it appears that all previous studies, although just a few on sanded surfaces, have made observations on the quality of processed earlywood and latewood areas without excluding the wood anatomy from the evaluation of the processing roughness.

A proper evaluation of the quality of the sanding operation implies not only that the roughness data has to be free of distortions, but also that irregularities due to wood anatomy are excluded from the numerical characterization of the processing roughness (Westkämper and Riegel 1993, Schadoffsky 2000, Gurau et al. 2007)..

The influence of earlywood and latewood areas was studied on single specimens of European oak (*Quercus robur*), beech (*Fagus Sylvatica*) and spruce (*Norway spruce*).. Oak had a density ρ_0 = 632 kg/m^3, which was close to beech with ρ_0 = 697 kg/m^3, while spruce had the lowest density ρ_0 = 396 kg/m^3. Species were conditioned to a uniform moisture content of approximately 12% by storage in a climate-controlled environment.

The specimens were cut to surface dimensions of 100x90mm, suitable for sanding on a Makita 9402 portable belt sander. The grit sizes were P120 for beech and spruce and P180 for oak, which represent abrasives commonly used in the furniture industry for the final sanding before coating.

The surface measurements were carried out as described in Gurau (2014).

The total roughness profiles, which contain both processing roughness and wood anatomy, were obtained by filtering the surface with the Robust Gaussian Regression Filter from ISO/TS 16610-31 (2010), with cut-off length of 2.5mm. The anatomical irregularities were separated from processing irregularities with the method presented in section 1.2.6.1.

The processing roughness was evaluated with the roughness parameters *Ra, Rq, Rt, Rsk, Rku* from ISO 4287 (1998) and the modified parameter *RSmw* (as from section 1.2.7). Other calculated parameters were *Rk*, *Rpk* and *Rvk* from ISO 13565-2 (1996).

Each roughness parameter was calculated as a mean of all values obtained from each individual profile for earlywood and latewood and mix areas and their corresponding mean coefficients of variation for oak P180, beech P120 and spruce P120 respectively. Supplementary, was calculated the mean roughness value for the earlywood and latewood combined as (EW + LW)/2. Roughness parameters from latewood and earlywood were compared by the ratio LW/EW. Roughness parameters measured individually from earlywood and latewood were further compared with roughness parameters from mix areas containing both earlywood and latewood.

Table 7 contains mean values of the roughness parameters for earlywood and latewood and their corresponding mean coefficients of variation for oak P180 (other details in Gurau 2014).

It could be seen that all the roughness parameters showed that latewood was smoother than earlywood, which is in agreement with Cotta et al. (1982), who made this observation from surface photographs and with Sieminski and Skarzynska (1987), although they did not separate processing and anatomical roughness. Latewood roughness, as defined by parameters which measure the height of the irregularities, was only approximately 46-50 % of the earlywood roughness of oak P180 (Table 7), followed by spruce P120 with approximately 65-72 % and beech with 76-84 %. These results can be explained by the anatomical differences between earlywood and latewood, which led to different densities and consequently to different depths of the sanding marks. Kollmann and Côté (1968) recorded the existence of different densities of earlywood and latewood (Table 12). The density ratios in Table 12.seem to agree well with the ratios of roughness parameters from earlywood and latewood for all three species. The ratio of LW/EW for *Ra*, which is a mean roughness parameter, aproximated the best the inverse ratio EW/LW of densities (upper range values), as they were reported by Kollmann and Côté (1968).

Parameter	Oak P180				
	EW	LW	LW/EW	(EW + LW)/2	Mix
Ra	2.29 (13.79)	1.13 (12.65)	0.50	1.71	1.86 (9.56)
Rq	2.70 (12.56)	1.32 (11.27)	0.49	2.01	2.19 (8.45)
Rsk	-0.13	-0.12		-0.13	-0.07
Rku	2.22 (4.78)	2.13 (6.36)		2.18	2.17 (4.10)
Rt	11.08 (13.35)	5.22 (13.34)	0.47	8.15	8.85 (9.32)
Rk	7.25 (9.03)	3.55 (5.92)	0.49	5.40	5.96 (4.92)
Rpk	1.26 (32.66)	0.60 (35.97)	0.48	0.93	1.01 (16.12)
Rvk	2.20 (25.75)	1.01 (24.05)	0.46	1.61	1.62 (21.89)
RSmw	67.7 (7.51)	47.4 (6.70)	0.70	57.5	65.2 (5.08)

Table 11 The influence of earlywood and latewood on roughness parameters of oak sanded with P180. Values represent mean roughness parameters (μm). The values in brackets are mean percentage coefficients of variation. EW – earlywood; LW – latewood; Mix - mix of both earlywood and latewood (Gurau, 2014)

Species	ρ_0 earlywood (kg/m^3)	ρ_0 latewood (kg/m^3)	Density ratio $\frac{\rho_0(LW)}{\rho_0(EW)}$	Density ratio $\frac{\rho_0(EW)}{\rho_0(LW)}$
Spruce	307	601	1.96	0.51
Oak	317 – 454	888 – 930	1.96 – 2.80	0.36 – 0.51
Beech	502 – 536	748 – 883	1.34 – 1.76	0.57 – 0.75

Table 12 Absolute density values ρ_0 of latewood and earlywood for spruce, oak and beech (from Kollmann and Côté, 1968) (Gurau, 2014).

Roughness parameters in latewood and earlywood, but also on mix areas, seemed to be related to species density, as expected spruce was rougher than the other two. The influence of grit size can also be noted; although the oak had a lower density than the beech, all the roughness parameters were lower than those from beech, because the oak was processed with a finer grit size.

RSmw depended on the grit size; values for earlywood of beech and spruce sanded with P120 were very similar as were the latewood values, while for oak sanded with P180 the values were lower. This parameter appears less sensitive to density.

Given the differences in roughness between earlywood and latewood, it appears that the percentage of these areas on the surface under evaluation is important. However, mean values of roughness parameters measured separately on earlywood and latewood, (EW + LW)/2, had similar results to the processing roughness parameters measured from mixed areas.

Conclusions

A rigurous quantification of the effect of species, expressed by its latewood and earlywood growth areas, on the processing roughness at sanding implies that anatomical irregularities are removed from the evaluation of roughness parameters. Latewood was smoother than earlywood with the greatest ratio in oak, followed by spruce and beech. The ratio of latewood to earlywood processing roughness described by several roughness parameters was in an inverse relationship with the local density ratio of latewood to earlywood provided in literature. Furthermore, the roughness parameters in mix areas of latewood and earlywood seemed to be related to species density. Although it was not studied the exact correlation between the percentage of areas with earlywood and latewood and surface roughness, it appears that measured surfaces should contain both earlywood and latewood, to be relevant for assessing surface quality of wood. A mean of those extremes was a good approximation of surface roughness.

2.2 Research on surface quality of wood after various heat-treatments and processing

Heat treatment of wood can considerably improve some wood properties (Tjeerdsma and Militz 2005). Many aspects of heat treatment have been studied including: dimensional stability, wood durability, mechanical properties, equilibrium moisture content, mass loss, wettability, colour change, and chemical modification (Esteves and Pereira 2009). Some studies have examined the impact of heat treatment on machinability and the resulting wood surface quality (de Moura and Brito 2008; Budakci *et al*. 2011; Tu *et al*. 2014; Gaff *et al*. 2015; Kminiak *et al*. 2015; Kvietková *et al*. 2015a, Kvietková *et al*. 2015b; Ispas *et al.* 2016; Pinkowski *et al*. 2016; Gurau *et al*. 2017a). Machining of a wood surface is characterized by the surface quality, which is generally analyzed by the surface roughness measurements, resulting from the interaction between the cutting tool and the wood surface. However, surface quality of machined wood has been studied much less in comparison with other properties modified by thermal treatment of wood. Furthermore, the approach in evaluation the surface roughness was based on common standards, filtering was made with simple Gaussian filter, measuring and evaluation of surface roughness differed from study to study, leading to various results, which are difficult to compare.

The following studies pursued by the author of this thesis, together with the research team, aim to analyse the surface quality of thermally treated wood, processed by milling, planing and sanding by following the metrology method for wood surfaces outlined in chapter 1.

2.2.1 Milling of heat-treated beech wood (Fagus sylvatica L.) and analysis of surface quality

Milling is one important operation that usually precedes sanding. A good quality of milling is required in order to get the best results from the operations that follow.

Because of the chemical changes that wood undergoes during heat treatment, its density decreases, most mechanical strengths are weakened, and its brittleness increases with the deterioration of fracture properties due to the loss of amorphous polysaccharides (Esteves and Pereira 2009). Thus, heat-treated wood is more susceptible to mechanical damage during further processing, and it sometimes requires adapted technological conditions compared to untreated wood of the same species.

According to the ThermoWood Handbook (Finnish ThermoWood Association 2003), milling heat-treated, resinous wood can be regarded as similar to working with hard, brittle hardwoods. The sharpness of the cutters is important, in order to avoid tearing, especially when milling across the grain. The greatest problems with tearing, as well as enhanced and uneven, accidental, vibrational waviness, occur at the beginning and the end of the milling path, when the cutter gets into and comes out of the wood.

Some authors have compared the surface roughness of heat-treated wood with that of untreated wood, where the samples were processed prior to the heat treatment, but not afterwards. The measurements of surface roughness after heat treatment indicated slightly lower roughness for Turkish river red gum wood-*Eucalyptus camaldulensis* (Unsal and Ayrilmis 2005), red-but maple-*Acer trautvetteri* Medw (Korkut and Guller 2008), Turkish hazel- *Corylus colurna* L. (Korkut *et al*. 2008), European Hophornbeam-*Ostrya carpinifolia* Scop. (Korkut *et al.* 2009), and Rowan wood-*Sorbus aucuparia* L. (Korkut and Budakci 2010).

However, evaluating the surface roughness of heat-treated wood after machining is more interesting because in real practice the heat treatment precedes processing (milling, drilling, turning, sanding, *etc.*). The modifications that wood undergoes during a heat treatment, such as mass loss, might have an important impact on the surface roughness, seen as the result of wood-tool interactions, in a different way than in the above studies.

Budakci *et al.* (2013) determined the roughness (R_a) perpendicular to the grain of Eastern beech wood (*Fagus orientalis* L) heat-treated at 140 °C and 160 °C (for 3, 5, and 7 h), after milling at a rotation speed of 6000 rpm, with a 4-m/min feed speed and a 1-mm cutting depth, using two types of cutters (star blade and razor blade). The roughness values (R_a), as measured by a stylus with a 5-μm tip radius, for heat-treated wood were slightly higher (up to 8%) than those for untreated wood, and they increased with increasing duration of the heat-treatment.

Kvietkova *et al.* (2015a,b) investigated the roughness (R_a), measured along the feed direction by the stylus method, after milling beech wood (*Fagus sylvatica* L.). After varying the rotation speed, feed speed, clearance angle, rake angle, and cutting angle of the milling cutter, the authors concluded that the thermal treatment had no significant influence upon the average roughness of the milled surfaces. There was, however, a significant effect of the cutting speed and feed speed. The lowest value of R_a was found with a clearance angle of 20° and the highest value of cutting speed (40 m/s). The heat treatment (190 °C for only 1 h) may have been insufficient for detecting an effect of the treatment on surface roughness.

The main objective of the following study, published in an ISI journal (Ispas *et al*. 2016), **cited 5 times in ISI Web of Science**, was to *investigate the cutting power during milling with various cutting regimes, along with the subsequent surface roughness, of beech wood strips (Fagus sylvatica L) heat-treated by the ThermoWood method at 200 °C for 2.5 h, in comparison with untreated wood manufactured under the same conditions. The influence of different rotation speeds, feed speeds, and cutting depths upon the cutting power and the surface roughness were investigated.*

The material used within the experiments consisted of samples of 400× 50× 28 mm beech wood (*Fagus sylvatica* L.). Half of the samples were heat-treated in superheated steam in an industrial-scale TekmaWood kiln, manufactured by TekmaHeat Corporation (Lahti, Finland), according to the schedule presented in Ispas et al (2016). The other half of the samples were kept untreated as controls.

The average mass loss of the samples due to this heat treatment was 13.18% ± 1.36%. All of the samples were conditioned for 4 weeks at 20 °C and 55% relative humidity (RH) before being processed. The average moisture content of the samples after conditioning was 3% ± 0.2% for the heat-treated strips and 8% ± 0.5% for the untreated controls.

The samples were then processed by means of a conventional milling cutter head ϕ125, B118 with 6 cutters with 30× 12 × 1.5 mm carbide-tipped removable plates, on a vertical milling machine type MNF10 produced by UMARO SA (Roman, Romania).

Two different rotation speeds (n), five different feed speeds (u), and three cutting depths (h) were used:

n_1 = 3300 rpm; n_2 = 4818 rpm

u_1 = 4.5 m/min; u_2 = 9 m/min; u_3 = 13.5 m/min; u_4 = 18 m/min; u_5 = 22.5 m/min

h_1 = 1 mm; h_2 = 2 mm; h_3 = 3 mm.

Sets of ten heat-treated samples and respectively untreated samples were used for each milling condition. Milling was performed on the specimen edge. The two parameters measured were the cutting power and the surface roughness.

The roughness measurements were carried out immediately after milling using a MarSurf XT20 instrument manufactured by MAHR GMBH (Gottingen, Germany), endowed with a scanning head MFW 250 with a tracing arm in the range of ±500 μm and a stylus with a 2-μm tip radius and 90° tip angle, which measured the specimens at a lateral resolution of 5 μm, at a speed of 0.5 mm/s, and using a low scanning force of 0.7 mN.

For each milling condition, 6 profiles, 10 mm long, were randomly scanned on each specimen's milled edge across the grain (across the feed direction) to measure the roughness parameters. Two other profiles, 50 mm long, were randomly measured along the grain (in the feed direction) in order to analyze the waviness of the surface caused by process kinematics. This longer length was chosen so that longer wave irregularities, such as waviness, could be detected.

The sequence of operations for surface metrology followed the methodology from section 1.2.5.

A range of roughness parameters was calculated for the roughness profiles taken across the grain (across the cutting direction), such as R_a, R_q, and R_t, from ISO 4287 (1997). Parameters R_k, R_{pk}, and R_{vk} from ISO 13565-2 (1996) were included in this study. Although useful for variable surfaces as wood, these parameters have not been tested by previous researchers in the case of heat-treated wood. For the primary profiles taken along the grain, a primary profile parameter, P_t, was calculated from ISO 4287 (1997), in order to obtain a magnitude for the combined kinematic waviness and roughness after processing. The primary profile parameter (P_t) is similar to R_t, but it applies to the primary profile containing waviness and roughness in it. If kinematic waviness is an important effect after processing, then this parameter is useful.

ANOVA and Duncan's multiple range tests were performed to test significant differences between datasets.

The results clearly showed that the cutting power involved in the milling of heat-treated beech wood was up to 50% lower than that of untreated wood. However, here, only results regarding the surface roughness are presented.

The analysis of surface roughness was eventually limited to the depth of cut h_1 = 1 mm in combination with feed speeds from 4.5 m/min to 18 m/min and both rotation speeds (n_1 and n_2) for heat-treated and untreated beech wood. It was observed that for increased depths of cut (h_2, h_3) combined with high feed speeds (u_3, u_5), the surfaces of both heat-treated and untreated beech wood presented milling defects such as pull-off fibers, and therefore, roughness measurements would have been irrelevant. The same was true for a depth of cut h_1 = 1 mm combined with the highest feed speed (u_5 = 22.5 m/min). The measured values are contained in Table 13.

It is important to mention that the processed beech samples were randomly cut without considering the radial or tangential surfaces. For this reason, wood variability likely had an impact on the roughness results similar to that reported by Kantay and Űnsal (2002). A good quality cut is usually obtained when cutting to the grain, mainly in the tangential section of boards (de Moura *et al.* 2014). However, a generally increasing trend of surface roughness with increasing feed speed was observed for the cutting depth h_1 = 1 mm at both rotation speeds (n_1 and n_2) for all roughness parameters.

When comparing the mean values, the heat-treated wood had a slightly higher roughness in comparison with the untreated wood for both rotation speeds n_1 and n_2, and the surface quality had, generally, a larger variability as measured by standard deviation.

Gaps caused by a pulled group of fibers that detached from the surface during cutting were visible for the heat-treated wood. These kinds of defects were observed spreading along the processed surface of heat-treated wood, especially for high feed speeds of 13.5 m/min and 18 m/min. Reiterer and Sinn (2002) studied the fracture properties of heat-treated wood, and they noticed a lower resistance against fractures and higher brittleness in comparison with untreated wood. This behavior of heat-treated wood has been associated with the loss of amorphous polysaccharides due to degradation (Phuong *et al.* 2007).

Treatment	Feed Speed (m/min)	Rotation Speed (rpm)	R_a (μm)	R_q (μm)	R_t (μm)	R_k (μm)	R_{pk} (μm)	R_{vk} (μm)	R_k+ R_{pk}+ R_{vk} (μm)	P_t (μm)
NT	4.5	3300	5.39 (0.69)	8.08 (1.31)	55.29 (5.64)	11.85 (2.20)	5.56 (1.23)	15.73 (3.45)	33.15 (2.66)	81.81 (4.86)
		4818	4.01 (0.32)	5.93 (0.73)	44.89 (4.50)	9.36 (0.59)	6.25 (0.89)	12.35 (3.44)	27.95 (3.14)	112.4 (34.65)
	9	3300	6.82 (0.88)	10.00 (0.96)	60.50 (11.14)	13.50 (2.76)	7.75 (4.92)	19.45 (1.09)	40.71 (6.36)	109.61 (9.91)
		4818	6.41 (0.76)	9.77 (1.01)	57.92 (6.36)	10.54 (1.24)	4.79 (1.80)	20.15 (1.59)	35.47 (2.60)	80.4 (10.75)
	13.5	3300	6.85 (0.49)	9.94 (0.76)	59.54 (6.90)	14.06 (1.13)	5.24 (1.27)	18.52 (1.80)	37.82 (2.25)	100.14 (6.99)
		4818	6.99 (0.74)	9.97 (1.55)	62.30 (13.26)	15.09 (1.27)	6.89 (2.67)	17.81 (3.41)	39.79 (4.55)	97.49 (32.97)
	18	3300	6.68 (0.50)	10.37 (0.86)	67.91 (8.58)	11.99 (0.84)	8.55 (2.44)	21.95 (2.43)	42.50 (4.50)	171.85 (2.76)
		4818	5.82 (0.48)	9.18 (0.80)	59.11 (7.36)	10.05 (0.89)	6.56 (2.83)	19.57 (2.30)	36.18 (2.27)	99.36 (3.34)
HT	4.5	3300	6.78 (0.69)	10.12 (1.29)	58.31 (17.98)	11.98 (1.29)	3.5 (1.33)	19.14 (1.99)	34.61 (3.49)	79.96 (3.48)
		4818	5.53 (0.64)	8.43 (0.66)	47.65 (4.99)	9.86 (1.90)	3.68 (1.38)	16.81 (1.19)	30.36 (2.87)	58.65 (1.77)
	9	3300	7.05 (0.52)	9.99 (0.94)	58.84 (10.83)	14.69 (1.32)	7.05 (3.53)	17.62 (2.43)	39.37 (3.91)	88.75 (6.81)
		4818	6.53 (0.50)	9.47 (0.78)	64.81 (8.54)	12.47 (0.98)	6.88 (1.31)	17.31 (1.82)	36.66 (2.55)	65.04 (6.64)
	13.5	3300	7.62 (0.82)	10.94 (1.22)	65.95 (13.27)	14.98 (3.15)	5.88 (2.74)	20.00 (3.28)	40.86 (5.32)	94.21 (2.55)
		4818	6.39 (0.92)	9.64 (1.06)	58.48 (6.30)	11.89 (2.70)	5.89 (2.50)	19.39 (2.15)	37.17 (4.24)	45.3 (46.53)
	18	3300	8.39 (1.47)	12.72 (2.52)	84.91 (17.13)	15.54 (4.64)	4.12 (1.46)	23.60 (5.20)	43.26 (7.26)	105.60 (5.91)
		4818	8.14 (1.32)	11.22 (1.36)	69.35 (7.08)	18.53 (4.89)	4.86 (2.56)	19.03 (1.42)	42.42 (7.73)	98.14 (0.62)

Table 13 Roughness parameters—mean value and (standard deviation) for heat-treated (HT) and untreated (NT) beech wood processed by milling with four different feed speeds and two rotation speeds at a cutting depth of 1 mm (Ispas *et al*. 2016)

The R_a roughness parameter was taken as a reference because it was the most used parameter in the literature. For this parameter, the differences between wood treatments were significant (at 5% significance level), as measured by ANOVA and Duncan multiple range tests, for feed speeds 4.5 m/min and 18 m/min, but were not significant for feed speeds 9 m/min and 13.5 m/min, for both rotation speeds (n_1 and n_2). The surface roughness, measured by R_a, increased with the feed speed and the difference as relate to the control (4.5 m/min) was significant for both rotation speeds and for both: treated and untreated wood. Other authors also found an increase in surface roughness, measured by the R_a parameter, with increasing feed speed in the plane milling of beech (Kvietkova *et al.* 2015a,b).

For the R_k parameter, the differences were not significant between heat-treated and untreated wood or between processing with various feed speeds for the lower rotation speed (n_1). For the higher rotation speed (n_2), however, the differences between heat-treated and untreated wood were significant at high feed speeds (13.5 m/min and 18 m/min).

Increasing the rotation speed from 3300 rpm to 4818 rpm decreased the surface roughness for both treated and untreated wood. In the case of untreated wood, these differences were significant for feed speeds of 4.5 m/min and 18 m/min, but they were not significant for feed speeds of 9 m/min and 13.5 m/min, as judged from the R_a and R_k parameters. However, the differences were significant for R_a for all feed speeds in the case of heat-treated wood, with the exception of the differences for feed speed 18 m/min. Other authors have also found the decrease of surface roughness with an increase in cutting speed to be statistically significant for R_a (Kvietkova *et al.* 2015a,b). Although R_k was generally smaller for the rotation speed 4818 rpm, than 3300 rpm, these differences were not statistically significant for the heat treated wood.

The heat-treated wood had a smaller P_t than the untreated wood, which means that milling caused a smaller depth amplitude in the heat-treated wood. Generally, P_t increased with the feed speed, and it was smaller when a lower cutting speed was used. This result was comparable to the findings of Gaff *et al.* (2015), who measured the waviness as expressed by the W_a (arithmetical mean deviation of the waviness profile) parameter for plane milling of birch wood. W_a is similar to R_a, but applies to the waviness profile.

Conclusions:

The cutting power during the milling of heat-treated beech wood was up to 50% lower than that of untreated wood. and increased with increasing rotation speed, feed speed, and cutting depth for both untreated and heat-treated wood. All correlations were linear (detailed data was not included in this thesis report).

The surface roughness of heat-treated beech processed by milling was slightly higher than that of untreated wood. This result was significant (for $p < 0.05$ significance level) for Ra for both rotation speeds n1 = 3300 rpm and n2 = 4818 rpm and for feed speeds of 4.5 m/min and 18 m/min. An increase in the rotation speed from n1 = 3300 rpm to n2 = 4818 rpm decreased the surface roughness for both heat-treated and untreated beech.

The surface roughness of heat-treated and untreated beech wood increased with the milling feed speed.

The kinematic waviness, as measured by Pt, increased with the feed speed for both heat-treated and untreated beech. Pt measured along the cutting direction, for each feed speed was smaller in the case of heat-treated wood for both rotation speeds.

The surface roughness of heat-treated beech processed by milling was slightly higher than that of untreated wood.

2.2.2 Surface quality of planed beech wood (Fagus sylvatica L.) thermally treated for different durations of time

The planing operation preceded the thermal treatment for much of the research on the surface quality of heat-treated wood. In such studies, it appears that the surface roughness decreased with the temperature and duration of treatment. It was the case of Turkish river red gum wood-*Eucalyptus camaldulensis*, measured by R_a at 120 °C to 180 °C, for durations of 2 h to 10 h (Unsal and Ayrilmis 2005); red-but maple (*Acer trautvetteri* Medw.), measured using R_a and R_z for heat treatments at 120 °C, 150 °C, and 180 °C for 2 h, 6 h, and 10 h (Korkut and Guller 2008); Turkish hazel (*Corylus colurna* L.) (Korkut *et al.* 2008); and European Hophornbeam (*Ostrya carpinifolia* Scop.) (Korkut *et al.* 2009). Other studies with similar results were made on Rowan wood (*Sorbus aucuparia* L.) measured by R_a, R_z, and R_q for heat treatments at 120 °C, 150 °C, and 180 °C for 2h, 6 h, and 10 h (Korkut and Budakçı 2010); Oriental-beech (*Fagus orientalis*) measured by R_a, R_z, and R_q at 140 °C, 170 °C, and 200 °C for 2 h, 4 h, and 8 h (Baysal *et al*. 2014); alder (*Alnus glutinosa* L., Gaertn. ssp. *glutinosa*); and wych elm (*Ulmus glabra* Huds.) measured by R_a and R_z, perpendicular to the grain, at 180 °C and 200 °C for 2 h and 4 h (Aytin and Korkut 2016).

The modifications that wood undergoes during a heat treatment are likely to affect wood-tool interactions and, consequently, the surface roughness. In addition, commercial processes tend to heat treat and then machine the wood. Following this sequence, Skaljić *et al.* (2009) planed previously thermally treated beech (212 °C, duration unspecified) at 6 m/min, 12 m/min, 18 m/min, and 24 m/min feed speeds. None showed any significant differences in the surface quality, as measured by R_a along the feed direction, between thermally modified and control steamed beech wood specimens. Pinkowsky *et al*. (2016) researched plane milling of Scots pine (*Pinus sylvestris*) at 1 and 5 m/min, after previously thermally treating wood for 4 h at 190 and 220 °C. They found that the surface roughness measured by R_a, R_z, and R_t decreased with an increased modification temperature, In contrast, de Moura Palermo *et al*. (2014) examined the quality of *Eucalyptus grandis* thermally treated at 190 °C for 6.5 h and then planed at 15 m/min feed speed. They found that the R_a, as measured along and perpendicular to the grain, of thermally treated wood was slightly higher as compared with the control.

As seen above, the various studies in the literature indicate a variety of results for the surface roughness of thermally treated wood and various approaches (processing happening either before or after the thermal treatment). None of the previously published studies on the surface roughness of thermally treated wood have used a robust filter. In addition, the measuring length was often limited to 12.5 mm, which was considered too short for wood surfaces because of the material variations that are naturally present, *e.g.* the transition between earlywood and latewood (section 1.2.4).

The following study, published in an ISI journal (Gurau et al. 2017a), ***cited 3 times in ISI Web of Science****, examined the impact of heat treatments at 200 ℃ between 1 h and 6 h on the subsequent surface quality of planed beech wood (Fagus sylvatica L.). The new approach was that surface quality was assessed by following the metrology method for wood, tested in previous research (see chapter 1 and section 1.3). Also, a large number of roughness parameters were used for interpretation of the combined effect of processing and wood anatomy after filtering the data with a robust filter.*

Beech wood (*Fagus sylvatica*) samples of 400x 50 x 25 mm were heat-treated in an electric oven without air circulation, at atmospheric pressure, at 200 °C for 1 h, 2 h, 3 h, 4 h, 5 h, and 6 h. The heat-treatment schedule is presented in Gurau et al.(2017a).

The heat-treated and untreated samples were conditioned for four weeks at 20 °C and 55% relative humidity, and then planed at a feed speed of 10 m/min and a rotation speed of 4567 rpm on a FELDER D963 (Felder Group, Absam, Austria) thicknesser. The cylindrical cutter head had helical cutters with Tungsten carbide inserts. For each treating duration, three machined samples were selected at random for surface quality analysis. The faces of these samples had a mix of tangential, radial, semi-radial, or semi-tangential surfaces as is common in production process.

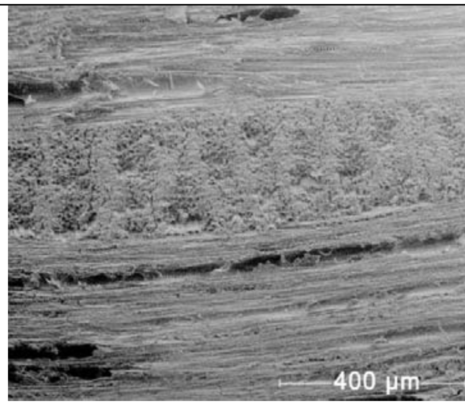
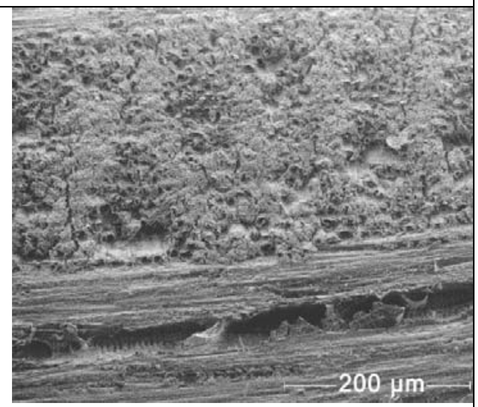
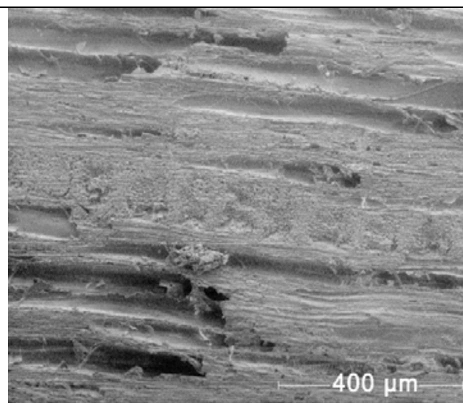
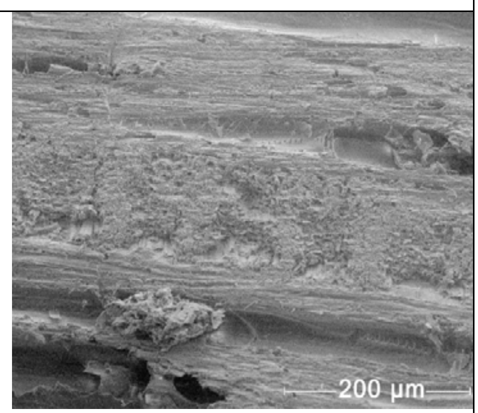
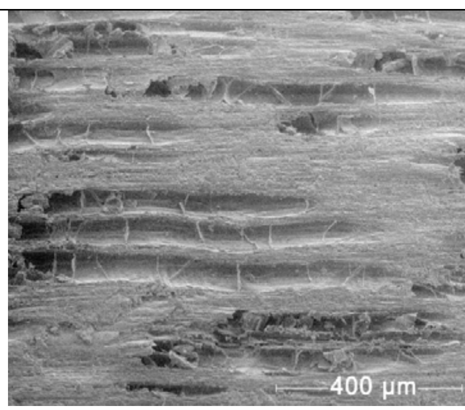
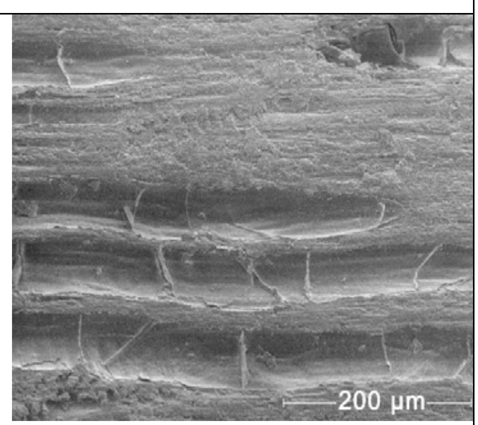
The surface quality was measured with a stylus MarSurf XT20 instrument with the same procedure as in section 2.2.2. The roughness parameters calculated from the roughness profiles were: R_a, R_q, R_v, R_t, R_{Sm}, R_{sk}, and R_{ku}. In addition, the parameters P_a, P_t, and P_{Sm} from ISO 4287 (1997) were calculated from the primary profiles, and R_k, R_{pk}, and R_{vk} from ISO 13565-2 (1996) were calculated from the roughness profiles. An ANOVA analysis and Duncan's multiple range tests were performed to test significant differences between controls and heat-treated samples for various treatment durations.

Microscopic images were taken with a Quanta 250 environmental scanning electronic microscope (ESEM) made by FEI (Hillsboro, OR, USA). The photos were taken in Lovac mode at a pressure of 90 Pa. The surface relief was more easily observed if the specimen was tilted 30°.

Results showed that the skewness, R_{sk}, was negative for all profiles tested, while the kurtosis, R_{ku}, was much higher than 3. The combination of these two parameters indicated that the presence of valleys in the profile that extended below the core roughness were more common than the peaks that protruded above the core roughness.

Electron micrographs with magnifications of 300x and 600x are provided in Figure 56. During a careful surface observation, it was noticed that the primary changes seemed to occur in the ray tissue. These changes might have occurred because this tissue was "softer," in the sense that it was non-structural and more easily altered by the heat treatment followed by processing.

The differences between processing and anatomical roughness were clear in the micrographs, where the processing roughness was seen as fine longitudinal traces and the vessels were large valleys (Figure 56). In addition to anatomical valleys, there were other valleys caused by the pull-out of the material by the planing knives. These pull-out regions were visible in the soft ray tissue in all of the micrographs and seemed to follow a regular pattern not visible elsewhere. Even though this pull-out occurred in the control and thermally treated samples, the pull-out seemed more extensive in samples that were heated for longer durations.

	300x	**600x**
CONTROL		
1TT		
2TT		

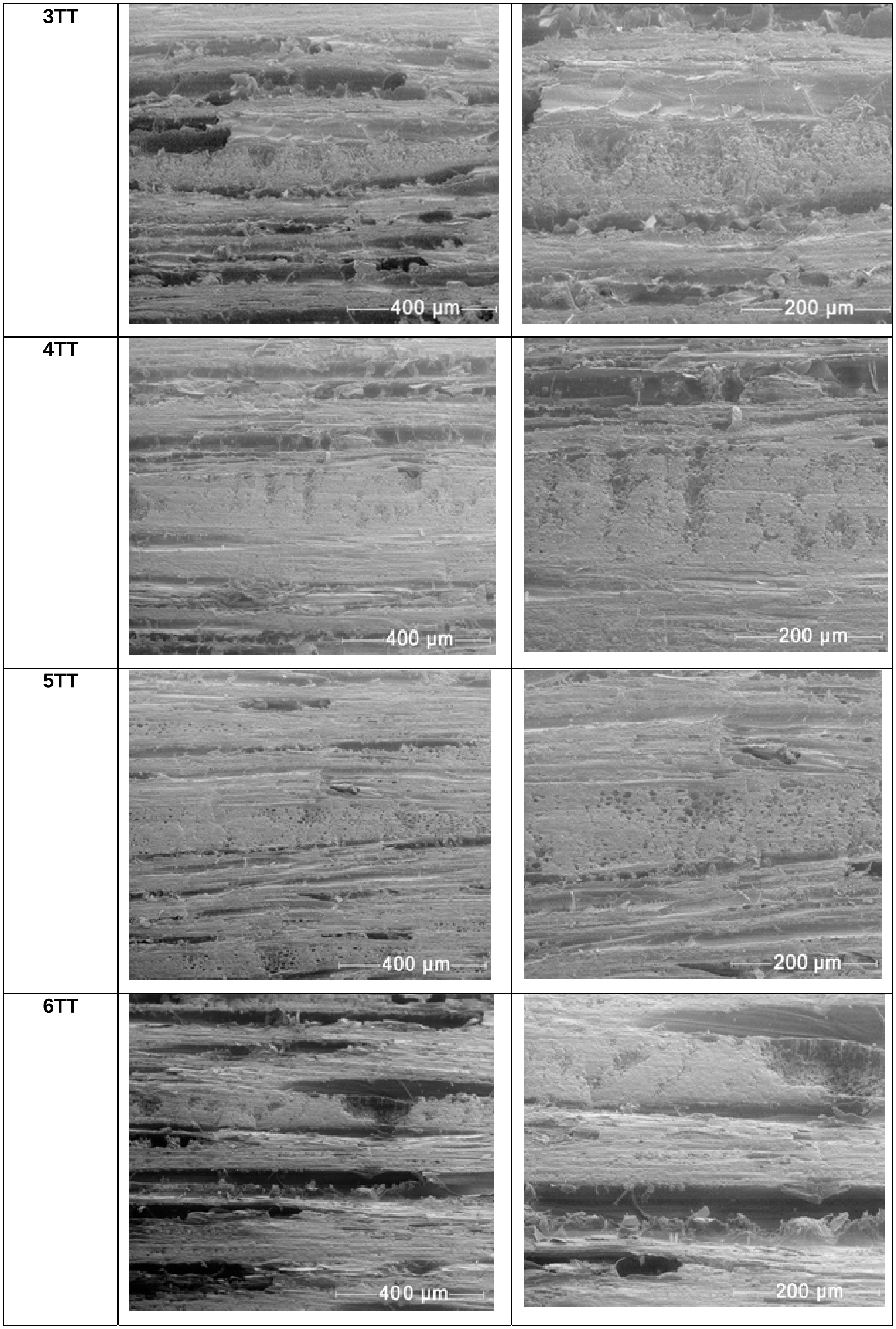


Figure 56 Microscopic images of beech, untreated and thermally treated with different durations (Gurau et al. 2017a)

Results detailed in Gurau et al (2017a) showed that there was little difference in the roughness parameters of untreated beech and that which was heated for 1 h or 2 h; significant differences began to appear after beech was heated for 3 h. The parameter most interesting for assessing the effect of planing following after the thermal modification was R_k, which is also the parameter the least influenced by the presence of wood anatomy (Gurau 2004). The variation in R_k, as measured by the standard deviation values, increased with the heat treatment duration. The gradual increase of R_k reduced the number and size of valleys that hung below the lower R_k threshold, thus reducing the skewness, R_{sk}, and kurtosis, R_{ku}. As a result, the effect of wood anatomy on surface quality decreased with the treatment duration. Because the valleys were caused by vessels, it was logical that R_{vk} also decreased with the heat treatment length.

From the electron micrographs (Figure 56) it would appear that certain anatomical features became increasingly obscured in samples subjected to long heat treatments. Compare, for example, the ray tissue in the control to the ray tissue shown in samples heat treated for 6 h. It was not clear if the ray cells collapsed under the tool pressure or whether the cutting tool displaced the cut material and pressed it into the surface. A certain level of plasticization of the cell wall was reported also by Salca and Hiziroglu (2014) after thermally treating black alder (*Alnus glutinosa* L.), red oak (*Quercus falcata* Michx.), Southern pine (*Pinus taeda* L.), and yellow poplar (*Liriodendron tulipifera* L.) for 3 h to 6 h at 190 °C. This masking of anatomical features did not result in a smoother surface.

R_a and R_q generally increased slightly for heat treated wood in comparison with untreated wood, but they fluctuated as wood anatomy can be a factor of bias.

The primary profile parameters P_a and P_{Sm}, generally showed a decrease in magnitude with the duration of the heat treatment and were statistically relevant lower for the heat-treated specimens as compared with the untreated beech wood. Lower standard deviation values were observed for the *P* parameters for the heat-treated wood in comparison with the untreated beech. These observations were only valid for measurements across the feed direction, because along the grain (feed direction), there was no specific trend.

Among the roughness parameters measured along the grain, only *Rk* showed a specific trend, which increased with the treatment length. Compared with untreated wood, the *Rk* increased 53% after 6 h of heat treatment. When measuring along the grain, the biasing effect of wood anatomy could have been higher and the measurement influenced by the location of the scanned profile (along a wood pore, outside the area of pores, areas with predominantly latewood or earlywood, etc.). Possibly, because of this anatomical variation, for measurements taken along the grain, no conclusion could be drawn that concerned the waviness in the profile. From these results, it appeared that the measuring direction perpendicular to the processing direction was more informative, and the measured parameters were more consistent with the duration of the heat-treatment.

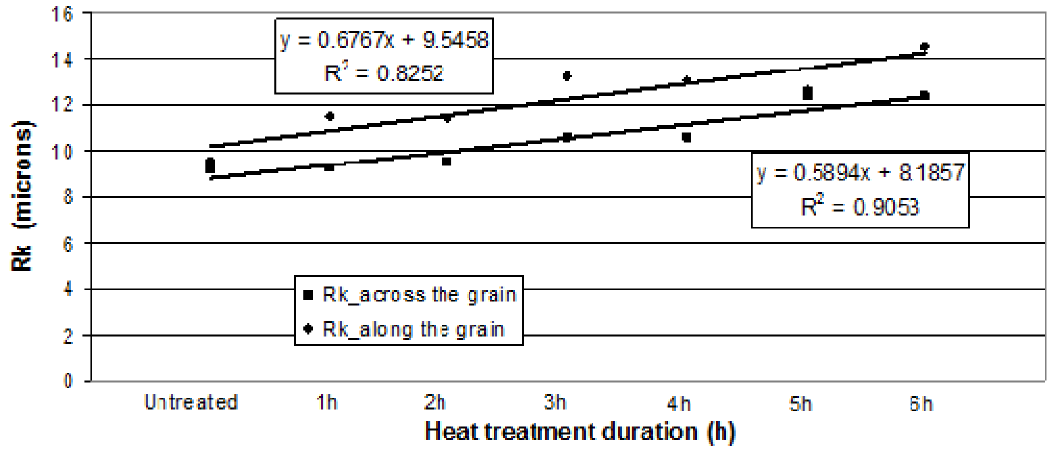


Figure 57 R_k measured along and across the grain as a function of the treatment duration (Gurau et al. 2017a)

Rk was the only roughness parameter that showed a clear trend with increased heat treatment duration in both scanning directions. *Rk* gave the clearest estimate of processing roughness, as the protruding peaks and valleys were not included in its calculation. Figure 57 shows that the processing roughness increased systematically with heat treatment time. Because the machining operation was the same for all of the specimens, these differences must have been due to the effects of the heat treatment on the physical and mechanical properties of the wood cell walls.

These findings indicated that R_k was a useful expression of the processing roughness after planing wood that was heat treated for different treatment durations. At the same time, it was difficult to correlate the increasing R_k values with any changes in the electron-micrographs, except for the greater pull-out of the ray tissue. The valleys created by this pull-out were unlikely to have influenced R_k because they were too deep. This finding demonstrated that it was necessary to calculate the roughness parameters to differentiate between two similar surfaces, as visual and tactile assessments were insufficiently sensitive.

Conclusions

The processing roughness by planing of heat-treated beech as measured by R_k increased systematically with heat treatment time. Profiles obtained across the grain were more sensitive to the duration of the heat treatment than those obtained along the grain. The effect of wood anatomy on the surface quality decreased with the treatment duration.

The visual assessment of micrographs in the control and in thermally treated samples showed a kind of surface plasticization, as well as pull-out regions in the soft ray tissue, which seemed more extensive in samples that were heated for longer durations.

The waviness across the grain, showed a statistically relevant decrease in magnitude for the heat-treated wood as compared with the untreated wood, and decreased with the duration of treatment. This decrease could indicate that the planed material had a different elasticity response.

It has to be noted that previous sections 2.2.1 and 2.2.2 presented joint research regarding the effect of thermal treatment on some properties of wood, which are part of an ongoing PhD research, where the author of this habilitation thesis acts as member of the advisory board and as involved researcher..

2.2.3 Surface roughness of heat treated and untreated beech (Fagus sylvatica L.) wood after sanding

Only few studies in the literature compared the surface roughness of untreated and heat-treated wood after sanding. De Moura Palermo *et al*. (2014) found an increase in surface roughness of heat-treated *Eucalyptus grandis* compared with untreated wood after sanding with P80 and P100 grit sizes. In that study, after high temperature treatment (190 °C for 6.5 h), the abrasive grits penetrate the wood more deeply than the untreated wood because of the reduced mechanical strength of the former. A number of studies have shown that heat treatment affects the mechanical properties of wood (Bekhta and Niemz 2003; Boonstra *et al*. 2007; Windeisen *et al*. 2009; Calonego *et al*. 2012). A recent example is that published by Borůvka *et al*. (2018) where they studied beech and birch wood samples.

Increased surface roughness of heat-treated of *Eucalyptus grandis* and *Pinus caribaea* as compared to untreated was also found after sanding by de Moura and Brito (2008) and de Moura *et al*. (2011). These studies contained a comparison between untreated and heat-treated wood for temperatures ranging from 140 °C to 200 °C subjected to sanding with following grit size combinations: 60-80; 80-100; and 100-120. The results showed a higher surface roughness in the case of heat-treated wood and this increased with the treatment temperature.

A different result was obtained by Tu *et al*. (2014) on *Eucalyptus urophylla* x *E. camaldulensis* subjected to heat treatments with temperatures ranging from 180 °C to 210 °C followed by sanding with a sequence 60-120 grit size. The surface roughness evaluated by parameter R_a showed slightly lower values for heat-treated wood, but with no significant differences between treatment temperatures.

Fewer studies are available in the literature on the study of surface roughness of sanded heat treated wood in comparison with untreated wood. However, in order to further understand the effects of sanding on wood an in-depth analysis is required.

The following study, ***published in an ISI journal (Gurau et al. 2019****) compared the effects of sanding with three commonly used sanding grit sizes P60, P100, and P150 on the surface roughness values of beech (Fagus sylvatica L.) wood. The wood samples were treated by the ThermoWood process at 200 °C for 2.5 h. A large range of standard roughness parameters (Ra, Rq, Rv, Rt, RSm, Rsk, Rk, Rpk, and Rvk) and two waviness parameters (Wa and Wt) were included in the analysis, as well as environmental scanning electron microscope (ESEM) images of the sanded surfaces.*

This study improves on previous research by using the robust filtering procedure (section 1.2.5), by increasing the measuring length to cover more wood variation and by adding a large range of roughness parameters in order to give a comprehensive interpretation of data.

Detailed description of specimens preparation is included in Gurau et al. (2019). All specimens were processed by sanding along the grain by using a wide belt sander with aluminium oxide belts, P60 grit size, at a contact pressure of 0.0055 N/m^2 and at a feed speed of 4.5 m/min. The depth of sanding was 0.3 mm/pass, and there were three passes for each specimen in order to make sure that irregularities from planing were completely removed. After this first sanding with grit size P60, 6 treated and 6 untreated specimens were kept for measurements and the others were further sanded with P100 by three passes though the machine. Again, 6 treated and 6 untreated specimens were retained and the others were sanded with P150 grit size in three passes. All sanded surfaces were tangential to reduce the influence of wood variability on the measured results.

The roughness measurements and roughness evaluation were achieved by using a MarSurf XT20 instrument as in section 2.2.1. A range of roughness parameters were calculated from each roughness profile including: R_a, R_q, R_{sk}, R_v, R_t, and R_{Sm} from ISO 4287 (1998); and R_k, R_{pk}, and R_{vk} from ISO 13565-2 (1996). The sum of parameters R_k+R_{pk}+R_{vk} was used by Magross (2015) in a study on surface roughness of sanded wood and was also included in this study for comparison. Waviness parameters W_a and W_t, from ISO 4287 (1998) measured the longer wavelength components in the profiles.

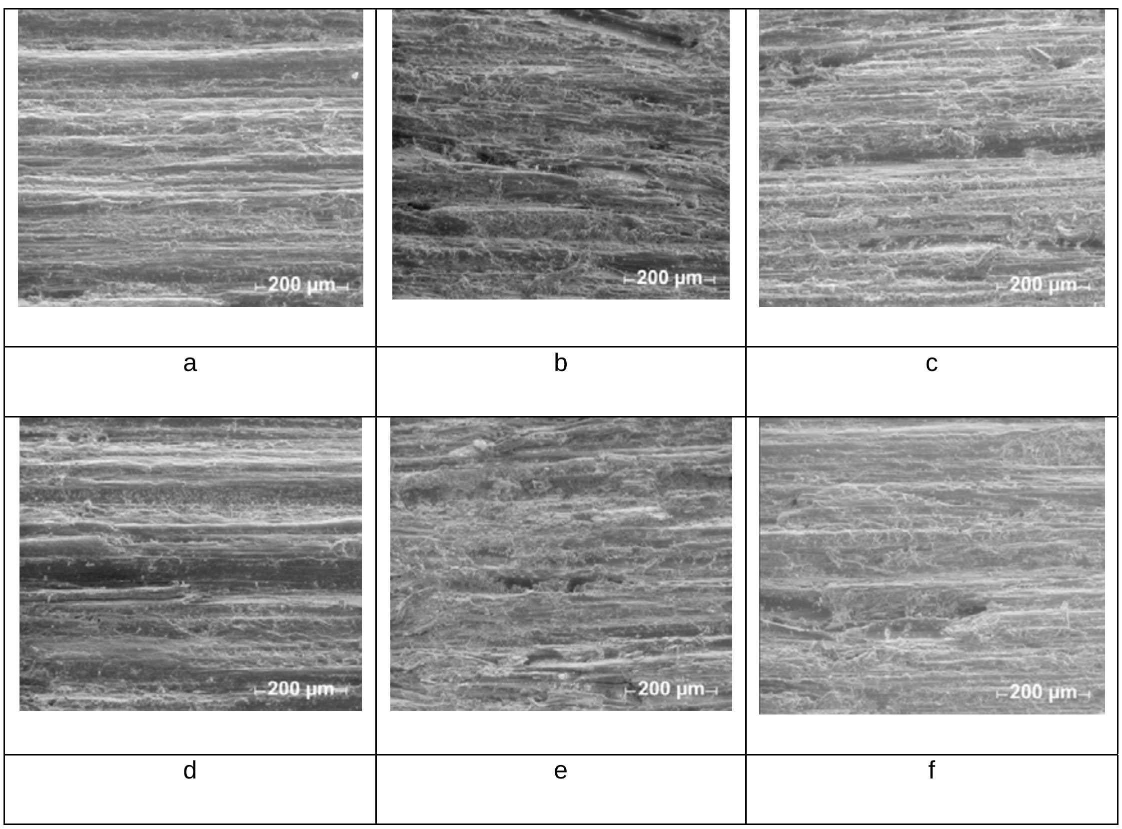


Figure 58 Comparative ESEM images, with magnification 400x, of untreated (UT - a,b,c) and heat treated (HT - d,e,f) beech (Fagus sylvatica L.) sanded with grit sizes P60 (a,d); P100 (b,e); and P150 (c,f) (Gurau et al. 2019).

The parameter R_k measures the core roughness of a profile, and it is sensitive to wood processing and surface heat treatment. It is expected that in the case of sanding, the highest concentration of data points will correspond to the marks caused by the mean grit diameters occurring with the highest frequency.

However, grit particles come as a range of values, where minimum and maximum grit diameters will have a low frequency. The grit particles that are larger than the mean value can be expected to create valleys that are deeper than the processing roughness. The R_{pk} parameter (the reduced peak height) is expected to be sensitive to fuzziness (fibres pulled out during sanding). The R_{vk} (the reduced valley depths) for beech, is typically associated with wood anatomical valleys, but can also be influenced, as R_v or R_t, by isolated high grit penetration in case of rough sanding.

ANOVA and Duncan's multiple range tests were performed to test statistical significant differences between datasets (treatments and processing types). The ESEM images were taken with a Quanta 250 made by FEI (Hillsboro, OR, USA). The photos were taken in Lovac mode at a pressure of 90 Pa. The surface relief was more easily observed if the specimen was tilted by 30°.

From the micrographs (Gurau et al. 2019) was difficult to notice any major differences in surface quality between untreated and heat-treated beech wood. However, it was observed that sanding traces were clearly visible as horizontal bands, and their depth and width were gradually reduced with the grit number. For all grit numbers, for both heat treated (HT) and untreated wood (UT), vessels were clearly visible, being uncovered by the grits ploughing into wood. The presence of vessels with simple pits was detailed by higher magnifications (400x) as shown in Figure 58.

Heat treatment reduces waviness such that W_a was smaller by 14% to 28%, and W_t by 10% to 14% than the values observed for the untreated wood. The differences were significant as tested with Duncan multiple range test (details in Gurau et al. 2019). Heat treatment had a marked effect on the mechanical properties of wood and, therefore, its response to mechanical solicitation, such as sanding, could be affected. This may explain the reduced surface waviness observed here and in previous studies on planed heat treated beech (Ispas *et al.* 2016).

Grit size		R_a (µm)	R_q (µm)	R_v (µm)	R_t (µm)	R_{Sm} (µm)	R_{sk}	R_k (µm)	R_{pk} (µm)	R_{vk} (µm)	R_k+R_{pk}+ R_{vk} (µm)
P60 UT	mean	12.6	16.4	74.2	126.4	381.5	-0.8	37.8	13.2	22.5	73.5
	stdev	0.73	1.13	15.60	18.38	27.86	0.26	2.28	0.96	3.26	4.80
	signif	A	A	A	A	A	AB	A	A	A	A
P100 UT	mean	9.0	11.6	51.78	92.1	249.5	-0.7	27.8	9.1	14.5	51.5
	stdev	0.56	0.74	8.69	13.72	15.44	0.21	2.04	1.12	1.52	3.59
	signif	B	B	B	B	B	B	B	B	B	B
P150 UT	mean	5.8	7.5	39.79	63.2	198.8	-0.9	17.7	5.5	10.2	33.5
	stdev	0.37	0.50	7.67	10.35	9.12	0.19	1.13	0.60	0.99	2.09
	signif	C	C	C	C	C	AB	C	C	C	C
P60 HT	mean	13.4	17.5	81.98	139.3	390.3	-0.8	40.0	14.4	24.4	78.8
	stdev	0.57	0.96	14.31	20.56	23.65	0.31	1.70	1.79	3.13	4.18
	signif	D	D	D	D	A	A	D	D	D	D
P100 HT	mean	9.6	12.3	55.35	90.7	262.2	-0.8	29.4	9.2	16.2	54.8
	stdev	0.56	0.70	6.30	6.93	12.15	0.14	2.03	0.93	1.30	3.09
	signif	E	E	B	B	D	B	E	B	E	E
P150 HT	mean	6.4	8.4	44.37	66.5	211.7	-1.1	19.2	5.7	12.2	37.2
	stdev	0.34	0.47	5.22	5.10	7.02	0.16	1.04	0.56	1.27	2.04
	signif	F	F	C	C	E	A	F	C	F	F

Table 14 Mean values of roughness parameters and standard deviations for treated (HT) and untreated (UT) beech wood subsequently sanded with three different grit sizes (Gurau et al. 2019)

Note: Groups with the same letters in columns indicate that there was no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range test. The meaning for stdev- standard deviation; signif- significance.

Roughness profiles generated in MathCad, showed clear differences between grit sizes of the same treatment, but the difference between treatments was hard to observe (details in Gurau et al.2019).

In Gurau et al (2019), upon comparing a profile from planing with those from sanding, it could be observed that the former provided more detailed anatomical features than sanding. Some authors reported that "sanding reduces the number of open cell capillaries" (de Meijer 2004). Magross (2015) also observed that sanding caused a clogging effect on the surface and decreased the number and size of wood anatomical cavities of beech. A reduced density of anatomical valleys of a beech surface sanded with a very fine grit size, P1000, used to minimize the effect of sanding marks and enhance the presence of wood anatomical irregularities, in comparison with the planned profile, confirmed that **sanding operation tends to obscure the wood anatomical cavities of beech in comparison with planing**. Sanding with P60 created some cavities deeper than the mean pore diameter or even deeper than the maximum pore diameter. Those features, most probably, were caused by grits higher in magnitude than the mean sized grits from FEPA 43-1 (2006), and were extending below the lower threshold and even beyond the anatomical cavities. Similar observations were made by Laina *et al*. (2017) regarding the sanding with P60 grit size. This is not surprising, since there is a range of values for grit particles that characterizes every grit size, where mean values have the highest occurrence in characterizing the core roughness.

The grit size is defined as the nominal size of abrasive particles that corresponds to the number of openings per linear inch in a screen through which the particles can just pass (Lee 1989). FEPA 43-1 (2006) defines the nominal diameter of the abrasive particles corresponding to a specified grit size as a range, whereby a middle value is usually taken as a reference. It is assumed that the mean grit diameter influences the core roughness or processing roughness, measured by R_k. Other scratches caused by isolated grits higher in magnitude than the mean, would influence parameters such as R_v, which measures the deepest feature on a surface and this can be true as long as wood anatomical cavities do not obscure the sanding depths by a higher magnitude.

The next question is: **how deep a grit particle can penetrate the surface**? According to Chung *et al.* (2011), the abrasive grit penetration (surface roughness) depends on the grit diameter, the number of grits per unit area, the nominal pressure per particle, and the modulus of elasticity of the sanded material. A simplified approach comes from Nastase (1981), who considered that the grit depth of penetration in wood varies directly proportional with the diameter of the grit and inversely with the specimen density. A relationship is given by [26] as shown below, where it is considered that the penetration is higher for a new belt than for a worn belt:

$$H = (110 \pm 20)\frac{d}{\rho} \qquad [26]$$

where H is the height of the grit penetration (μm), d represents the abrasive grit diameter (μm), ρ is the wood specimen density (kg/m^3), while (+) stands for a new belt and (-) for the case when the belt is worn.

This formula [26] was used to calculate theoretical scratch depths for both HT and UT wood and the data are presented in Table 15.

A mean value, from new and worn belt scenarios, of the grit depth of penetration was calculated. It is interesting to note that the calculated mean depth of penetrations were relatively close to the processing roughness parameter, R_k (Table 15). The correlation between R_k with the mean grit penetration depth was linear, with an R^2 value of 0.965 when the data from UT and HT beech were combined.

Wood Treatment	UT			HT		
Grit size	P60	P100	P150	P60	P100	P150
Mean grit diameter (µm) FEPA 43-1 (2006)	269	162	100	269	162	100
Grit penetration-new belt (µm)	48.0	28.9	17.9	56.7	34.1	21.1
Grit penetration-worn belt (µm)	33.3	20.0	12.4	39.2	23.6	14.6
Mean value grit penetration (µm)	40.7	24.5	15.1	48.0	28.9	17.8
R_k (µm)- Mean values	37.8	27.8	17.7	40.0	29.5	19.2
R_v (µm)- Mean values	74.2	51.8	39.8	82.0	55.4	44.4
R_v (µm)- Max. values	110.8	75.6	54.4	118.3	70.4	57.9
Mean pore diameter (µm)	45 (Wagenfuhr 2000); 55.3 (Hass *et al*. 2010)					
Max. pore diameter (µm)- Wagenfuhr (2000)	85					

Table 15 Estimated values of grit penetration in wood as function of the mean grit diameter, material density, belt processing stage (new *vs.* worn) in comparison with roughness parameters R_k, R_v, and pores diameter (Gurau et al. 2019)

For grit size P60, the deepest valleys seemed to have been caused by isolated grits with diameters higher than the standard mean, and for P100 and P150, the highest sanding marks seem to overlap with beech wood anatomical cavities.

The next target was to evaluate **how the roughness parameters correlate to the mean grit diameter**. A good correlation means a strong influence of grit size on the surface quality evaluated by roughness parameters. A weak correlation would indicate that surface roughness is biased by other type of features on the surface apart from marks from sanding, for example, wood anatomical cavities or maybe accidental processing gaps in the surface. Results (Gurau et al. 2019) have shown that, with the exception of R_{sk}, all roughness and waviness parameters had a very high linear correlation with the mean grit diameters, for both HT and UT wood.

Also, it could be observed that slightly better correlations occurred for HT wood compared to UT wood. This result may be due to the fact that, by heat treatment, the wood anatomical cavities tend to be attenuated/obscured by a phenomenon of cell collapse and surface texture changes that often resemble melting, which increased with heat treatment duration (Boonstra *et al*. 2006; Bakar *et al*. 2013; Salca and Hiziroglu 2014; Gurau *et al*. 2017a). As wood anatomical cavities are a factor of bias for roughness parameters, a slight reduction in data density for these irregularities may explain the slightly better correlation of roughness parameters with the mean grit diameters in the course of sanding of HT wood.

Conclusions

The surface roughness of beech wood was increased by heat treatment of beech by the ThermoWood method at 200 °C for 2.5 h followed by sanding with various grit sizes that are typically used to prepare surfaces for finishing, i.e., P60, P100, and P150.

Lower waviness was observed on heat-treated beech wood surfaces in comparison with untreated beech wood. All roughness and waviness parameters had a strong linear correlation with the mean grit *diameters for both untreated and heat-treated wood.*

The R_k values closely approximated the calculated mean grit penetration depth for all grit sizes applied to untreated and heat-treated beech wood The influence of wood anatomy in the valley domain increased as the grit size became finer.

2.2.4 Surface quality of EDS patented heat-treated wood after planing, sanding and finishing

EDS company was founded in 1984 as a timber manufacturer. Its main concern is directed towards the protection of the natural environment in all its richness, especially towards the protection of forests. This strategy was put into practice by developing several sollutions for the more rational use of wood, the valorization of inferior wooden resources and cellulosic plants which were not targeted for industrial uses until now, as well as a recycling-oriented use of wooden resources.

One of the main contributions of EDS company is an innovative technique (Ishii 1991) of heat-treating wood as a log in order to change, by means of high temperature (70-200°C) and smoke, its chemical composition so as to improve some of its properties.

The technique has proven its efficiency on low-value species from Asia (e.g. Acacia mangium, Albizia falcataria, palm wood, rubber tree wood, bamboo, coconut timber) (http://www.eds-lab.jp/english/jyumoku.htm).

In order to test the EDS technique in Romania, an international **contract "Experimental research regarding the characteristics of beech (*Fagus japonica*) heat treated by EDS technology" (No. 15826/11.11.2016- period: 2016-2017)** was concluded between Transilvania University in Brasov and **EDS Laboratory-Japan**. The research was carried out under the coordination of the author of this habilitation thesis, in order to investigate the effects of the EDS treatment upon Japanese beech wood (*Fagus japonica*), envisaging in case of positive results, a potential valorization of this technique on European beech (*Fagus sylvatica* L.)

The wooden material used within the experiments consisted of 50mm thick timber pieces originating from two logs of Japanese beech: one with red heart (average oven-dry density: 640kg/m^3), the other one without red heart (average oven-dry density: 626kg/m^3).

Half of the timber pieces from each log were first heat-treated by the EDS method in the EDS kiln in Japan. The maximum temperature inside the kiln during the treating process was 150°C. The temperature inside wood was monitored continuously. It was raised up to 80°C and then maintained at this level for 72 hours, then cooled down to 50°C for further 48 hours.

Afterwards, all pieces were conditioned for 2 months under constant parameters, at 20°C and 55% RH and then shipped to Romania. The material was then subjected to drying in the faculty laboratory.

A series of tests were performed targeting to compare beech wood with and without red heart, treated with EDS method and untreated, such as: drying tests, physical, mechanical, prelucrability and finishing tests. *Evaluation of surface quality before and after planing, sanding and coating was another target of this research.*

First target was to evaluate the drying time and drying quality of Japanese beech wood (*Fagus japonica*), with and without red heart, after being treated by the EDS method, in comparison with untreated wood originating from the same tree. The influence of the red heart presence was also pursued. The procedure and results are detailed in a **research paper in ProLigno journal** (Campean et al. 2017). It appeared that *the EDS treatment had benefitting effects both upon the drying time and the drying quality of Japanese beech wood. The effects were more visible in case of wood with red heart, which is normally more unhomogenous and more difficult to dry than beech wood without red heart. Under the effect of EDS treatment, wood dries faster than untreated wood without red heart and more uniform than all other considered wood types.*

In brief, the EDS treatment reduced the density difference between the knots and the wood from the trunk to the assortment with the red heart, coming from the same log. There was a tendency of the EDS treatment to homogenize the shrinkage between the outer and central areas of the log. In logs without red heart the volumetric shrinkage was similar for untreated and EDS treated wood, but EDS treated wood behaved better than untreated wood in swelling.

The EDS heat treated wood was easier to process by planing and sanding than the untreated. The treatment of beech wood by the EDS process determined significant color changes for both the wood with red heart and the one without red heart.

EDS heat treatment determined a similar surface quality as the untreated wood for tangential cut surfaces. In EDS treated wood, the quality of the tangential surface after planing was slightly lower in the assortment without red heart and better in the assortment with red heart, but the differences were small.
The research on the EDS treated wood **has generated 5 research reports**, among which, only the first report was disseminated **-1 paper in 2017, in a journal in international databases**. The other results are subject for futher publication and therefore were not included in this thesis.

2.3 Research on surface quality of wood after laser engraving

The literature provides very little information about engraving or decorating wood using a laser beam. Apart from cutting wood and wood-based materials, laser has been used for wood decoration, a popular method for producing artistic items from wood (Yakimovich et al. 2016). Laser engraving is the practice of using lasers to engrave or mark an object. Laser engraving consists in the removal of material from the top surface down to a specified depth. Petutschnigg et al. (2013) explored the option of treating wood surfaces with laser beams to develop new aesthetic possibilities and found an application in ski design. Wood colour was measured for various species treated with a CO_2 laser beam intensity of 40 to 120 W and found that laser beams affected the colour changes in different patterns and was species-dependent. Li *et al.* (2018) studied the effect of laser power, feed speed and sweep width on the color changes of poplar (*Populus* L.). They used Response surface methodology (RSM) for modeling and analysis of the effects of processing variables with a CO_2 laser on the colour changes of wood. The colour change, ΔE*, decreased with an increase in feed speed and sweep width and increased with an increase in the laser power.

In a study by Yakimovich *et al*. 2016, the highest aesthetic value of engravings with a CO_2 laser on beech were obtained for laser powers ranging from 5 to 10 W, combined with scanning speeds of 600 to 800 mm/s. The evaluation of surface quality was made by the perception of experts, using grades from 1 (low) to 5 (high quality).

Lin et al. (2008) investigated the effect of feed speed ratio and CO_2 laser power on the engraved depth and colour difference of Moso bamboo lamina. It was found that the laser engraved depth became deeper for either a higher laser power or a lower feed speed ratio.

The main research areas on laser engraving for the metal industry are the process parameters and the resulting surface roughness (Agalianos et al. 2011). However, no study has been reported on the investigation of the surface roughness of wood engraved by the laser in spite of its importance for surface finishing and aesthetics.

The following two studies aimed to investigate the effect of the laser engraving on the quality of two wood species. Those studies are part of an ongoing PhD research (Adrian Petru- co-author) on the laser effects on wood, where the author of this habilitation thesis acts as advisor regarding the surface quality.

2.3.1 The influence of CO_2 laser beam power output and scanning speed on surface roughness and colour changes of beech (Fagus sylvatica).

Previous literature studies on surface roughness have mainly focused on metals processed by the laser and resumed to a simple Gaussian filter for separating the roughness from longer wavelength irregularities and to roughness parameters as *Ra* (Eltawahni et al. 2013; Patel and Patel 2014; Pritam 2016) and *Rz* (Agalianos et al. 2011). However, heterogeneous materials, like wood, require robust filters for roughness and more roughness parameters that better evaluate and provide a greater understanding of the various aspects of the surface (Gurau and Irle 2017). Therefore, a robust filter for delimiting the surface roughness and a range of roughness parameters capable to give specific information about the stratified structure of the surface needs to be employed.

The following study (Gurau *et al.* 2017b) *aimed to find the influence of varying some parameters of a CO_2 laser beam (laser power output and scanning speed) on the surface roughness and colour of beech wood (Fagus sylvatica) for aesthetic applications such as decorative drawing.* It is important to develop such information to understand the effect of the two parameters on the surface quality and colour of beech when estimating superficial decoration with minimum engraving (below 1 mm) using lasers.

For superficial decorative engraving/drawing, a CO_2 laser (model SLG-4030 lsct with LaserCut software version 4.03 included, imported from China by SpotLine, Bucharest, Romania), with a wavelength of

10.6 µm, a lens of 73 mm focal length, and maximum output power of 40 W was used. The scanning gap was 0.0254 mm and the pulse frequency was 20,000 Hz.

For laser treatment, two parameters were varied, namely, the laser output power and the laser speed. Laser output powers used for this study were fractions from the maximum output power of 40 W: 13% (5.2 W), 14% (5.6 W), 15% (6 W), 16% (6.4 W), and 17% (6.8 W). For simplicity, they are symbolized in this study as L13, L14, L15, L16, and L17, respectively. The tested scanning speeds were 100, 200, 300, 400, and 500 mm/s. The target was to analyse their influence on the colour changes occurring on laser scanned beech wood as well as on surface roughness parameters.

Five beech (*Fagus sylvatica*) specimens, conditioned at 20 °C and 65% relative humidity of the ambient air, were prepared by first planing, then dimension cutting, then calibration with P60, and finally manual sanding with P100 grit size to their final dimensions of 340 mm x 100 mm x 8 mm. The surfaces were semi-radial, which were preferred to tangential because they have less colour and anatomical wood variation along the surface. The beech species was selected because of its availability.

Each of the five specimens was scanned with a different laser power output (from L13 to L17) as described above. On each specimen and for each output power, 20 areas (25 mm x 25 mm) were laser scanned with scanning speeds from 100 to 500 mm/s, so that for each scanning speed there were four replicates.

Colour measurements were performed as in Gurau et al (2017b).. The CIE L*a*b* colour coordinates were measured.

Surface quality measurements were performed using a MarSurf XT20 instrument with stylus parameters as used in previous sections of this report.

From each laser processed area, one profile, 20 mm long (Figure 59a), was stylus scanned across the grain for surface roughness analysis of the combined effect of laser power and scanning speed, so that, for each laser power (except L13) and scanning speed, four profiles were analysed. For all laser powers (L14 to L17) and five scanning speeds, there were 80 scanned profiles in total.

Those profiles and their roughness parameters were compared with similar 20-mm-long profiles of untreated wood, stylus scanned in the immediate vicinity of the laser modified areas (Figure 59b), so that each laser power/scanning speed combination corresponded to one roughness profile from unmodified wood. This meant that for each specimen, five wood profiles were analysed, resulting in a total of 20 profiles for all laser powers examined (L14 to L17). Those profiles were used as references to observe any increase in surface roughness of laser scanned surfaces caused by the laser action.

To visualize those roughness differences, another group of profiles, 40 mm long, were scanned so that they covered half a laser engraved region and half unprocessed wood (Figure 59c). This meant five mixed profiles for each specimen, 20 mixed profiles in total. After measuring, a range of roughness parameters was calculated for profiles, such as R_a, R_q, and R_t from ISO 4287 (1997) and R_k, R_{pk}, and R_{vk} from ISO 13565-2 (1996).

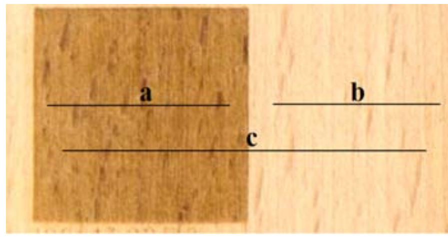


Figure 59 Details regarding the profiles measurement: a: profile from laser modified area (20 mm long); b: profile from unprocessed wood (20 mm long); c: mixed profile measuring laser scanned and unprocessed wood (40 mm long) (Gurau et al. 2017b)

As far as the colour results are concerned, It was observed that ΔE decreased sharply from a scanning speed of 100 to 300 mm/s and generally increased with laser power.

Among the roughness parameters, the best correlation with the laser power and scanning speed was obtained for the depth of the profile $Rk + Rpk + Rvk$, which was further used as a reference for comparisons. All results of roughness values and correlations are detailed in Gurau et al.(2017b).

Figure 60 shows the variation of the combined roughness parameter $Rk + Rpk + Rvk$ with the laser power and scanning speed in comparison with the reference, for unprocessed beech. The best correlations were obtained for a third-order polynomial, which was fit for all laser power data points. The coefficients of correlations R^2 were high for all curves, with the highest values recorded for the laser power L17. The roughness values increased with the laser power.

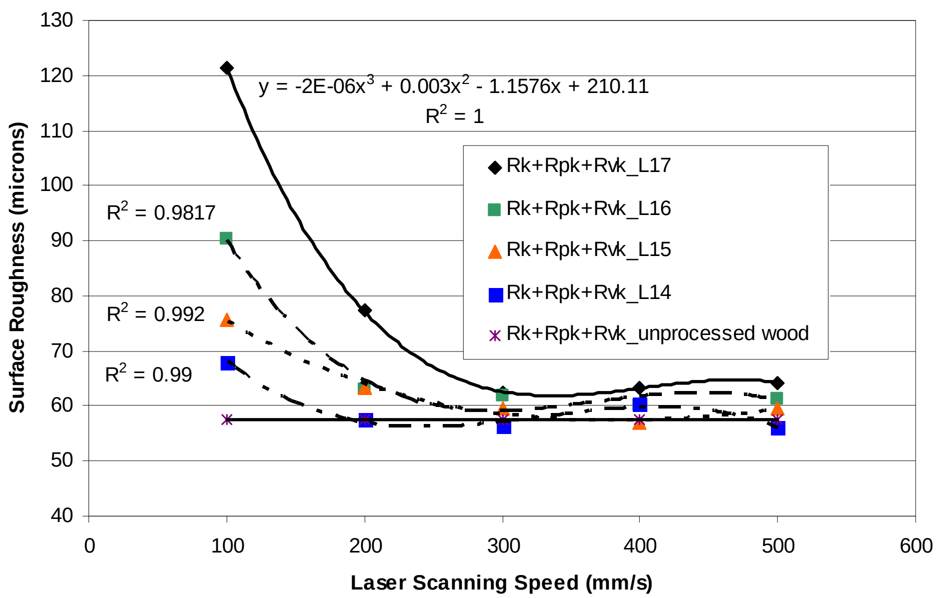


Figure 60 Variation of the depth of the profile (R_k + R_{pk} + R_{vk}), with the laser power and laser scanning speed in comparison with unprocessed beech (solid horizontal line) (Gurau et al. 2017b)

The laser scanning speed had a strong influence on the surface roughness values. The highest values were recorded for all laser powers at a scanning speed of 100 mm/s, which in case of high powers, L16 and L17, caused burning of the surface, which was perceived as a strong dark colour and as a level difference from the surrounding wood (engraving effect less than 1 mm).

It was interesting to evaluate how much roughness change was caused by the laser action on wood. In Table 16, the extreme cases of laser processing effect on wood were included. The minimum effect was obtained for laser power L14 combined with a scanning speed of 500 mm/s, which was compared with the roughness of wood measured in the proximate vicinity. The increase in roughness in the laser processed area is presented as a percentage. Similarly, the maximum effect on wood was produced by the combination of laser power L17 and a scanning speed of 100 mm/s.

	Laser power L14 at 500 mm/s	Neighbouring wood	Roughness increase (%)	Laser power L17 at 100 mm/s	Neighbouring wood	Roughness increase (%)
R_a (μm)	9.6	9.59	0.10	22	9.44	133.05
R_q (μm)	12.3	12.18	0.99	27.8	12.1	129.75
R_k (μm)	29.9	29.6	1.01	69.5	29.3	137.20
R_{pk}(μm)	10.4	7.91	31.48	18.2	7.04	158.52
R_{vk}(μm)	15.7	15.4	1.95	33.8	17.02	98.59
$R_k + R_{pk} + R_{vk}$ (μm)	56.1	52.91	6.03	121.4	53.36	127.51

Table 16 Minimum and maximum effect of laser power-scanning speed on surface roughness of wood in comparison with neighboring unprocessed wood (Gurau et al. 2017b)

The greatest effect of laser action on wood was observed on R_{pk} (surface fuzziness), which increased by 31.48% for laser power L14 and by 158.52% for laser power L17. An increase in roughness was observed for all roughness parameters, but the parameter $R_k + R_{pk} + R_{vk}$ showed a strong cumulative effect: surface roughness of beech wood laser scanned with L17 at a scanning speed of 100 mm/s increased the surface roughness by 127.51%, corresponding to an absolute height difference of approximately 68 μm. The value R_k increased by 137.20%, corresponding to an absolute difference of 40 μm. For finishing applications, this surface is considered very rough. The rougher the surface is, the more finish (lacquer) it will absorb.

Compared with the laser power L14, for a scanning speed of 100 mm/s, the core roughness *Rk* for L17 doubled, while *Rk* increased by 43.5% for L16 and by 15.7% for L15. *This shows that the laser power has a strong impact on surface roughness for low scanning speeds*.

The strong influence of laser scanning speed on the surface roughness of beech wood can be seen for laser power L17 in Figure 61, where a mixed profile is presented with approximately half the length from the laser scanned surface and half from unprocessed wood. The first half of the profile shows a high magnitude of irregularities in comparison with the second half, where wood was left unprocessed.

The correlation between colour change, expressed by the total colour difference Δ*E* and the surface roughness, measured by the composed parameter $R_k + R_{pk} + R_{vk}$ were calculated with the CORREL function available in Microsoft Office Excel 2003 for two groups of values. The colour change and surface roughness correlated very well, with high coefficients of correlation for all laser powers, combined with various scanning speeds. The coefficients ranged from 0.8 in case of L14 to 0.94 for L17 (data is available in Gurat *et al*. 2017b).

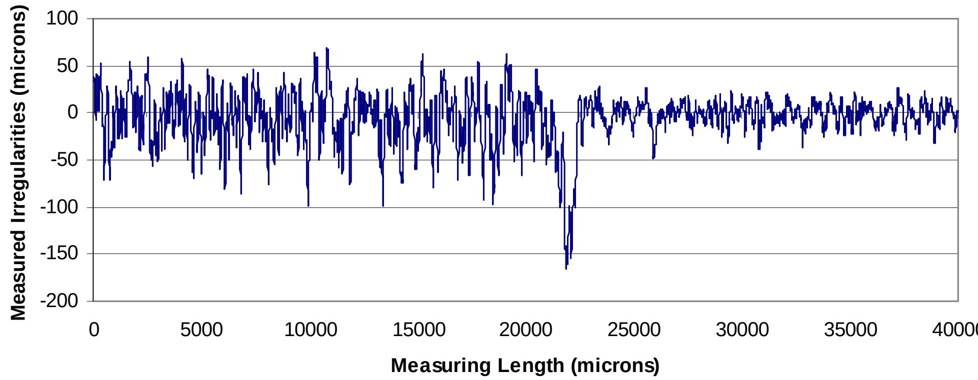


Figure 61 Mixed profile measuring approximately half length from beech engraved with L17 laser power at 100 mm/s scanning speed and half from unprocessed beech. Profile length: 40 mm (Gurau et al. 2017b)

Figure 62 shows the variation of the total colour difference, Δ*E*, with the composed roughness parameter, $R_k + R_{pk} + R_{vk.}$ The correlations from Figure 62 can be useful to select the laser power-scanning speed combination that will produce a similar colour change, but with a reduced surface roughness.

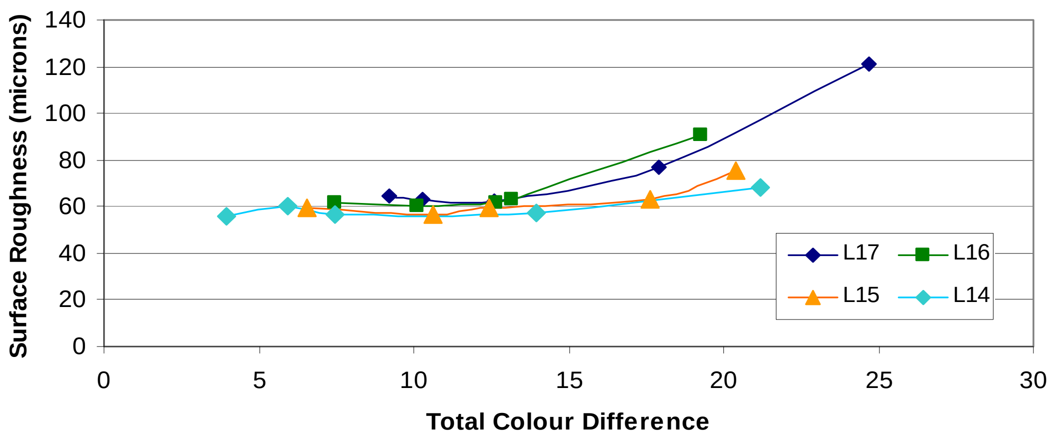


Figure 62 Variation of the total colour difference, Δ*E*, with the composed roughness parameter, $R_k + R_{pk} + R_{vk}$ (Gurau et al. 2017b)

L16 and L17 laser powers caused wood burning for lower scanning speeds of 100 and 200 mm/s, but for a scanning speed of 300 mm/s they are not a reasonable choice because of an increased surface roughness compared with unprocessed wood, while the colouring effect on wood was not much different than using a lower laser power such as L15.

For each of the laser powers, for speeds of 300 to 500 mm/s, the surface roughness was similar, while the total colour difference slightly decreased.

This study can be extended for higher laser powers and different combinations of scanning speeds to understand how these parameters modify the surface colour and surface roughness.

Conclusions

The surface roughness and total colour difference as measured by ΔE increased with the laser power and decreased with the scanning speed. The highest changes as compared to unprocessed wood were obtained for the lower laser speeds of 100 and 200 mm/s. For speeds higher than 300 mm/s, the colour changed slightly while the surface roughness was nearly the same.

The laser power L13 (5.2 W) was too small to generate colour changes in wood for scanning speeds higher than 100 mm/s. The laser powers L16 (6.4 W) and L17 (6.8 W) caused surface burns and an engraving effect (depths below 1 mm).

The best descriptor of the surface roughness change due to laser action was the composed parameter Rk + Rpk + Rvk. The most pronounced topographic effect of the laser on wood was an increase in surface fuzziness as measured by Rpk, combined with an increased core roughness (Rk) and deeper Rvk.

The correlation curves of surface roughness and total colour difference can help when choosing the laser power-scanning speed combinations capable of giving the targeted colour change with minimum surface roughness.

2.3.2 The influence of CO_2 laser beam power output and scanning speed on surface quality of Norway maple (Acer platanoides)

Similarly to the previous study, *the following research (**Gurau and Petru 2018**), with **2 citations in ISI Web of Science**, aimed to find the influence of varying the laser power output and scanning speed of a CO_2 laser beam on the surface quality of another species, namely Norway maple (Acer platanoides), for aesthetic applications such as decorative drawing/engraving.*

For this study, the same laser was used for engraving, as in section 2.3.1 The laser power output represented fractions from the maximum output power of 40 W: 14% (5.6 W), 15% (6 W), 16% (6.4 W), 17% (6.8 W), 18% (7.2 W), 19% (7.6 W), and 20% (8 W). The fractions of laser power were symbolized L14, L15, L16, L17, L18, L19, and L20. The second parameter tested was the laser scanning speed, which was varied from low to high, 100, 200, 300, 400, and 500 mm/s, and was combined with all laser powers. The specimens, 300 mm × 160 mm × 13 mm, were cut from Norway maple (*Acer platanoides*) in a similar way as in section 2.3.1.

Maple is very common for laser drawing and engraving because its colour is light and uniform. Four specimens with radial surfaces were used for this study, in order to display an even sequence of earlywood-latewood areas. The specimens were laser scanned with all laser powers and scanning speed combinations on areas (25 mm × 25 mm), with 4 replicates for each combination. For each laser power combined with all scanning speeds, there were 20 scanned areas. The size of each specimen allowed 40 scanned areas on the same face of the sample. A single specimen was scanned by two different laser power fractions. They were grouped on the four specimens as follows: L14 to L15, L16 to L17, L18 alone, and L19 to L20. Grouping the laser powers on the same piece of wood can be advantageous, because the wood variation is reduced to a minimum and the changes in surface roughness and wood colour caused by the laser action can be analysed with a higher degree of confidence.

Processing	Laser Scanning Speed (mm/s)	R_a (µm)	R_t (µm)	R_{sk} (µm)	R_k (µm)	R_{pk} (µm)	R_{vk} (µm)	R_k+ R_{pk}+ R_{vk} (µm)	R_{pk}/ R_{vk} (µm)
L14 (5.6 W)	100	10.9	101.0	-0.8	32.1	11.2	19.1	62.4	0.59
	200	6.6	63.4	-0.8	20.5	7.0	12.1	39.6	0.58
	300	6.6	63.6	-0.8	20.1	6.8	11.7	38.7	0.58
	400	6.8	70.3	-0.6	20.3	8.1	11.8	40.2	0.68
	500	7.6	70.6	-1.0	23.0	6.8	13.5	43.4	0.51
Unprocessed wood (vicinity of L14)	100	7.1	75.0	-0.7	20.4	9.7	13.0	43.1	0.75
	200	6.8	63.1	-0.7	21.7	6.4	11.4	39.5	0.56
	300	7.1	74.5	-0.7	21.0	7.2	11.8	40.1	0.61
	400	7.4	60.2	-0.7	23.4	6.7	12.3	42.4	0.55
	500	7.7	74.0	-1.0	23.5	7.2	13.4	44.1	0.53

Table 17 Comparative mean values of roughness parameters measured from laser scanned areas (Laser power L14-5.6 W) and from neighboring unprocessed wood (Gurau and Petru 2018).

Processing	Laser Scanning Speed (mm/s)	R_a (µm)	R_t (µm)	R_{sk} (µm)	R_k (µm)	R_{pk} (µm)	R_{vk} (µm)	R_k+ R_{pk}+ R_{vk} (µm)	R_{pk}/ R_{vk} (µm)
L20 (8 W)	100	25.8	218.9	0.3	81.0	38.0	30.1	149.1	1.26
	200	19.6	157.4	-0.2	62.6	23.4	24.9	110.9	0.94
	300	15.5	134.6	-0.7	46.9	15.4	25.9	88.2	0.60
	400	12.3	98.0	-0.8	36.9	11.2	19.8	67.9	0.57
	500	9.7	89.4	-0.9	28.7	10.1	17.7	56.6	0.57
Unprocessed wood (vicinity of L20)	100	6.4	57.4	-0.5	20.5	7.7	10.3	38.5	0.75
	200	6.6	50.6	-0.4	21.1	6.8	9.5	37.4	0.71
	300	6.6	78.8	-0.7	20.9	6.6	9.9	37.4	0.66
	400	6.8	62.4	-0.5	20.5	7.1	10.8	38.4	0.65
	500	6.8	60.1	-0.5	21.5	7.4	10.8	39.7	0.68

Table 18 Comparative mean values of roughness parameters measured from laser scanned areas (laser power L20-8 W) and from neighboring unprocessed wood (Gurau and Petru 2018).

The surface measurements and measured roughness parameters were the same as in the previous study (section 2.3.1.). The mean values of roughness parameters for the surfaces scanned with laser powers L14 to L20 combined with scanning speeds from 100 to 500 mm/s, as well as those measured from the unprocessed maple surfaces located in the proximate vicinity were calculated. Here, only the effect of L14 and L20 were included (Table 17 and Table 18), but results for all laser powers are presented in Gurau and Petru (2018).

The roughness parameters increased with the laser power and decreased with the laser scanning speed. By increasing the laser power and decreasing scanning speed, the ratio R_{pk}/R_{vk} increased and the skewness, R_{sk}, increased from negative towards positive values indicating a trend towards the prevalence of peaks in the profiles against valleys. In comparison with L14, L20 more than doubled the surface roughness for a scanning speed of 100 mm/s (2.37 times for R_a, 2.53 times for R_k, and 2.39 times for $R_k + R_{pk} + R_{vk}$) and tripled for a scanning speed of 200 mm/s, decreasing towards a scanning speed of 500 mm/s. This was because L14 caused a change in the surface roughness for a scanning speed of 100 mm/s. At higher speeds, the surface roughness was in the domain of variation of wood irregularities (Table 17). A similar observation for laser power L14 was made in the previous study on beech surfaces.

In comparison with the unprocessed wood, the surface roughness for the wood processed with L20 and 100 mm/s scanning speed increased approximately 4 times. As the scanning speed increased, the differences in surface roughness between the laser scanned and the unprocessed wood decreased.

In absolute values, L20 combined with 100 mm/s scanning speed increased Ra with 19.4 µm, Rk with 60.5 µm, and $Rk + Rpk + Rvk$ with 110.6 µm, which corresponded to a very rough surface. The absolute difference decreased with an increase in the scanning speed, thus, for 500 mm/s, the difference of the laser processed - unprocessed wood became 2.9 µm for Ra with, 7.2 µm for Rk, and 16.9 µm for $Rk + Rpk + Rvk$. The highest absolute difference was measured for Rt, which was sensitive to extreme values (peaks and valleys).

The roughness parameters were correlated to the laser powers and scanning speeds by the R^2 values.It was found that the variation of roughness parameters with the laser power had a linear trend.The best correlation was registered for the composed parameter $R_k + R_{pk} + R_{vk}$, which showed a very good linear correlation with the laser power as measured by R^2 (detailed information in Gurau and Petru 2018)

The best correlation was obtained for a scanning speed of 300 mm/s and this was valid also for the other roughness parameters. The lowest correlation was observed for a 500 mm/s laser scanning speed and this was due to the fact that the laser effect on wood fades for such high scanning speeds. The variation of the roughness parameters depends on the local wood anatomy which, in case of a 500 mm/s speed obscures the laser effect on wood.

Judging by the best correlation, a laser scanning speed of 300 mm/s seems to combine the best with the laser power. As the scanning speed decreases to 200 and 100 mm/s, the laser starts changing the surface morphology, which is decreasing the correlation. These observations were made for the majority of the roughness parameters. A low scanning speed is increasing the heat transferred to the surface and wood surface reacts in an interesting way. The latewood bands, higher in density than the earlywood, seem to expand, maybe as a result of a thermal dilatation or maybe the differences in thermal conductivity between earlywood and latewood may increase the local temperature in earlywood bands contributing to an easier vaporization and material removal as compared with latewood. However, some authors considered this phenomenon of surface undulation as being attributed, instead, to the differences in local wood density and to the fact that it takes longer time to the laser to remove the high-density latewood than the earlywood (Johansson and Sandberg 2007).

For all laser power values, the combination with a low scanning speed as 100 mm/s is causing an ablation effect on wood, the material is burnt and volatized and the laser processed surface will appear engraved as related to the unprocessed surface reference. This is clearly visible in Figure 63, which shows examples of measured profiles for each laser power scanned surface in the first half and the neighboring unprocessed wood in the second half. The profiles were offset as relate to each other in order to show the evolution of the laser effect from L14 (bottom) to L20 (top). The higher the laser power, the deeper its engraving effect, the higher the gap between the surfaces and the more pronounced undulating surface earlywood-latewood. The surfaces scanned with L20, L19 and L18 and a scanning speed of 100 mm/s, had a pyrolitic aspect with visible burns. It seems that a longer interaction time between the wood sample and the gas jet enhances the combustion process and removal of the vaporised material (Hernandez-Castaneda *et al.* 2009). The ridges, were clearly visible with naked eye for high laser powers, but they occured also for low laser powers, however detected only by examining MathCAD profiles in Figure 63.

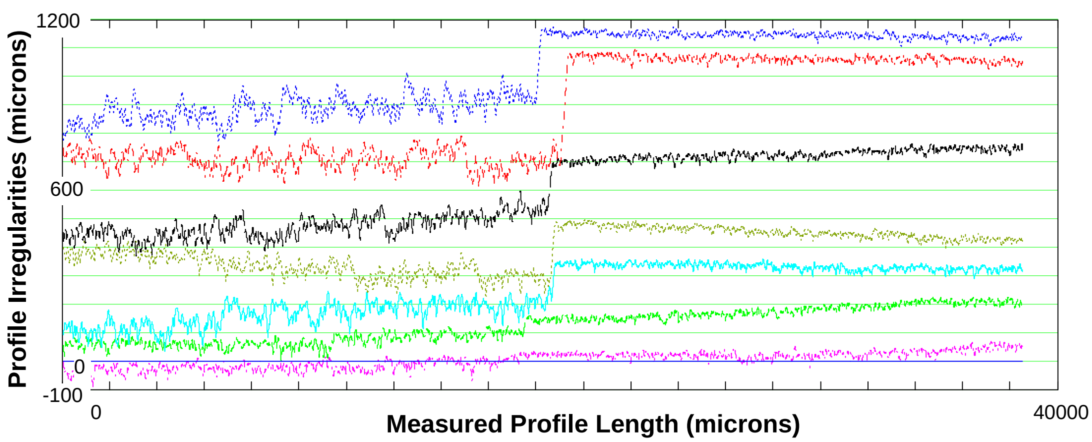


Figure 63 Measured profiles on Norway maple, first half scanned by laser with a scanning speed 100 mm/s and second half unprocessed (in order from the bottom to the top: with magenta-laser power L14; with light green-laser power L15; with light blue-laser power L16; with dark green-laser power L17; with black-laser power L18; with red-laser power L19; with dark blue-laser power L20). For comparison, profiles are offset one from another (Gurau and Petru 2018).

Weak correlation was found for *Rsk* with the laser power for slow laser speeds 100 and 200 mm/s, while for 300, 400 and 500 mm/s speeds no correlation was found between the laser power and surface skewness. This suggests that the surface skewness for speeds higher than 200 mm/s is not influenced by the laser action, but probably is more influenced by the wood local variability.

It was found that roughness parameters had a logarithmic correlation, with the laser scanning speed for all laser powers with the exception of L14. The result is not surprising. L14 had little impact on wood for a scanning speed of 100 mm/s, but for higher laser speeds, the roughness values were in the wood domain of variation and it can be said that the laser action was negligible. The best correlation occurred for $Rk + Rpk + Rvk$, which is in agreement with results from the previous study on beech. Good logarithmic correlations with the laser scanning speeds for laser powers higher than L14 were remarked also for *Rk, Ra* and *Rt*. The logarithmic correlation of *Rpk* with the laser scanning speed was best for L20 and decreased with the laser power. This confirms the fact that the laser influence on the surface fuzziness and isolated peaks on the surface increases with the laser power. High laser powers L20 and L19 caused an effect predominantly on the surface peaks and less on the surface valleys, proved by a weaker correlation with *Rvk* and by an increase in the ratio *Rpk/Rvk*. The presence of ridges on the surface had a strong effect on *Rpk* and this effect increased with the laser power and for low scanning speeds. Among all parameters, *Rpk* had the highest percentage increase, as relate to the unprocessed wood in agreement with the previous study of authors on beech wood (section 2.3.1).

The analysis with different roughness parameters revealed various aspects of the surface scanned by the laser. Not only a single roughness parameter should be used in surface roughness analysis for a comprehensive interpretation of the surface status.

The observations and results from this study can be further extended to other species or scanning variables, such as the scanning gap, to evaluate the result on surface roughness and optimize the selection of processing parameters for a minimum roughness combined with the targeted engraving and colouring effect.

Conclusions

All roughness parameters increased with the laser power and decreased with the laser scanning speed on Norway maple. It was found that the variation of roughness parameters with the laser power had a linear trend. A logarithmic correlation with the laser scanning speed was noticed for all laser powers with the exception of L14 (5.6 W). The best correlation was found for the composed parameter Rk + Rpk + Rvk, which may be the best parameter selection to describe the laser action.

The roughness parameters seem to correlate best with the laser power for a laser scanning speed of 300 mm/s. The lowest correlation was observed for a 500 mm/s laser scanning speed and this was due to the fact that the laser effect on wood tends to become obscured by local wood anatomical irregularities.

Rpk seems the most affected parameter by the laser action on wood. The laser has a clear effect on surface peaks, measured by Rpk, causing ridges on the surface which appear as push-up latewood bands as relate to earlywood. The effect increases with the laser power and with a decrease in scanning speed.

An ablation effect on wood was observed as a level difference between the laser scanned area and the unprocessed wood. This effect increased with the laser power and with a decrease in the scanning speed.

2.4 Research on surface quality of wood modified by plasma

The development of highly efficient protective wood coatings is the subject of intense current research. Particularly to protect wood from photodegradation, inorganic UV absorbers such as ZnO and TiO_2 have been widely studied and have proven to successfully protect the surface (Clausen et al.2010, Salla et al. 2012).

The following study (**Wallenhorst *et al.* 2018**) published in ***Applied Surface Science journal*** (**5.155 impact factor**) and **7 citations in ISI Web of Science** was an international joint research where *the contribution of the author of this habilitation thesis regarded the effect of plasma treatment on wood surface roughness. In this study, artificial ageing of beech wood coated with Zn/ZnO particles by means of a cold plasma spraying process as well as coating systems including a Zn/ZnO layer and additional conventional sealings were examined.* As ascertained by colour measurements, the particle coatings significantly decreased UV light-induced discolouration. Even though no significant colour changes were observed for particle-coated and alkyd-sealed samples, ATR-FTIR measurements revealed photocatalytic degradation of the alkyd matrix. In contrast, the polyurethane sealing appeared to be stabilised by the Zn/ZnO coating. Furthermore, morphologic properties of the pure particle coatings were studied by SEM and roughness measurements. Here, only surface roughness results are presented.

Roughness measurements were performed for uncoated (kept as control) as well as particle-coated surfaces (coating B) of beech specimens (6 x 10 x 4 cm^3, previously processed by planning), as well as for polypropylene samples (6 x 10 x 3 cm^3). Wood is an example of a surface with inherent anatomical irregularities (for example wood pores), while polypropylene is a homogeneous material chosen for comparisons of the effect of the particle coating on surface morphology. For the roughness measurements, a MarSurf XT20 measuring system with XT 20 Topography manufactured by MAHR Göttingen GmbH was used. The instrument was endowed with a scanning head MFW 250 with tracing arm in the range of ±500 µm and a stylus with 2 µm tip radius and 90° tip angle. The specimens were measured at a speed of 0.5 mm/s, at a vertical resolution of 7 nm, a lateral resolution of 1 µm, and with a low scanning force of 0.7 mN. Both for coated and uncoated materials, five replicates were measured by randomly tracing three profiles per sample with a length of 70 mm, so that 15 profiles were available for evaluation of each combination of treatment and material. In the case of beech specimens, the measurements were carried out perpendicular to the grain direction, which corresponds to the direction of the highest roughness.

After filtering according to the methodology in section 1.3, a range of roughness parameters were calculated for the profiles, such as: *Ra, Rq, Rt*, from ISO 4287 and *Rk, Rpk, Rvk* from ISO 13565-2. *Rk measures the core roughness of a profile, is the parameter least biased by inherent variation in wood anatomy and should best indicate the modifications in roughness caused by coating the surface*. For treated and untreated surfaces and each roughness parameter, a mean value and the standard deviation were calculated. ANOVA with single factor was performed to test significant differences between reference samples and those treated with zinc particles.

The surface roughness results are summarised in Table 19 and Table 20.

Sample	*Ra*	*Rq*	*Rt*	*Rk*	*Rpk*	*Rvk*
Reference beech	5.7	8.6	72.3	12.0	6.5	18.4
stdev	0.30	0.65	8.11	0.92	0.90	1.56
Particle-coated beech	6.2	9.1	80.4	13.67	9.12	17.89
stdev	0.24	0.48	7.50	1.66	1.63	2.22

Table 19 Roughness parameters (mean values) and standard deviations for untreated and particle-coated beech surfaces (values in microns) (Wallenhorst et al. 2018)

Sample	*Ra*	*Rq*	*Rt*	*Rk*	*Rpk*	*Rvk*
Reference polypropylene	0.019	0.028	1.101	0.056	0.027	0.038
stdev	0.001	0.009	0.837	0.003	0.005	0.015
Particle-coated polypropylene	5.325	7.370	61.622	14.068	12.405	2.098
stdev	0.287	0.343	9.417	1.385	0.703	1.115

Table 20 Roughness parameters (mean values) and standard deviation for untreated and particle-coated polypropylene surfaces (values in microns) (Wallenhorst et al. 2018)

From Table 19 and Figure 65, it can be seen that the particle coating increased the surface roughness of beech. This increase is more reliably evaluated by the *Rk* parameter, because it is the parameter least biased by beech wood anatomy (see section 1.2.7). *Rk* increased with 13.6 % in the case of particle-coated beech and this difference was significant for a 95 % confidence interval ($p < 0.05$) according to the ANOVA test. In absolute values, this means a surface 1.64 µm rougher if coated. The fact that the surface was coated has generated, as expected, an increase in surface peaks as measured by the parameter *Rpk*, which exhibited the highest increase (41%) for coated beech compared to untreated surfaces. *Rvk*, which may be a measure of wood anatomical irregularities (mostly wood pores) for uncovered wood, decreased by 2.6 % as compared to untreated beech, which is an indication that the particles may have penetrated into the wood anatomical cavities and obscuring them to a certain extent.

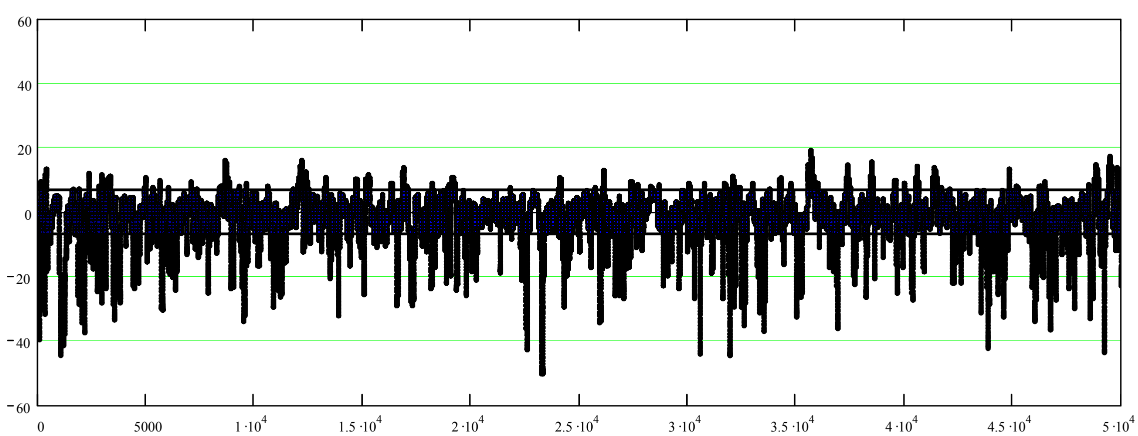


Figure 64 Profile of untreated beech with core roughness (blue) delimited by an upper and a lower threshold. Values in microns (the procedure of separation as in section 1.2.6.1)

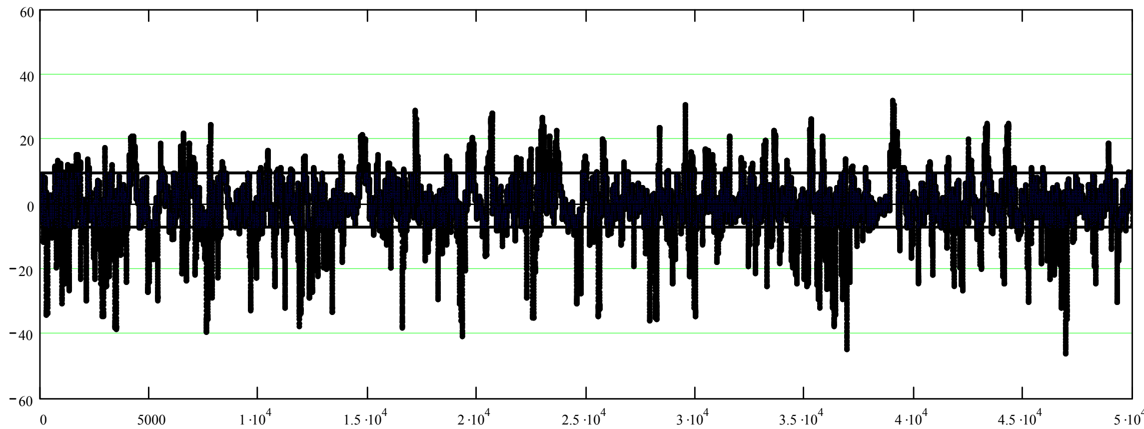


Figure 65 Profile of Zn-coated beech with core roughness (blue) delimited by an upper and a lower threshold Values in microns (the procedure of separation as in section 1.2.6.1)

From Table 20, it can be observed that the particle coating caused a large increase in surface roughness of plastic surfaces for all measured parameters. For example, the *Rk* parameter increased 249 times, but the highest increase was recorded again for *Rpk* (461 times), while *Rvk* exhibited the minimum increase (55 times). This indicates that the particle coating increased the occurrence of isolated peaks on the surface for both polypropylene and beech surfaces. In comparison with polypropylene, the particles penetrate into the wood anatomical irregularities (gaps) and its overall effect on surface roughness is small.

Conclusion

In this study, Zn/ZnO coatings deposited by cold plasma spraying on wood and polypropylene were investigated with regard to morphologic aspects as well as their impact on photodegradation of wood and possible sealing materials. Roughness measurements showed a slight roughness increase for particle-coated beech, as measured by the Rk parameter, and a tendency of particles to increase the surface peaks as well as to reduce wood anatomical gaps, most probably by filling the wood pores to some extent.

2.5 Research on surface quality of various wood based composites

The lack of a dedicated standard metrology is also a limitation in the evaluation of surface roughness of wood based panels, such as medium-density fiberboard (MDF) or particleboards. The surface roughness of MDF is significant when panels are used as the substrate for overlays such as thin melamine paper or vinyl. Fine irregularities on the board surface resulting from sanding/calibration will show through the overlays, affecting product grade and quality (Hiziroglu 1996). Similarly, studies on the surface quality of particleboards underline the importance of measuring the surface roughness prior to coating or covering with overlays (Nemli et al. 2005, 2007; Hiziroglu and Suzuki 2007, Rolleri and Roffael 2010).

Furthermore, all previous studies on surface roughness of wood based panels have used a simple Gaussian filter for separating the surface roughness from other surface irregularities, which was found unreliable for wood (see section1.2.5). There was no consensus in selecting the measuring length, which ranged from 8 (Sütcü and Karagöz 2012), 12.5 mm (Ayrilmis *et al.* 2010) or of the filter cut-off length, some authors used 0.8 mm (Pinkowski *et al*. 2011), while others used 2.5 mm (Gaitonde *et al*. 2008b, Davim et al. 2009, Ayrilmis *et al*. 2010). This makes any comparison between measurements from different authors problematic.

In response to these various approaches in the literature, the following three studies were using the metrology method proposed in chapter 1, in order to evaluate the influence of certain variables on the surface roughness of MDF, particleboards and wood plastic composites. Using a tested methodology for wood surfaces provides a more reliable surface quality evaluation.

2.5.1 Effect of species and grinding disc distance on the surface roughness parameters of medium-density fiberboard

The studies found in the literature regarding the surface roughness of MDF mainly focused on evaluating the influence of various mechanical processes such as: milling (Gaitonde et al, 2008b; Davim et al., 2009; Sütcüto and Karagöz 2012), CNC cutting (Pinkowski et al., 2011), rip sawing (Aguilera, 2008), drilling (Davim et al, 2007a, 2007b; Davim et al, 2008; Gaitonde et al, 2008a; Palanikumar et al, 2012, Prakash et al., 2014), sanding (Ayrilmis et al., 2010) or even heat-treatment of MDF (Ayrilmis and Winandy, 2009), and research on MDF kept in variable climatic conditions (Rolleri and Roffael, 2008). All those studies were based on the surface measurements, the majority of them by using a stylus (Gaitonde et al, 2008b; Ayrilmis and Winandy, 2009; Davim et al., 2009; Ayrilmis et al., 2010; Sütcü and Karagöz 2012; Pinkowski et al., 2011; Prakash et al., 2011) with a software attached and based on a common Gaussian filtering method, which lately, in measurements made on wood surfaces proved to be unreliable due to some bias effects caused by wood anatomy. Furthermore, if the roughness parameters are to be useful, they must be repeatable, which implies some standardization of factors affecting their measurement and calculation. Such factors include the measuring instruments, measuring and filtering methods and the choice of standard or non-standard parameters applicable to wood described in detail and proposed for wood surfaces in chapter 1 of this habilitation thesis.

In the following study, which was a result of an international joint research, Gurau *et al.* (2017c), published in the ***European Journal of Wood and Wood Products (1.401 impact factor in 2017),*** *the effects of three wood species and defibration disc distance on the surface roughness of MDF panels were investigated based on the robust filtering method and on the tested wood surface roughness methodology detailed in chapter1.*

Seven different fiber types were produced applying the laboratory refiner of the Institut für Holztechnologie Dresden GmbH (IHD) (Dresden, Germany), without adding any additives or resin in the flash tube dryer (blow-line). In order to achieve fibers of different size, the grinding disc distance was varied. With the intention to understand the effect of wood species, various species were used. In the first phase, the influence of wood species (Scots pine, beech, birch, poplar and a mixture (50/50 wt) of Scots pine and beech) was determined. For this aim, the temperature (170 °C) and time (4 min) in the digester, stock outlet (radial), and grinding disc distance (0.15 mm) were kept consistent. In the second phase, the influence of grinding disc distance (0.06, 0.15, and 0.6 mm) was determined on fibers where steaming temperature (170° C), steaming time (4 min), stock outlet (radial) and wood species (Scots pine) were kept consistent. Subsequently to the refining process the fibers were blow-line dried and collected in plastic bags. The manufacturing details of the investigated fibers are presented in Gurau *et al.* (2017c).

Liquid urea-formaldehyde (UF) resin (Kaurit 350, BASF, Ludwigshafen, Germany) was used as an adhesive in the manufacture of experimental MDF panels. Ammonium nitrate (NH_4 NO_3) solution with 40 wt% solid content was used as a hardener for the UF resin. The preparation of MDF panels is fully detailed in Gurau *et al.* (2017c). The target MDF thickness and density were 16 mm and 650 kg/m^3. Three replicate panels were made for each fiber type. Twenty-four specimens with dimensions of 50 mm x 50 mm x 16 mm were used for each code of MDF. Test specimens were conditioned in a climatic chamber at 20 °C and 65% relative humidity for 2 weeks before testing.

The specimens were scanned on tracing lengths of 40 mm based on the former experience on wood surfaces that variation in wood anatomy gives instable roughness parameters for shorter evaluation lengths (see section 1.2.4.1). It is assumed that a similar evaluation length on MDF surfaces can give more reliable results. Three profiles were recorded for each specimen, so that a total of 72 profiles were available for further evaluation of parameters for each species tested and for each grinding gap condition. The protocol for measuring and evaluating the surface roughness was the one recommended in chapter 1 (section 1.3). A range of roughness parameters were calculated such as: *Ra*, *Rq, Rz*, *Rt, Rsk, Rku, RSm* from ISO 4287:1998 and *Rk*, *Rpk*, *Rvk, A1(*peak area of the material ratio curve)*, A2(*valley area of the material ratio curve)*,* from ISO 13565-2:1996 (described in section 1.2.7). Some parameters describing the waviness in the profile were calculated according to ISO 4287:1998: *Wa*, *Wq* and *Wt*. Their meanings are similar to their equivalent roughness parameters, but apply to the waviness profile. The waviness profile is the primary profile from which roughness was subtracted. These parameters are interesting because they evaluate a surface by its longer wavelength characteristics. Waviness in the profile can be sensitive to species elasticity, but can also measure the surface unevenness caused by the manufacturing process.

It was observed an increase in the surface roughness, as follows: MDF from Scots pine/beech, followed closely by poplar, then by birch, Scots pine and beech. All results are detailed in Gurau *et al.* (2017c).

From the roughness parameters and by examining measured profiles created in MathCAD (detailed in Gurau *et al.* 2017c) it was concluded that deeper surface gaps and fuzziness (raised fibers), in comparison with the other species occur in the case of MDF manufactured from beech, known as the most susceptible to swelling amongst those species.

The occurrence of higher magnitude valleys outside the core roughness compared to protruding peaks was visible for all species tested and depicted by a negative skewness, *Rsk* as well as by a clearly higher *A2* compared to *A1*. This was reflected also by a higher ratio *Rvk/Rk* compared to *Rpk/Rk*. The reason of these outlying valleys in the profiles can be attributed to a number of factors, such as: unavoidable anatomical cavities (earlywood pores lumen or earlywood tracheids, isolated resin canals) or gaps between glued fibers resulted after the manufacturing of MDF boards (details in Gurau et al. 2017c)..

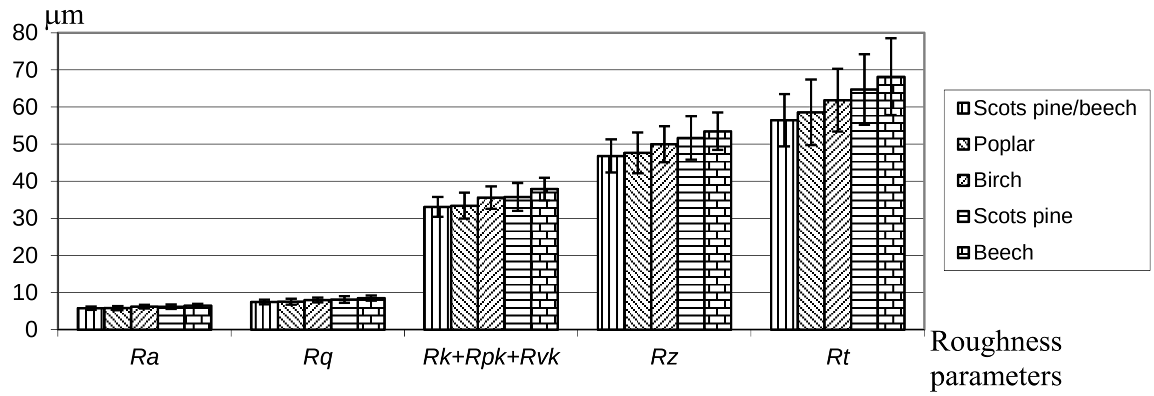


Figure 66 Comparative surface roughness parameters for MDF boards manufactured from different wood species (mean values in microns) (Gurau et al. 2017c)

The surfaces of MDF manufactured from Scots pine had the highest maximum height waviness *Wt.* It may be that differences between resin and species fibres elasticity have an influence on the surface waviness of MDF panels. However, combining Scots pine and beech in the structure of MDF boards seem to have compensated the disadvantages of both, Scots pine and beech, and the surface quality of the combined species was the best, followed closely by surface of MDF made of poplar. It was interesting to observe that the surface quality of MDF manufactured from different species did not depend on the MDF density, but it was influenced by the type of species.

Another finding was that the roughest surface was produced when a grinding disc distance of 0.6 mm was used. The use of a grinding gap of 0.06 mm instead of 0.15 mm did not improve the surface quality, and generally, surface parameters for the two types of grinding disc distances were close (Table 21), a little higher for 0.06 mm gap. A grinding gap of 0.6 mm caused a sharp increase in roughness parameters and waviness, but also of surface uneveness reflected by much higher standard deviation values compared to the other two. The most sensitive parameters to the increase of grinding gap to 0.6 mm were, as in case of varying the species, *Rt* and *Rvk*. No correlation of MDF surface quality with its density was noticed.

Grinding disc distance (mm)	Roughness and waviness parameters (mean values in microns)- ISO 4287									
	Ra	*Rq*	*Rz*	*Rt*	*RSm*	*Rsk*	*Rku*	*Wa*	*Wq*	*Wt*
0.15	6.17 (0.59)	8.11 (0.88)	51.7 (5.9)	64.7 (9.5)	214.5 (15.2)	-1.04 (0.32)	4.58 (0.86)	4.67 (1.4)	5.79 (1.7)	29.42 (9.0)
0.06	6.72 (0.74)	8.80 (1.01)	54.7 (6.5)	68.5 (10.5)	219.7 (16.17)	-1.00 (0.30)	4.43 (0.82)	5.12 (1.5)	6.40 (1.9)	32.59 (9.4)
0.6	6.74 (1.21)	9.33 (2.03)	59.2 (12.0)	77.3 (19.5)	259.7 (36.4)	-1.47 (0.59)	6.29 (2.08)	5.62 (1.5)	6.94 (1.7)	34.03 (8.5)

Table 21 Surface quality parameters according to ISO 4287 for MDF manufactured from Scots pine defibrated with three values of grinding disc distance (Gurau et al. 2017c)

Conclusions

The effects of three species and grinding disc distance on surface roughness of MDF panels were investigated based on the methodology proposed in chapter 1 (section 1.3) The influence on MDF panels surface roughness of varying the species (beech, poplar, birch, Scots pine, mixture 50% Scots pine/beech) and grinding disc distance (0.06 mm, 0.15 mm, 0.6 mm) was examined, while the other manufacturing parameters were kept constant. The overall variation in surface roughness extending beyond the core roughness was attributed to the wood anatomy and fuzziness. Therefore, an increase in surface roughness occurred for the MDF from Scots pine/beech, followed closely by the MDF made of poplar, then by birch, Scots pine and beech. The surface quality of MDF manufactured from different species did not depend on the MDF density, but it was influenced by the type of species. A grinding gap of 0.6 mm caused the highest MDF surface roughness. The smoothest surface was obtained when a grinding gap of 0.15 mm was used closely followed by results for 0.06 mm. This indicates that a very low grinding gap distance will not improve the surface quality of MDF panels.

2.5.2 Effect of raw material composition of wood plastic composites on surface roughness parameters evaluated with a robust filtering method

Finishing properties of WPCs are mainly dependent upon the properties of the raw materials such as polymer and wood flour content and characteristics, and manufacturing parameters. For the direct painting, the surfaces of WPCs have to be smooth, stable, and not highly absorbent. Therefore, it is important to quantify surface roughness of the panel to have a better overlaying of the WPC. Previous studies reported that surface roughness of WPCs was significantly affected by the type and ratio of the thermoplastic, wood, and additives (Jarusombutis and Ayrilmis 2011, Ayrilmis et al. 2012, Calvimontes et al.2016). However, evaluation of surface roughness in case of wood or of any wood based composite requires a special consideration.

If the Robust Gaussian Regression Filter (RGRF) (section 1.2.5) works well on wood surfaces, can work reliably for any surface that contains wood ingredients (wood fibers, wood chips, wood flour), which all may be a source of bias and distortion during filtering with the common simple Gaussian filter. Furthermore, researchers generally used a limited number of roughness parameters, from the ones available in the standards, to evaluate the surface quality, such as *Ra* (Wechsler et al. 2008) or *Rq* (Gupta et al. 2007) or a combination of *Ra* and *Rz* (Jarusombutis and Ayrilmis 2011, Soury et al. 2011, Calvimontes et al. 2016). However, these parameters cannot give a complete picture and interpretation of the surface status. A thorough understanding of the surface condition is needed, especially for composite materials where wood is used in combination with other materials and so introducing a degree of uneveness.

Therefore, *in the following study, an international collaboration-* ***Gurau and Ayrilmis (2019)- Journal of Thermoplastic Composite Materials (*****1.343** ***impact factor)****, a large number of surface roughness parameters were used from roughness profiles obtained after robust filtering with RGRF of the injection* *molded WPCs produced from different amounts of the filler, polymer matrix, and additives, to have a better understanding of the overlaying quality of the samples.*

Virgin polypropylene (PP) granulates were used as polymer matrix in the production of thermoplastic composites. The density and melt flow index (MFI) of the PP were 0.904 g/cm^3 and 12 g/10 min, respectively. Pine wood (*Pinus sylvestris*) chips without bark were grinded in the grinder and then sieved to obtain wood flour having 0.25 mm size. The wood flour was dried in a laboratory oven with a fan at 100 °C for 24 h to the moisture content of 0-0.5% before the manufacturing process. The particle size of the mineral filler (calcite) was 0.15 mm. The amounts of compatibilizing agent, maleic anhydride modified homopolymer PP (MAPP), mineral filler, wax, UV absorber, zinc borate, antioxidant, and color pigment are given in Table 22. Nine different raw material formulations were selected in a broad spectrum based on commercial formulations of WPC injection molding for different applications.

Type of raw material	Raw material composition of WPCs (wt%)								
	A1	A2	A3	A4	A5	A6	A7	A8	A9
Polypropylene	40.1 (MFI: 3.6)	40.1 (MFI: 12)	40.1 (MFI: 25)	28 (MFI: 12)	30 (MFI: 12)	29 (MFI: 12)	43.7 (MFI: 12)	39.7 (MFI: 12)	22.5 (MFI: 12)
Wood flour	50	50	50	60	40	50	50	50	60
Mineral filler	0	0	0	0	20	10	0	0	10
Coupling agent	3	3	3	3	1.5	2	3	3	3
Wax	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
UV-absorbent	0	0	0	0.5	0.5	0.5	0	0	0.5
Zinc borate	4	4	4	4	4	4	0	4	0
Antioxidant	0.4	0.4	0.4	0.7	0.8	0.8	0.8	0.8	0.8
Color pigment	0	0	0	1.3	0.7	1.2	0	0	0.7
Total amount	100	100	100	100	100	100	100	100	100

Table 22 Experimental design (Gurau and Ayrilmis 2019).

The injection molded WPC composites were prepared as in Gurau and Ayrilmis (2019).

The surface roughness measuring lengths of WPC's were generally rather short: 4 mm (Hutyrová *et. al.* 2015) or 12.5 mm (Jarusombutis and Ayrilmis 2011, Calvimontes et al. 2016). However, in this research, the specimens (four replicates for each WPC combination) were scanned on tracing lengths of 50 mm, because longer tracing length gives more accurate results (see section 1.2.4.1). Four profiles were recorded for each specimen, two on each specimen face, so that a total of 16 profiles were available for further evaluation of parameters for each WPC combination. The profiles were measured in areas which displayed, as much as possible, homogeneity of the mixture. The lateral measuring resolution was set for 1 μm, so that any variation in surface irregularities could be detected with accuracy. The metrology of WPC surfaces was the one recommended in section 1.3. The cut-off used was 2.5 mm as recommended in previous research (section 1.2.5.5) and also used by various researchers specifically on WPC surfaces

(Calvimontes et al. 2016, Jarusombuti and Ayrilmis 2011). The roughness parameters were the same as in previous sections. Individual profiles of WPC combinations were also separately examined by using MathCad Professional (Gurau and Ayrilmis 2019). This allowed a visual comparison of the magnitude of irregularities between WPC compositions.

A1, A2, and A3 had an identical composition, except for the MFI values. As for the melt flow index (MFI) of the PP, the lowest *Ra* value was found in the WPCs produced with the PP having a MFI value of 25 (Table 23).

WPC type	Surface roughness and waviness parameters (μm)								
	Ra	*Rq*	*Rt*	*Rsk*	*Rku*	*Rk*	*Rpk*	*Rvk*	*Rk+Rpk+Rvk*
A1	1.6 (0.19)	2.4 (0.37)	27.0 (6.31)	0.2 (0.96)	8.6 (3.16)	4.4 (0.58)	3.6 (1.16)	3.0 (0.61)	11.0 (1.52)
A2	1.6 (0.18)	2.4 (0.37)	28.5 (6.71)	-0.2 (1.13)	10.4 (3.97)	4.3 (0.52)	3.6 (1.42)	3.6 (1.11)	11.4 (1.72)
A3	1.5 (0.15)	2.3 (0.30)	27.9 (5.45)	-0.8 (1.07)	11.3 (8.39)	4.0 (0.37)	3.0 (0.63)	3.6 (0.94)	10.7 (1.48)
A4	1.9 (0.36)	2.8 (0.65)	26.4 (6.44)	1.4 (0.84)	8.2 (2.64)	4.4 (0.81)	5.1 (1.85)	3.1 (1.03)	12.7 (2.66)
A5	1.7 (0.22)	2.6 (0.65)	32.5 (8.46)	1.1 (0.95)	10.1 (3.33)	4.0 (0.92)	4.9 (1.67)	3.1 (0.87)	12.0 (2.73)
A6	1.8 (0.40)	2.6 (0.68)	26.7 (9.99)	0.6 (1.00)	7.4 (2.16)	4.3 (0.85)	4.6 (1.72)	3.4 (1.17)	12.4 (3.15)
A7	1.6 (0.43)	2.5 (0.60)	29.0 (7.28)	0.9 (1.10)	9.6 (3.24)	3.8 (1.16)	4.5 (1.13)	3.2 (1.19)	11.5 (2.90)
A8	1.6 (0.40)	2.4 (0.61)	25.4 (5.71)	0.9 (1.05)	8.4 (1.91)	3.6 (0.97)	4.3 (1.43)	3.2 (0.93)	11.2 (2.70)
A9	2.2 (0.44)	3.2 (0.69)	35.5 (6.12)	0.2 (0.92)	8.2 (1.47)	5.2 (1.00)	5.2 (1.79)	4.5 (1.06)	15.0 (3.18)

Table 23 Mean values roughness parameters (μm) for WPC composites made with different material ratios. Standard deviations are given in paranthesis (Gurau and Ayrilmis 2019).

The fluidity of polymers increased with increasing MFI value. This resulted in better penetrating the wood cell cavities, which improved the surface smoothness of WPC measured not only by *Ra* and *Rq* parameters, but also by the core roughness parameter *Rk* and the composed parameter *Rk+Rpk+Rvk* which gradually decreased from MFI 3.6 to MFI 25 (Table 23). It can be remarked that roughness parameters for A1, A2, and A3 compositions were very similar and indicated the smoothest WPC surfaces together with A7 and A8 compositions. ANOVA test ($p<0.05$) confirmed that there were insignificant differences between the roughness parameters of these three groups (A1, A2 and A3). Furthermore, the standard deviation values for some of the most representative roughness parameters: *Ra, Rq*, *Rk*, *Rk+Rpk+Rpk* were the smallest amongst all WPC combinations. From the compositions of A1, A2 and A3, A2 were compared with the other compositions, because the MFI of the polymer was the same, respectively MFI 12.

The surface roughness of A2 was similar with the roughness of A7 and A8 compositions for the majority of parameters. It was noticed that those compositions, A2, A7, and A8 had the same percentage of wood flour (50%) and no mineral filler. The compositions A2 and A8 differed slightly, by 0.4% less polymer in A8 compensated by the same more amount in additives (0.4% more antioxidant). Composition A7 had 3.6% more polymer than A2 compensated with 3.6% less additives (no Zinc borate, but 0.4% more antioxidant). These slight differences in composition did not change the surface roughness results as measured by *Ra*, *Rq* and *Rk*+*Rpk*+*Rvk.* but the core roughness *Rk* slightly decreased to 3.8 μm for A7 and 3.6 μm for A8 in comparison with 4.3 μm for A2, while peaks measured by *Rpk* increased to 4.5μm for A7 and 4.3 μm for A8 in comparison with 3.6 μm for A2. The parameter *Rsk* was 0.9 for both, A7 and A8 compositions, in comparison with -0.2 for A2. This shows again, a slight trend for the irregularities on the surface to display isolated peaks rather than valleys. It is not clear if these results can be attributed to the 0.4% addition of antioxidant in A7 and A8 compositions.

WPC surfaces having the highest wood flour percent (60%) had the highest roughness values (A9 followed by A4), but A5 having the smallest wood flour content (40%) wasn't the smoothest surface. It was noticed that not only the wood flour percentage matters, but the combination wood flour-mineral filler is also important. Thus, compositions having the highest wood flour- mineral content, contributed to the highest roughness values of WPC composites. The roughest surface, judged by *Ra, Rq, Rk, Rpk, Rk*+*Rpk*+*Rvk*, was measured for A9, which had 70% wood flour -mineral filler (60% wood flour, 10% mineral filler). It was followed by A4, A6, and A5 with 60% wood flour-mineral filler (60% wood flour, 0% mineral filler in A4, 50% wood flour and 10 % mineral filler in A6 and 40% wood flour plus 20% mineral filler in A5). As the amount of mineral filler was replaced with wood flour in the composition, the surface roughness of the WPCs increased. This was attributed to the lower particle size (0.15 mm) of mineral filler as compared to the wood flour (0.25 mm). A4 and A9 had identical flour composition (60%), but A9 had 10% more mineral filler and 4.5% less additives. Reducing polymer content and additives in favour of mineral filler has increased the surface roughness of WPC to an *Ra* of 2.2 μm in A9 compared to 1.9 μm in A4. The core roughness *Rk* increased in A9 to 5.2 μm compared to 4.4 μm in A4. Similarly, *Rk*+*Rpk*+*Rvk* and *Rt* increased to 15 μm, respectively 35.5 μm in A9 in comparison with 12.7 μm respectively 26.4 μm in A4.

A6 and A5 have similar polymer contents, which were 29% and 30%, respectively, but the A6 differentiated from A5 by the percentages of wood four and mineral filler. 10% more mineral filler complemented by 10% less wood flour in A5 led to a slightly smoother surface, which can be explained by the smaller size of mineral particles.

With regard to the polymer content, it can be seen that WPC compositions with the lowest polymer amount, A9 (22.5%), followed by A4 (28%), A6(29%), and A5 (30%) in favour of more wood flour and mineral filler, led to rougher surfaces in comparison with A7, for example, having the highest polymer percentage (43.7%). These differences were significant when analysed with ANOVA ($p<0.05$).

Conclusions

The smoothest WPC compositions corresponded to a participation of 50% wood flour, 0% mineral filler and around 40% polymer. By increasing the fluidity of polymers, respectively the MFI value from 3.6, to 12 and 25, the surface roughness decreased due to a better polymer penetration inside the wood cell cavities. At the extreme, the roughest surface was measured for A9 (60% wood flour plus 10% mineral filler), followed by A4, A6, and A5, where the wood flour percentage alone or in combination with mineral filler was the highest. The WPC compositions with lower polymer amount in favour of more wood flour and mineral filler, led to rougher surfaces. It was noticed that not only the wood flour percentage matters, but the combination wood flour-mineral filler was also important. As the amount of mineral filler was replaced with wood flour in the composition, the surface roughness of the WPCs increased. Reducing polymer content in favour of mineral filler, while keeping the same wood flour percentage has increased the surface roughness of WPC. For similar polymer and additives participation, more mineral filler complemented by less wood flour led to a slightly smoother surface. These results should be helpful to anticipate the effect on surface roughness of the percentage participation for each amount of the wood or mineral filler, polymer matrix, and additives in further development of WPC combinations.

2.5.3 Effect of particleboard density and core layer particle thickness on the surface roughness

Studies on the surface quality of particleboards underline the importance of measuring the surface roughness prior to coating or covering with overlays (Nemli et al. 2005, Hiziroglu and Suzuki 2007; Nemli et al. 2007, Rolleri and Roffael 2010). However, the lack of a dedicated standard metrology is a limitation in the evaluation of surface roughness of wood based panels, such as of particleboards (Gurau and Irle 2017). Previous researchers have based their surface roughness interpretation on general standards, which apply well for homogeneous materials, but it was shown they produce distortions and misinterpretation of surface data if applied to wood and wood based panels (chapter 1).

The aim of the following work (international joint research-Gurau et al. 2019b- to ***Drewno journal****-0.857 impact factor) was to investigate if the size of particle thicknesses (thin, normal, thick) in the core layer and different particleboard densities (650 and 500 kg/m^3) have an influence on particleboards surface roughness.*

Test specimens (50 mm x 50 mm) were cut from three-layered lab-made particleboard with a nominal thickness of 16 mm and target densities of 500 and 650 kg/m^3. Wood chips for core layer particle chipping (thin, normal, thick), face layer particles, core layer particles for reference sample, liquid urea-formaldehyde (UF) adhesive, and paraffin emulsion were obtained from commercial particleboard plant (Swiss Krono Sp. z o.o., Zary, Poland). Adhesive content was 11% (based on dry wood mass) in the face layers and 8% in the core layer. According to target density, the relation of face-to-core layer ratio were 35/65 (650 kg/m^3) and 46/54 (500 kg/m^3).

A total of 24 experimental particleboards with three panels for each of the eight panel types were made (details about manufacturing of panels in Gurau *et al*. in press). Core layer particle thickness (thin, normal, thick) and panel density (500 and 650 kg/m^3) were varied. Particleboards with the core layer particle “Reference” were made to benchmark the results with lab-made particles in the core layer. From each panel three specimens were cut, the total number of test specimens for each core layer particle type and target density was nine. Prior to testing, specimens were conditioned in a climatic chamber at 20 °C and 65% relative humidity.

For measuring and evaluation of surface data, the surface roughness methodology proposed in section 1.3 was used in this research. The specimens were scanned on tracing lengths of 40 mm. Six profiles were recorded for each specimen, 3 on the face surface and 3 on the back surface distanced by 15 mm from each other, so that a total of 54 profiles were available for further evaluation of parameters for each core layer particle type and target density. A large number of roughness prameters was calculated as in previous sections (2.5.1). To visualize the effect of core particle size and particleboard density, individual profiles were computed in MathCAD Professional 2000. For statistical analysis the Duncan multiple range test were applied. The level of significance was chosen as $p < 0.05$.

The mean values of the roughness and waviness parameters together with their standard deviation in brackets are presented in Table 24. The letter symbols were determined by using the Duncan’s multiple range test comparing the mean values of all groups. Groups with the same letters in rows (presented separately for the two particleboard densities) can indicate that there is no statistical difference ($p<0.05$) between the samples.

	Particleboard density: 500 kg/m^3				Particleboard density: 650 kg/m^3			
	Reference	Thin	Normal	Thick	Reference	Thin	Normal	Thick
Ra	20.4 (3.7) a	19.0 (2.8) b	19.4 (3.1) ab	18.7 (3.0) b	13.8 (1.9) a	13.7 (1.9) a	13.3 (1.2) a	14.0 (1.7) a
Rq	32.1 (6.3) a	29.6 (5.0) b	30.1 (5.1) b	29.0 (5.0) b	21.9 (3.4) a	21.5 (3.3) a	20.7 (2.3) a	21.6 (3.0) a
Rz	164.7 (29.3) a	154.9 (23.4) a	156.4 (24.5) a	155.6 (20.8) a	122.3 (17.0) a	121.7 (16.7) a	116.7 (13.0) a	121.8 (13.5) a
Rt	228.9 (55.9) a	218.4 (43.8) a	219.7 (52.5) a	219.3 (42.7) a	171.5 (33.7) a	175.8 (32.2) a	161.5 (27.4) a	174.2 (33.1) a
Rv	128.2 (24.5) a	118.6 (19.3) b	119.7 (18.1) b	118.6 (18.2) b	94.0 (14.5) a	91.9 (15.7) a	88.5 (12.2) a	92.2 (12.2) a
Rsk	-2.5 (0.4) a	-2.4 (0.3) a	-2.3 (0.4) a	-2.3 (0.5) a	-2.5 (0.5) a	-2.4 (0.6) a	-2.4 (0.4) a	-2.4 (0.4) a
Rk	41.0 (7.1) a	39.5 (5.0) a	40.5 (5.4) a	39.3 (5.8) a	29.2 (4.2) a	30.5 (3.8) ab	29.6 (2.7) a	31.3 (3.4) b
Rpk	13.8 (7.1) a	15.6 (8.8) a	15.4 (10.8) a	15.9 (7.9) a	11.0 (5.4) a	12.9 (6.4) a	11.3 (4.7) a	11.7 (3.7) a
Rvk	64.2 (13.6) a	58.6 (11.8) b	59.5 (10.9) b	56.8 (10.7) b	44.6 (7.6) a	43.3 (8.3) a	41.9 (6.2) a	43.8 (7.2) a
Rk+ Rpk+ Rvk	118.9 (21.8) a	113.7 (20.5) a	115.5 (21.4) a	112.0 (17.2) a	84.8 (12.2) a	86.6 (12.1) a	82.8 (8.9) a	86.8 (9.7) a
A1	462.5 (331.4) a	551.8 (359.8) a	518.4 (415.2) a	571.3 (316.8) a	407.8 (237.6) a	494.9 (320.7) a	430.9 (208.1) a	447.0 (167.3) a
A2	7504 (2053) a	6571 (1704) b	6682 (1553) b	6341 (1693) b	4697 (1107) b	4280 (1033) b	4217 (811) b	4347 (1062) ab
A1+ A2	7966 (2152) a	7123 (1824) b	7200 (1696) b	6912 (1743) b	5105 (1140) a	4775 (1006) ab	4648 (814) b	4794 (1056) ab
RSm	701.4 (91.4) a	700.5 (97.4) a	720.0 (96.0)	706.5 (87.5)	641.2	656.5 (83.8)	662.2 (72.6)	654.5 (70.6)

			a	a	(69.1) a	a	a	a
Wa	14.3 (3.34) a	13.6 (3.6) a	14.7 (4.3) a	13.9 (3.2) a	10.2 (2.0) ac	10.2 (2.0) ac	10.8 (2.3) bc	11.3 (2.3) b
Wq	17.2 (3.8) a	16.7 (4.7) a	17.9 (6.1) a	17.1 (3.8) a	12.7 (2.5) ac	12.7 (2.4) ac	13.2 (2.6) bc	14.1 (2.7) b

The same letters in each column show statistical differences ($p < 0.05$) among the roughness parameters.

Table 24 The surface roughness parameters and waviness parameters for particleboards (Gurau *et al.* in press).

a)Analysis of roughness and waviness parameters for particleboard groups with density 500 kg/m^3

From Table 24 it can be seen that the highest mean values of *Ra*, occurred for Reference particleboard and this result is statistically relevant. However, no significant differences were found for the lab-made particleboards (Thin, Normal, Thick). *Rv* is a component of *Rz* and it measures the means of the deepest valleys of the profiles, calculated from five sampling lengths of each profile. *Rv* for Reference group of panels was app. 8% higher than for the lab-made types of particleboards. Also, higher value of standard deviation for the commercial particleboard shows that these particleboards were less homogeneous in comparison with the ones made in laboratory. All skewness values, *Rsk*, were negative, which indicates the prevalence of deeper valleys in the profiles. This means that profile gaps extending below the core datapoints, probably anatomical valleys, gaps between chips, were higher in magnitude than the size of peaks (raised fibres) for all groups tested.

For particleboards with density of 500 kg/m^3, the mean values of *Rk* did not show any difference between the groups (Table 24). As for the majority of parameters, the standard deviation of *Rk* calculated for Reference group was higher, indicating a lower homogeneity of the commercial particleboards in comparison with the lab-made ones. *Rk*+*Rpk*+*Rvk* is a cumulative parameter containing information about the size of the core roughness, plus the isolated peaks, plus the isolated valleys. The order of magnitude, judged by the mean values, starts with Reference, followed by Normal, Thin and Thick. Apparently, according to this cumulative parameter, the particleboards with the roughest chip size gave the smoothest surfaces. However, the differences between the groups were negligible and statistically insignificant (Table 24).

b)Analysis of roughness and waviness parameters for particleboard groups with density 650 kg/m^3

From Table 24 it can be seen that values for all roughness and waviness parameters were smaller for the denser particleboards, which means that a higher density of the particleboards improves their surface quality. The same trend was found in the values of standard deviation, which indicated that by increasing the particleboard density, its surface became more homogeneous.The higher density particleboards do not show, in general, significant differences between the surface quality of different groups. Exception made *Rk*, which showed a slightly higher values for Thick category particleboards as compared with the other groups. Also, the surface waviness (*Wa*, *Wq*) was higher for the particleboards with coarser core.

Conclusions

Investigating the surface quality of particleboards of different density and varied particle thickness in the core layer,– with some exceptions (Rk, Wa, Wq) forparticleboards with a target density of 650 kg/m^3 – no *significant effect of particle thickness on the surface quality was to be found. For particleboards with the higher target density, predominantly no differences in quality between the panels with lab-made particles and industrial-made particles were found. In the case of low-density particleboards, some of the roughness parameters of the panels with industrial-made particles in the core layer were found to be significantly higher than that of the panels with lab-made particlesin the core layer. Comparing the particleboards' surface roughness and waviness parameters at the two density levels, the surface quality of the low-density particleboards was found to be below that of the conventional-density particleboards.*

The research results from chapter 2 contain several applications to determining the surface roughness for a diverse types of materials: simple wood, to determine the differences in roughness between earlywood and latewood, wood treated by various thermally treatments, wood surface modified by plasma, wood surface engraved by the laser, wood based composites (MDF and particleboards) and WPC (wood plastic composites). **In all those cases, it was used the metrology method from chapter 1, which it has been demonstrated is more reliable for wood and most probably for any composite panel based on wood ingredients.** *Therefore, **further research is unlimited** and can be extended for any wood species and treatment variable, for any wood based composite, for any wood modification process, with the purpose of surface quality optimisation*. Chapter 2 was the result of joint research in several teams, national and international.

The results of chapter 2 were disseminated in 14 publications, among which:

- 9 papers in ISI Web of knowledge journals.The most cited in ISI web of Science was:
  - Wallenhorst L., **Gurau L**. et al.2018. UV-blocking properties of Zn/ZnO coatings on wood deposited by cold plasma spraying at atmospheric pressure. *Applied Surface Science* 434: 1183–1192. ISSN: 0169-4332 (**5.155 impact factor, 11 citations (in ISI Web of Science)**.
  - **Gurau** et al. 2019. The surface roughness of heat treated and untreated beech (Fagus sylvatica l.) wood after sanding. *BioResources* 14(2): 4512-4531.
  - **Gurau** et al. 2017a. Surface quality of planed beech wood (Fagus sylvatica L) thermally treated for different durations of time. *BioResources* 12(2): 4283-4301
  - **Gurau** et al.2017c. Effect of species and grinding disc distance on the surface roughness parameters of medium-density fiberboard. *European Journal of Wood and Wood Products* 75(3), 335-346.
- 1 Journal paper in other international databases
- 4 International conference papers

  To which can be added:
- ***Contribution to one doctoral study on thermally treated wood by Hacibektasoglu Murat.*** The author of this habilitation is currently **member of the advisory board** for this PhD student. **Another contribution** was to an ongoing **PhD research (Adrian Petru- co-author) on the laser effects on wood,** where the author of this habilitation thesis acts as advisor regarding the surface quality.

3. CHAPTER 3.THE QUALITY OF SECONDARY WOOD RESOURCE AND VALUE-ADDED WOOD BASED PANELS

The following research was performed by the author of this habilitation thesis together with the other members of a **research project granted by the CNCSIS (The National Council of Scientific Research in the Higher Education) type A 450/2006**: "***Eco-conception and eco-technology for furniture and other wood made products obtained from natural secondary resources***" (2006-2008). With an official duration of two years, but with **research extended till 2016**, the project was meant to explore the potential of secondary wood resource, like wood branches, wood from youung trees or juvenile wood, in order to understand its properties (structure, microscopy, physical and mechanical properties) and find possible applications. New type of wood panels with increased aestetics were created, made of crosscut wood branches or from crosscut thin logs, in order to increase the value of this, otherwise, neglected resource. The research on the characteristics and properties of the raw material was complemented with research on the physical and mechanical properties of those panels, as well as with investigations regarding the surface quality of those panels after sanding.

3.1 Research on the quality of secondary wood resource

The search for alternatives to stem wood in the manufacture of new wood based materials represents one of the priorities of the wood industry due to a decreasing level of raw material supply and an increased responsiveness to environmental pressures. Branch wood represents 25-32% of the total wood volume (Hilton, 2001) and is a secondary resource with a potential for high value applications that has been insufficiently explored. Increasing the added value of wood branches means finding alternative uses for it other than as fire wood or as particles for wood based panels.

From the knowledge in the literature it can be concluded that branches have narrower annual rings (Fegel 1941, Tsoumis 1968, Bowyer et al. 2003), smaller cell and lumen diameter (Fegel 1941, Brunden 1964, Bannan 1965, Tsoumis 1968, Taylor 1977, Hakkila 1989, Bowyer et al. 2003), smaller cell wall thickness (Hakkila 1989) and smaller cell length (Fegel 1941, Bannan 1965, Manwiller 1974, Taylor, 1977, Hakkila 1989, Vurdu and Bensend 1979) than stem wood. The length of branch wood cells increases with branch diameter and this is probably because small branches contain proportionally more juvenile wood (Hakkila 1989); the fiber length increases from the pith to the bark with a greater percent than in stem wood (Vurdu and Bensend 1979). Branch wood is generally characterised by a higher percentage as volume of fibers and longitudinal parenchyma with hardwoods (Hakkila 1989, Vurdu and Bensend 1980) and by an increased number of resin canals with softwoods (Fegel 1941, Tsoumis 1968, Hakkila 1989, Bowyer et al. 2003). Rays are more numerous (Tsoumis 1968, Bowyer et al. 2003) and vessels are smaller and in a greater number (Tsoumis 1968, Vurdu and Bensend 1980) in branch wood than in stem wood. Branch wood is generally higher in density than stem wood (Fegel 1941, Kollmann and Côté 1968, Tsoumis 1968). According to some researchers, the difference between stem wood and branch wood densities appears to vary among species rather unpredictably (Manwiller, 1979, Hakkila

1989). Brunden (1964) and Philips et al. (1976) found branches of softwoods 5-20% lower in density than stem wood.

Although the literature contains a number of studies regarding the microscopic and macroscopic structure of branch wood compared with stem wood, there are almost no reports regarding the mechanical properties of branch wood. From a literature review on branch wood properties of Gurau et al. (2006b) it appears that normal branch wood 50-100 mm in diameter has similar compression strength parallel to the grain and similar shock resistance as normal stem wood, but greater plasticity (Vanin,1953), while no studies were found for other mechanical properties.

As reaction wood behaves quite differently from normal wood due to its anatomical different structure (Kucera and Philipson 1977), and as its presence especially in softwood branches is the rule rather than the exception (Tsoumis 1968, Hakkila 1989), it decisively affects many important properties of branch wood. Generally, strength increases with increasing density, but this relationship does not apply to reaction wood (Tsoumis, 1968).The modulus of elasticity and tensile strength of compression wood are lower than of normal wood (Tsoumis 1968, Hakkila 1989), but the compression parallel to the grain and bending strengths are higher (Hakkila 1989). With regard to branch wood of hardwoods, in an extensive survey of tension wood on a large number of temperate and tropical species, Höster and Liese (1966) found that only 50% of the species had tension wood. Tension wood has lower compressive and bending strengths than normal wood (Tsoumis 1968, Hakkila 1989, Bowyer et al. 2003). In the green condition, tension wood is particularly low in tensile strength, but when air dried its tensile strength is higher than that of the normal wood (Kollmann and Côté 1968).

If stem wood is an excellent material for manufacturing solid wood panels, branch wood may be used in new added value products as an alternative to stem wood, providing its mechanical strengths are known and understood. Insufficient data in the literature makes any comparison of branch wood with stem wood difficult, unless mechanical tests are specially conducted and SEM micrographs are examined.

An important contribution of the author on this subject was a **paper in Wood and Fibre Journal** (in ISI Web of Knowledge) and **10 citations in ISI Web of Knowledge- Gurau *et al*. (2008a),** which *contains a comparison between the compression strength parallel to the grain, the bending strength MOR and modulus of elasticity MOE of branch wood and stem wood to understand the extent to which this secondary resource, wood branches, differs from stem wood.*

Specimens of stem wood available as sawn timber and branch wood of beech (*Fagus sylvatica* L.), maple (*Acer* spp) and Scots pine (*Pinus sylvestris* L.) were cut for testing in compression parallel to the grain (ISO 3787:1976) and prepared as described in detail in Gurau et al. (2008a).. The stem specimens were mature wood for maple and beech and heartwood for Scots pine. Specimens of maple and Scots pine were cut (BS 373: 1957) –details of specimen preparation in Gurau et al. (2008a). The moisture content was determined after testing by the oven-dry method and a mean value for each set of specimens was recorded. A reference specimen density was calculated for a nominal 12% moisture content in accordance with ISO 3131 (1975).

The overall diameter of the raw material of the branch wood specimens was about 60 mm for the Scots pine (age 18), 90 mm for the beech (age 65) and 100-120 mm for the maple (age not measured). With such relatively small diameters it was impossible to comply with the requirements of ISO 3787 (1976) and BS 373 (1957), whereby the growth rings should be parallel with one face of the specimen. The Scots pine and beech specimens contained the pith more or less centrally, while the maple contained material from near the pith on one side of the specimens. The annual ring orientation in the stem wood specimens did comply with the standards' requirements.

The ultimate compressive strength was determined according to ISO 3787 (1976), while the MOE and MOR of each bending specimen were calculated by algorithms developed to comply with BS 373, then mean values were calculated for each combination of species, tree location: branch wood and stem wood.

At the moment of testing the specimens had a range of moisture contents, so to allow comparison, all the test results were recalculated for 12% MC with formulae contained in ISO 3787 (1976) for compression strength, ISO 3349 (1975) for MOE and ISO 313 (1975) for MOR.

To better understand the behaviour of branch wood and stem wood specimens subjected to mechanical testing at a microscopic level, specimens were prepared of beech, maple and Scots pine- details in Gurau et al.(2008a) They were examined in a Cambridge 150 Scanning Electron Microscope using secondary electron imaging. Images at 50, 75, 153 and 500 magnifications of branch wood and stem wood microscopy were captured with I-Scan digital image equipment and compared.

a.Compression strength

Species and wood type	Moisture content at testing (%)	Density uncorrected (kg/m^3)	Density corrected for 12% MC (kg/m^3)	Compression strength uncorrected (MPa)	Compression strength corrected for 12% MC (MPa)
Beech					
stem	15.4	678	669 (2.1)	43.7	49.6 (13.3)
branch	33.8	856	805 (2.9)	28.7	49.3 (13.1)
Maple					
stem	11.8	597	598 (2.2)	55.6	55.2 (8.7)
branch	16.9	692	678 (0.8)	43.1	51.5 (11.8)
Scots pine					
stem	15.3	596	586 (10.2)	50	56.6 (20.8)
branch	20.9	518	492 (3.9)	23.4	31.8 (9.3)

Table 25 Experimental results for compression strength parallel to grain. Coefficients of variation (%) in paranthesis (Gurau et al. 2008a).

The mean values obtained by test and contained in Table 25 were compared with equivalent values for stem wood reported in the literature and it was observed that the mechanical properties of stem wood obtained experimentally were similar to findings in the literature. Compression stength for beech stem was 49.6 MPa similar to result of Filipovici (1965) 46.5 MPa; for maple stem was 55.2 MPa, which falls in between the values obtained by Lavers (1983) 48.2 MPa and Filipovici (1965) 56.8 MPa and for Scots pine was 56.6 MPa, which is close to the value obtained by Filipovici (1965) 53.9MPa. Note that no reference values for branch wood were found in the literature.

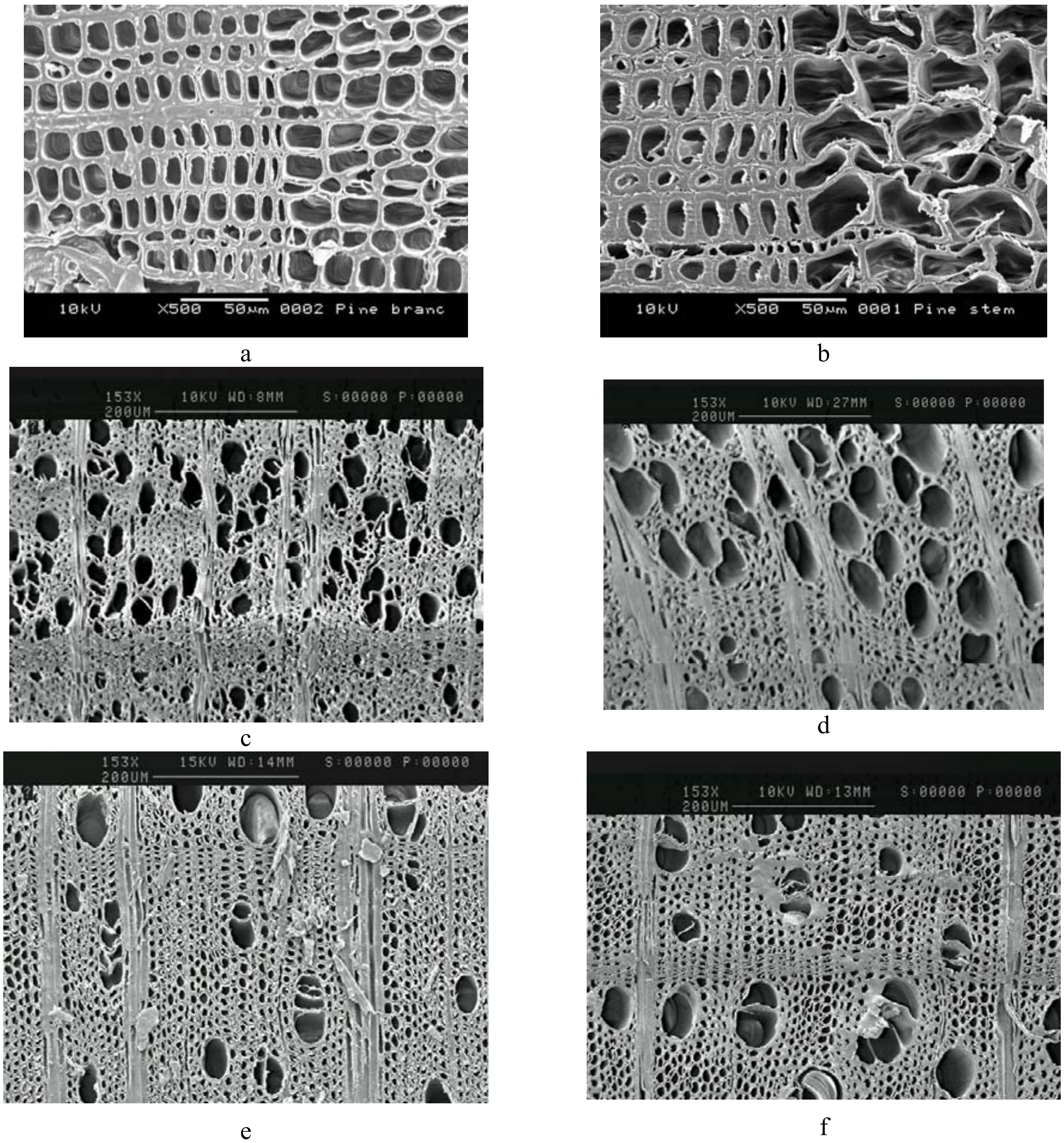


Figure 67 Transverse SEM micrographs: a,b-Scots pine (magnification 500×), branch wood, respectively stem wood; c,d- Beech (magnification 153×), branch wood, respectively stem wood; e,f- Maple (magnification 153×), branch wood, respectively stem wood; (Gurau et al. 2008a).

Micrographs of hardwoods in Figure 67c,d,e,f show that branch wood contains a greater number of medullary rays than stem wood, which according to Hakkila (1989) citing Koch (1972), can lower compression strength parallel to the grain. As can be seen in Table 25 although the density of branch wood in beech and maple was higher than that of stem wood, the compression strength parallel to the grain was slightly lower for maple and was about the same for beech. These results support those of Vanin (1953).

All Scots pine branch wood specimens contained compression wood and most probably juvenile wood too as the specimens contained the pith and the tissue surrounding it. The juvenile wood is characterised by large microfibril angles and shorter tracheid lengths than mature wood (Zobel and Sprague 1998). Perhaps as a consequence, compression strength of Scots pine branch wood was only 56% of the stem wood strength. This result is similar to findings of Pazdrowski and Splawa-Neyman (2003) who tested juvenile wood in Norway spruce and found its compression strength lower than that of stem wood. With regard to the branch wood specimens, maple was slightly stronger than beech, but about 60% stronger than Scots pine.

Within the species, although the compression strength increased with an increase in density for stem wood, it had no specific trend for branch wood. As Vanin (1953) noted, branch wood appears to have a greater plasticity than stem wood . This behaviour was observed during testing in that branch wood specimens bent under compression rather than failing in “shearing rupture” (according to ASTM, 1997) as the stem specimens did. The trend for bending may also have been a consequence of the higher moisture content of the branch wood specimens.

b.Static bending strength

The MOE of stem wood obtained experimentally showed similar results as in the literature for Scots pine, 11,708 MPa compared to 11,760 MPa found by Filipovici (1965), while for maple it was higher, 10,764 MPa compared to 9,400 MPa found by Lavers (1983).

The MOE of maple branch wood was about 85% of the MOE of maple stem wood (tables in Gurau et al 2008a). As stated before, branch wood contains shorter fibres and a higher proportion of vessels and longitudinal parenchyma cells, which are characterized by thinner walls, than stem wood. These differences are likely to cause branch wood to be less stiff in bending than stem wood. In compensation, maple branch wood frequently contains tension wood, which increases tensile strength of areas subjected to tensile stresses. This may explain the more extended shear failure of maple branch wood than stem wood, corresponding to a higher resistance to local tensile stresses. The type of failure for both maple branch and stem specimens was as “simple tension” as described by ASTM, 1997.

In contrast, the MOE of Scots pine branch wood was only about 28% of the stem wood. The branch wood specimens contained compression wood on the side in tension as well as juvenile wood, which caused a failure pattern characterized in ASTM (1997) as “brash failure”. This result supports the statement of Hakkila (1989) that compression wood decreases the MOE and breaks as brash-failure. The tesults for Scots pine branch wood seem similar to those of Pearson (1988) as cited by Larson et al. (2001), who found that the MOE of juvenile Scots pine was only 37% of that of mature wood.

The higher bending strength of Scots pine stem wood may be associated with the type of failure characterized by ASTM as “splintering”.

The MOE of maple branch wood was 2.8 times higher than of Scots pine branch wood. As with compression strength, no correlation was observed between density and MOE for branch wood. This observation is similar to that of Adamopoulos et al. (2007) who attributed the lower strength of the juvenile wood of Black locust compared to mature wood of the same species, to its anatomical properties rather than specimen density.

The MOR obtained experimentally for stem specimens was very close to the values found in the literature: 106.2 MPa for maple was in between the values obtained by Lavers (1983) 99 MPa and Filipovici (1965) 109.7 MPa; Scots pine with 99 MPa experimental value was similar to 98 MPa found by Filipovici (1965).

The MOR of maple branch wood was around 10% higher than that of maple stem wood which may be linked to the higher density of the branch wood. In contrast, the MOR of Scots pine branch wood was only around 55% of that of Scots pine stem wood, which in this case may be linked with the higher density of the stem wood. The orientation of the test specimen, with the compression wood at the tension edge and the pith at the compression edge, may have been critical in determining the results of the test. The results seem similar to those of Pearson (1988) as cited by Larson et al. (2001) who found that the MOR for Scots pine juvenile wood was 52% of that of mature wood.

The MOR of maple branch wood was twice that of Scots pine and for both maple branch and stem wood, was directly linked with specimen density.

There was greater plasticity in bending of branch wood than stem wood for both species, as measured by the maximum deflection. The maximum deflection of maple branch wood was 1.86 times that of stem wood, while for Scots pine it was 2.76 times higher. It is not clear to what extent this is due to differences between branch and stem wood, rather than due to the higher moisture content at test of the branch wood.

c.Microscopic appearance of branch and stem wood

Micrographs of transversal and longitudinal sections showed that all cell diameters, wall thicknesses and lumen diameters of fibres and vessels (hardwoods) or tracheids (Scots pine) were smaller in branch wood than in stem wood. This is in agreement with findings in the literature presented before.Vessels and medullary rays are more numerous in the branch wood than the stem wood of maple and beech. Figure 67 a,b,c,d,e,f are comparable images of branch wood and stem wood for Scots pine, beech and maple.

The density of the branch wood of maple and beech was higher than that of their stem wood, a result which appears to be in agreement with the findings of Fegel (1941) and Kollmann and Côté (1968). This is probably due to the smaller cell lumina in branch wood than stem wood. However, all branch specimens contained the pith.For Scots pine, the branch wood density was substantially lower than the stem wood density.

Branches normally contain juvenile wood around the pith. In softwoods the juvenile wood has different physical properties than mature wood, but the differences are less pronounced in hardwoods (Zobel and Sprague 1998, Bao et al. 2001). The lowest density wood in Scots pine is produced near the pith of the tree, where the growth rings are usually wide with relatively small proportion of latewood, while in broad leaved trees, the highest density wood is usually produced near the pith (Kollmann and Côté 1968). Orsler et al. (1972) found the density of juvenile wood significantly lower in Scots pine than that of its mature wood. It should not be neglected that the proportion of juvenile wood in a tree as in its branches depends on the age of the tree and of the branches respectively. Zobel and Sprague (1998) found that 15 year old loblolly pines have about 85% of their volume juvenile wood, while 40 year old trees have only 19%. Since the age of the tested Scots pine branches was app. 18 years, its proportion of juvenile wood may have become important and therefore decreased branch density.

Conclusions

The MOE and compression strength of maple branch wood were slightly lower than those of the stem wood,the maple MOR was slightly higher for branch wood and beech compression strength was similar for branch and stem wood. However, the MOR and compression strength of Scots pine branch wood were approximately half those of stem wood, while the MOE was around a third. Maple branch wood had similar compression strength as beech branch wood, but compared to Scots pine branch wood was 60% stronger in compression, had a double MOR and almost triple MOE.

The poor performance in mechanical tests of Scots pine branch wood compared with maple and beech, may be attributed to the presence in Scots pine of compression wood and juvenile wood. Branch wood had a higher density than corresponding stem wood, except for Scots pine. No correlation was observed between branch density and mechanical strengths except for MOR, which increased with density.

For all species and tests, branch wood exhibited greater plasticity in its behaviour than stem wood but this may be attributed at least in part to the higher moisture content of the branch wood.

Other ISI journal papers on the physical and mechanical properties of branch wood and wood from thin logs were published in **Gurau et al. (2009c)** and **Olarescu et al.(2016).** The first paper, compared the compression strength parallel to the grain of branch wood of maple (*Acer spp*), beech (*Fagus sylvatica L.*) and Scots pine (*Pinus sylvestris L.*) with compression strength of stem wood. Results were interpreted on micrographs viewed on SEM and Laboval compound microscope. Excepting Scots pine, who's strength was only a half, maple and beech branch wood had similar strengths to stem wood of the same species, which makes them alternative raw materials. Maple and beech branches had higher density than stem wood, probably due to the smaller diameter and lumen diameter of fibers and vessels, while density of branch Scots pine was lower, perhaps due to the occurence of pith and the juvenile tissue around it.

The second paper, investigated moisture – related dimensional and volumetric changes of thin sessile oak trees (*Quercus petraea* spp. (Matt.) Liebl) provided from thinning, MOR, MOE and compression parallel to grain. The values of the mechanical properties (MOE, MOR and compression parallel with the grain) of wood from thin trees of *Quercus petraea* Liebl. were very close to the values for mature trees.

A comparative study of microscopic characteristics of juvenile wood of beech (*Fagus sylvatica* L.) and maple (*Acer platanoides* L.) obtained from young trunks and mature wood from mature trees of the same species was provided with contribution of the author of this habilitation thesis, in **Dumitrascu et al.**

(2010). The pores of the juvenile wood were less numerous in beech and more numerous in maple than those in the mature wood and contained helical thickenings. Also, it was observed that wood from juvenile trunks presents relatively narrower rays compared to the mature wood and this was more obvious in maple.

The properties of the secondary wood resource (microscopic, macroscopic, physical and mechanical properties) were intensively researched and were disseminated in 18 publications (2 books, 3 papers in ISI journals, 5 papers in international data bases, 8 papers in international conferences). The author contributed as "first author" or as "correspondent author" in the majority of them. However, *only a representative paper was extensively presented in this section*. Since the subject of research was not directly linked to the title of this habilitation thesis, the other research papers on this topic were not included.

3.2 Research on the quality of value-added wood based panels from secondary wood resource

The research on the properties of secondary wood resource was extended from the raw material to the properties of a new type of panels with crosscut grain. An original alternative is suggested to increase the added value of wood branches by manufacturing panels with an enhanced design as in Figure 68.

a b

Figure 68 Panels with crosscut grain made of branch wood and their possible use in small furniture objects (Gurau et al. 2008b)

The following studies focussed on the mechanical properties of this new type of panels, as well as on the surface quality of those panels after sanding, in order to explore their potential of being used in furniture products.

3.2.1 Bending strength and stiffness of panels made of crosscut branch wood

The following study (Gurau et al.2008b) *suggests a way of recovering one of the secondary wood resources by giving it a new destination in panels made of crosscut branches. The panels are tested in bending and their MOE and MOR are compared with reference values from literature of other composite panels.*

Branch panel structures with an original grain design were proposed. Compared to reconstituted solid wood panels, which have the grain parallel to the panel axis, the proposed new structures show the end grain on panel faces, displaying an attractive design (Figure 69).

Branch wood is characterised by the frequent occurrence of reaction wood: compression wood in softwoods and tension wood in hardwoods. This increases dimensional instability in a direction parallel to the grain, especially with compression wood, where the linear shrinkage coefficient can reach 6 – 7 %, compared with normal wood at only 0.1 – 0.2 %, while swelling and shrinkage are lower across the grain (tangential and radial) than normal wood (Kollmann and Côté, 1968). This behaviour may turn into an advantage if branch wood panels are manufactured by gluing crosscut sections of branches together.

The new branch wood structures have a mainly decorative purpose as small furniture parts, rather than a use as structural members. The end uses for such panels may be small table and chair tops, decorative panelling, small doors, drawer fronts and other similar small sized furniture parts.

Although the destination of such panels does not subject them to substantial bending stresses, it was considered useful, given the new grain structure, to test the panels and have comparative results with other composite boards for the modulus of elasticity (MOE) and the modulus of rupture (MOR).

The choice of species for this research was based on their easy accessibility, low acquisition price, range of dimensions suitable for processing (diameters greater than 60 mm and lengths over 400 mm), as well as their attractive appearance after processing. Other softwood and hardwood species could be also considered, but this research was based on one softwood and one hardwood species: Plane maple (*Acer platanoides*) and Scots pine (*Pinus sylvestris*). Branch wood was obtained in various lengths with diameters ranging between 6-10 cm. The initial moisture was 13% for maple and 27% for pine. The branches were squared into prisms of 30 x 30 mm section, by successive operations of planing and thicknessing and were further crosscut into slices 20 mm thick.

The crosscut slices were then glued edge to edge with polyvinyl acetate so that one panel of each species was obtained measuring 510 x 270 x 20 mm. For clamping, screw clamps were used, acting on the sides and on the top. After a clamping for 4 days, the panels were sanded and then stored for 7 days.

a

b

Figure 69 Branch panels after sanding: a- maple; b- pine (Gurau et al. 2008b)

EN 13353 (2003) contains recommendations for testing solid wood panels. For non-structural applications it refers to EN 310 as the standard for determining the MOE and MOR in three point bending. The modulus of elasticity in bending and the bending strength were determined by applying the load to the centre of the test piece supported at two points. The testing apparatus had two parallel adjustable cylindrical roller-bearing supports of 15 mm diameter set at a distance of 400 mm and a central cylindrical loading head of 30 mm diameter placed equidistant from the supports. The load was applied at a constant rate of 12 mm/min.

Tests were conducted at Forest Products Research Centre in High Wycombe, UK, on a screw driven Instron 4411 universal testing machine fitted with ±5kN load cell, as described in Gurau et al. (2008b). The data was processed in MathCad Professional 2000 according to the procedure in EN 310 (1993). The arithmetic mean of the bending strengths and moduli of elasticity for each group of test pieces taken from the same board were calculated.

EN 310 recommends conditioning the panels before testing to a constant mass in a relative humidity of 65±5% and a temperature of 20±2°C. However, panels tested were conditioned only for 11 days and their moisture at the moment of testing reached 13 % for maple and 22.9% for pine. Solid wood reaches equilibrium moisture content at about 12% when kept at the relative humidity and temperature above and this represents the reference wood moisture value (ISO 3349). To allow comparison, all test results were recalculated for 12% moisture content with formulae contained in ISO 3349 (1975) for MOE and ISO 313 (1975) for MOR.

Data obtained experimentally was compared with values of MOE and MOR of standard composite panels having similar thickness, determined according to EN 310 (1993) and contained in the literature (Table 26).

For dry indoor environment (including furniture)					
Material thickness (mm)	***MDF (19-30)***	***Chipboard (13-20; 20-25)***	***OSB (18-25)***	***Blockboard (<20)***	***Softwood panels (≤24)***
Source	EN 622	EN 312	EN 300	Schniewind	Schniewind
MOE (MPa)	2100	1500-1600	1400-3000	4500-6500	6000-8000
Middle of the range	2100	1550	2200	5500	7000
MOR (MPa)	18	11.5-13	8.00-16	20	50-70
Middle of the range	18	12.25	12	20	60

Table 26 MOE and MOR reference values from the literature (from related standards and Schniewind *et al* (1989) as cited by Barbu ,1999)

The mean values of modulus of elasticity and modulus of rupture obtained experimentally for both maple and pine branch wood panels are given in Table 27. The MOE and MOR of the 20 mm thick panels were compared with reference values (middle of the range) of other composite panels of similar thickness found in related standards and literature and detailed in Table 26.

From Table 27 it can be observed that the MOE of the maple branch wood panel was double than that of the pine branch wood panel. However, both types of panel were less stiff than all composite boards.

Chipboard is the material with the lowest MOE of the composite boards presented in the analysis. The MOE of the pine panel was app.25% of the MOE of chipboard and the MOE of maple was app. 50%.

Material/ Test	Pine branch panel	Maple branch panel	Chipboard	OSB	MDF	Blockboard	Softwood panel
MOE (MPa)	398	799.4	1550	2200	2100	5500	7000
MOR (MPa)	3.6	6.8	12.25	12	18	20	60

Table 27 Mean values of MOE, MOR of pine and maple branch panels determined experimentally compared with middle of the range values of other composite panels from Table 26 (Gurau et al. 2008b)

The MOR of the maple branch panels was 1.88 times higher than the MOR of the pine panels, in spite of the latter's slightly higher density, 704 kg/m^3 pine panel, compared to 640 kg/m^3 maple panel. The higher moisture content of the pine panel during testing may have contributed to this result.

The MOR of both branch wood panels was the lowest among the composite boards. This result is to be expected given the non-conventional grain orientation of the wood slices in branch wood panels, with the length perpendicular to the panel surface.. The particular grain orientation of the branch panels means the development of tensile stresses and splits perpendicular to the grain, an orientation with the minimum wood strength.

Their destination as small furniture parts may be suitable when branch wood panels are not subjected to high bending stresses.

Conclusions

Maple branch wood panels with crosscut grain had an MOE double than that of pine branch wood panels, and an MOR 1.88 times greater.

Both types of branch wood panels had lower stiffness and bending strength than other composite boards: chipboard, OSB, MDF, blockboard and softwood panels. This result is mainly attributed to the grain orientation, which was perpendicular to the panel surface rather than to the material.

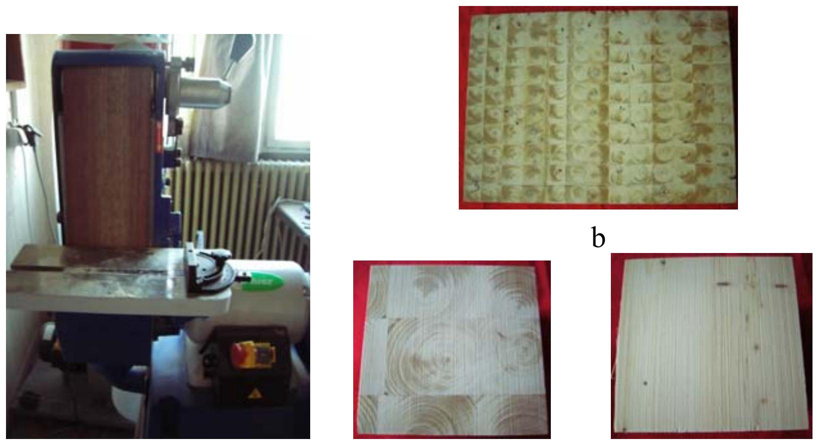
The use of such branch wood panels may be as small decorative furniture parts, which should avoid high bending stresses, unless some panel reinforcement is considered.

3.2.2 Surface quality evaluation of sanded fir branch panels with longitudinal and crosscut grain

The following study of **Gurau et al.(2009b)** published in **ISI Proceedings**, *examines the effect of the grit size on the processing roughness of fir branch panels with crosscut grain. For quality evaluation, it was used the metrology metodology from chapter 1.*

Two category of panels were prepared out of fir branch wood and two replicates for each panel type: with crosscut grain and with longitudinal grain.

The branch panels with crosscut grain (Figure 70b) represent a new unconventional type of eco-panels with highly aestetical appearance used for furniture (Cionca *et al*, 2006). The branches with over 60 mm in diameter were firstly cut into prisms of 30x30 (mm) that were glued with polyvinil acetate to form panels with longitudinal grain (Figure 70b). To obtain the other type of panels, strips 20 mm wide were crosscut from the longitudinal grain panel and re-glued on edges to form 500x300 (mm) branch panels with crosscut grain appearance (Figure 70b,c). Such panels differ from conventional reconstituted panels with longitudinal appearance because the grain is perpendicular to the surface and the abrasive grits penetrate along the grain rather than across.



b

a c d

Figure 70 a- Vertical sander SDB-612 CSA/UL; b- Fir branch panel with crosscut grain; Specimens 70x70x20 (mm) of fir branch wood panels sanded with 60 grit size: c- With crosscut grain; d- with longitudinal grain (Gurau et al.2009d)

Specimens 70x70x20 (mm) were cut out of each type of panels after prior conditioning. They were sanded with grit sizes: P60, P80, P120 and P220, 2 replicates for each grit size. For specimens obtained from panels with longitudinal grain the sanding was made along the grain, while for those from panels with crosscut grain the direction was kept parallel to the specimen length.

Sanding was performed on a vertical sander SDB-612 CSA/UL equipped with abrasive belts 150x1220 (mm), which were firstly worn for 2 minutes to remove the isolated high grits and reach the domain of working sharpness, which is characterised by a slow, but constant rate of decrease in the sanding capacity.

The surface measurements were made with an optical profilometer GMBH MicroProf® equipped with an optical sensor FRT CWL, which illuminates the specimen by focused white light. The size of the light spot was 1-2 μm in diameter. Two areas of 50x3 (mm^2) were scanned from each of the two specimens of each category investigated, with a scanning speed of 750 μm/s. The size of the measured area was considered sufficient to tipify the variability of a wood surface. This meant 30000 data points collected at a single measurement, with a resolution on x-axis (across the sanding direction) of 5 μm and on y-axis of 1000 μm.

Data was stored in ASCII format and processed with algorithms written in MathCad™. Form errors were removed with a 2nd order polynomial regression, which proved to be the best fit of the initial data.The roughness profiles were obtained by filtering the surface with a Robust Gaussian Regression Filter with a cut-off length of 2.5 mm. The processing roughness was separated from the other irregularities as described in section 1.2.6.1. The peaks and valleys that were not part of the processing roughness were replaced with zeros, which were excluded in the calculation of roughness parameters. Processing roughness profiles were evaluated with roughness parameters from ISO 4287 (1998): *Ra*, *Rq, Rt, RSm* and *Rk, Rpk* and *Rvk* from ISO 13565-2 (1996).

The results in Table 28 demonstrate that all the processing roughness parameters measured from branch fir specimens with crosscut and longitudinal grain were sensitive to the grit size. Their values were highest with 60 grit size and decreased as the grain was finer.

	P60		P80		P120		P220	
	L	T	L	T	L	T	L	T
Ra	24.51 (8.94)	20.03 (11.32)	19.73 (9.23)	14.84 (7.32)	10.27 (10.42)	7.41 (9,76)	7.08 (7,91)	4.78 (8,49)
Rq	28.66 (7.67)	23.70 (10.21)	23.28 (7.89)	17.46 (6.84)	12.05 (9.03)	8.77 (9,45)	8.38 (7.06)	5,64 (7.61)
Rt	112.00 (8.95)	95.68 (11.61)	92.92 (8.75)	67.53 (7.67)	46.97 (10.56)	33.41 (11,20)	33.08 (7.69)	22.68 (8.79)
RSm	133.68 (8.03)	165.42 (5.56)	96.85 (3.59)	113.00 (4.53)	81.47 (5,35)	71.65 (6,76)	52.24 (4.73)	62.00 (4.70)
Rk	85.41 (5.33)	67.33 (6.20)	67.86 (4.16)	51.75 (5.06)	35.71 (5,57)	26.27 (7,15)	24.01 (4.93)	16,41 (5.76)
Rpk	12.53 (15.46)	12.06 (13.14)	11.31 (18.88)	6.38 (10.90)	5.48 (22,43)	3.47 (25,70)	3.98 (17.54)	2.99 (18.01)
Rvk	12.87 (25.09)	14.95 (28.08)	11.97 (22.49)	9.02 (17.46)	6.57 (18,35)	4.66 (22,12)	4.61 (18.09)	2.87 (21.30)

Table 28 The influence of grit size on roughness parameters (mean values in μm) of sanded branch wood panels with longitudinal (L) and transversal (T) grain (values in brackets are coefficients of variation) Gurau et al.(2009b)

As in a toughness test, due to the grain orientation, the abrasive grits have penetrated deeper on the conventional panels than on the panels with crosscut grain for all grit sizes. The differences were higher for finer grits of app. 30% for P220 compared to app. 15-20% for P60 as far as the mean (*Ra*, *Rq*), the core (*Rk*) and the height (*Rt*) roughness parameters are concerned. *RSm*, which measures the width of the irregularities was generally higher for the cross grain panels than for those with conventional grain and this is possibly due to the biasing effect of the wood anatomy still retained in the evaluation of spacing parameters. However, *RSm* values for both longitudinal and transversal grain panels were as expected, smaller than the main grit diameter given by FEPA (2006), the difference decreasing with the grit size (details in Gurau et al.2009b).

Conclusions

The roughness of sanded fir branch panels increased with the abrasive grit size and all the roughness parameters tested were sensitive to variations in grit size.

The roughness parameters of fir branch panels with crosscut grain were smaller than their equivalent parameters of fir branch panels with longitudinal grain. This is attributed to the differences in wood *toughness as function of the grain orientation. Exception made the spacing parameter RSm, which probably was biased by the wood anatomy retained in the evaluation.*

The research results from chapter 3, of the **research project granted by the CNCSIS** (The National Council of Scientific Research in the Higher Education) **type A 450/2006: "Eco-conception and eco-technology for furniture and other wood made products obtained from natural secondary resources"** (2006-2008). were disseminated in **32 publications,** among which:

- 2 Books- Cionca et.al.(2008a)- ISBN 978-973-558-376-5 and Cionca et.al.(2008b)- ISBN 978-973-598-377-2, Ed.Transilvania University of Brasov
- 3 papers in ISI Web of knowledge journals.The most cited in ISI web of Science was:
  - **Gurau**, L., Cionca, M, Mansfield-Williams, H., Sawyer, G., Zeleniuc, O. (2008a). Comparison of the mechanical properties of branch and stem wood for three species. *Wood and Fiber Science* 40(4), pp. 647-656. ISSN 0735-6161. At the moment of writing, this paper had **10 citations (in ISI Web of Science)** and 25 in Google Scholar
  - **Gurau** et al. 2009c. Compression strength of branch wood as alternative eco-material to stem wood. *Environmental Engineering and Management Journal*. Vol. 8 (4). July/Aug.2009, pp. 685-690. ISSN 1582-9596.
- 3 ISI Web of Knowledge conference papers
- 6 Journal papers in other international databases
- 20 International conference papers

To which can be added:

- 3 patents as co-author in ISI Web of Knowledge: Patent.no: RO 125678-A2, no. RO123471_B1/ 30.08.2012 and RO 128819-A0/ 30.09.2013. Derwent primary accession numbers: 2010-M69346; 2012-P88359 and 2013-Q10140.
- Contribution to two doctoral thesis of two members of the research team (one defended in 2009-Alin Olarescu and the second in 2012-Ramona Dumitrascu). The author of this habilitation thesis was member of the advisory board for these two PhD students

4. CHAPTER 4. IMAGING METHOD (IMAGEJ) FOR SURFACE QUALITY EVALUATION AND OTHER APPLICATIONS

The last chapter of this habilitation thesis is referring to research studies pursued by the author, in parallel with studies from previous chapters, for a period stretching from 2009 till 2015 and they were focussed on ImageJ, a software offering many possibilities of application, which were not explored for wood before. Chapter 4 represents **an original approach to the evaluation of surfaces by using the imaging software -ImageJ**, freely available on the internet, developed at the National Institutes of Health in the United States of America. The author has experimented with this software on wood and wood based materials and **managed to find useful and original applications.**

Techniques for image processing, analysis and visualization of digital data have had a substantial development during the last two decades. This is specially the case with ImageJ, a program in the public domain, which has proved to be a most suitable package for processing, analysis and visualization of 2D and 3D data (Carrasco 2010)

ImageJ is an image processing program. Data acquisition, analysis and processing can be used for typical analysis like determining where the edges of an object are, counting similar objects, calculating the area, perimeter length, percentage of objects related to area and other useful measurements of each object (http://en.wikipedia.org/wiki/ImageJ).

The first section of this chapter, 4.1, is presenting a series of studies regarding the evaluation of the surface quality of wood based panels after being processed by drilling. This operation is often causing defects appearing as pull-out zones of material around the drilled hole. The size of this defect zone is very much depending on the selection of the tools and on the drilling parameters. ImageJ was a new and useful approach to measuring and evaluating this area of processing defect.

This chapter, in sections 4.3 and 4.4 is dedicated to the research carried on by the author in the framework of the **project CNCSIS PN2 Idei(Ideas) 856/2009-"Development and implementation of an advanced scientific research methodology for sustainable wood (furniture) restoration-conservation and ecodesign".** This project has continued the investigation of the secondary wood resource from chapter 3 (project CNCSIS- type A 450/2006: "Eco-conception and eco-technology for furniture and other wood made products obtained from natural secondary resources", by looking at the characteristics of the juvenile wood in comparison with mature wood. Furthermore, the project also referred to the creation and implementation of an advanced scientific research methodology applicable for the scientific conservation of wood (furniture). The research included in this chapter is just a part of the author contributions to this project. It referrs here to ImageJ-imaging method, that was used for evaluating the microscopic characteristics of the secondary wood resource and for species identification in restoration works. Another application of ImageJ was to evaluate the depth of penetration for wood consolidants, in order to assess the quality of this operation *the deeper and wider the penetration, the most successful the operation).

4.1 ImageJ-imaging method for evaluation of surface quality of drilled wood based panels

The following study is one original example of studies in which ImageJ was used by the author of this thesis **to evaluate the extent of delamination defect occurring around holes at drilling particleboards** (**Ispas et al.2015**). *The objective of this study was to measure and analyze the influence of the point angle of the drill bit and of the feed speed on the processing quality of pre-laminated particleboard, evaluated by de size of delaminations, both, at the entrance side and the exit side of the drill bit. To assess the defect, two parameters were used: the delamination factor and the effective area of delamination.*

Drilling is one of the most usual and frequent type of processing in the wood. This has developed along years into a massive production of cases made of doweled joint panels, where the main raw material is particleboard and mainly pre-laminated (according to FAOSTAT, the worldwide particleboards production in 2014 was of app. 110.5 mil.m^3, more than app. 106.3 mil. m^3 in 2013 and app. 97.1 mil. m^3 in 2012).

The operation of drilling, which is common for on-line processes, raises a surface defect noticed, at the pre-laminated particleboards, to occur around the drilled holes. Delamination is a processing defect which consists of a local detachment of the coating layer engaging chips/particles pull-offs from the particleboard surface. This phenomenon can occur during drilling at the entrance side as well as at the exit side (for drilled through holes). Its magnitude depends on the processing parameters and can be used as an indicator of the drilling quality (Davim et al. 2008).

Some long ago, Radu (1967), in his extensive study on drilling with twist drills, referred to the quality of drilling the particleboards in terms of visual qualifications of the surface in the neighbourhood of the processed holes. Parameters, as tool feed speed and tool geometry, were amongst the ones investigated, but the qualifications were limited to subjective qualitative assessments as: “good”, “weak”, “slight increase”, “slight decrease”.

More recently, the delamination caused by drilling the wood based panels, especially medium density fiberboards (MDF), was quantitatively assessed by using a parameter called delamination factor, F_d. Hence, Davim et al. (2008) investigated the relationships and parametric interaction between the feed rate and the cutting speed on the F_d at entry and exit side of the holes in drilling the MDF. Two types of MDF panels, melamine coated and veneered, were tested using cemented carbide (K20) drills. The F_d decreased with the increase of the cutting speed and increased with the feed rate for both materials. Palanikumar et al. (2009), Prakash et al. (2009) studied the performance characteristics given by F_d in drilling operations of MDF boards using carbide tools. The machining parameters considered were: the spindle speed, the feed rate and the drill diameter. They found that F_d decreases with the increase of the cutting speed and increases with the feed rate and drill diameter.

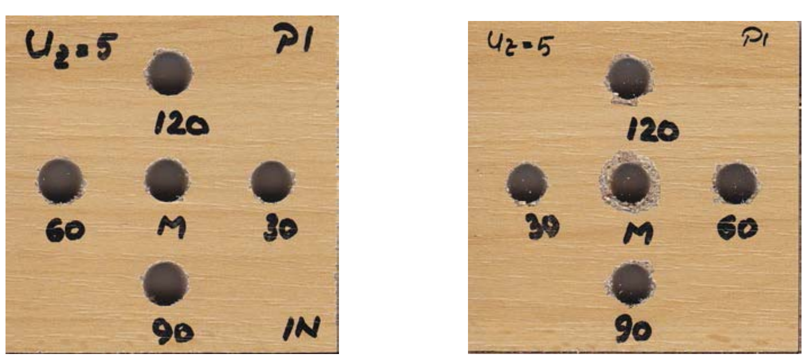
Prakash and Palanikumar (2011) investigated the influence, at MDF, of the spindle speed, feed rate and drill diameter on the surface roughness of the processed hole. The experimental result revealed that the most significant drilling parameter for the surface roughness was the feed rate followed by the cutting speed.

Regarding the drilling of particleboards, Valarmathi et al. (2013) advanced the idea that the thrust force developed during cutting play a major role in gaining a good surface quality and minimizing the delamination tendency. They studied the influence of the spindle speed, feed rate and point angle upon the thrust force. However, the drills they used had a geometry more specific to metals rather than for wood based materials (a tip angle $2\kappa_r \geq 100°$) and the same was true for the processing parameters (feed speeds v_f= 75 - 225mm/min). These experiments led to the same conclusions as with previous researchers concerning the trends for the delamination factor.

Studies on the processing particleboards with flat drills by Ispas et al. (2014) have showed that, in general, the combination of small tip angle with low feed rate minimizes the delamination of prelaminated particleboard panels at drilling. In conclusion, most of research on delamination of wood based materials focussed mainly on MDF and less to the drilling of pre-laminated particleboards. Therefore, this research is aiming to study the delamination defect which occurs when drilling pre-laminated particleboards, but compared to other studies, this one employs tools and cutting parameters used in the woodworking industry.

For the experiments, four twist (helical) drill bits with the point angle, 2κr, of 30°, 60°, 90°, 120° and one lip and spur drill bit, all having a cutting diameter of 10 mm, were used. The clearance angle of all drills was the same α = 20°. The symbols used for those drills were tip angle related: T30, T60, T90, T120, respectively TLS for the lip and spur drill.

Forty square samples, with 80 mm side, were cut from a single pre-laminated particleboard, 18 mm thick. They were divided into four groups of ten specimens each. Each specimen was drilled with five different drills (T30, T60, T90, T120, respectively TLS). Each group was processed with a different feed speed so that the tooth bite, fz, was different, having the following values: 0.1, 0.3, 0.5 and 0.7mm. The rotation speed, n, was kept the same for all five types of drills, namely 3000 rpm. This led to four feed speed values, vf: 0.6, 1.8, 3.0 and 4.2 m/min.



a b

Figure 71 Pre-laminated particleboard specimens drilled with the five types of drills (T30, T60, T90, T120, respectively TLS in the middle) when the tooth bite was 0.5 mm: a- the entrance side; b-the exit side (Ispas et al.2015).

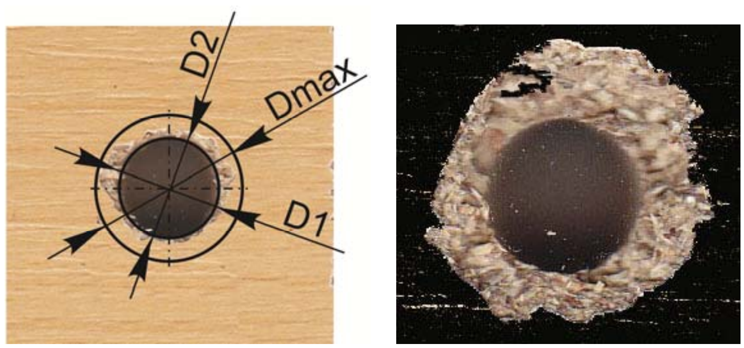
For drilling, a CNC type ISEL GFV/GFY was used, which allowed the exact set-up of the drills rotation speed and of their feed speeds. After drilling, each hole diameter was measured with an electronic calliper, with a 0.01mm precision, on two perpendicular directions and a mean diameter was calculated for both hole sides (entrance and exit), as can be seen in Figure 72a. All drilled specimens were then scanned on both sides and received codes, IN, for entrance side (Figure 71a) respectively OUT, for exit side (Figure 71b).

The scanned images were used to evaluate the delaminations that occurred around each hole, on both sides. Two methods were used for this purpose and they are presented as follows:

- the delamination was evaluated by the delamination factor Fd , given in [27], where Dmax is the diameter of the circle circumscribed to the defect, while D is the mean hole diameter given by caliper measurements D1 and D2 (Figure 72a)

$$F_d = \frac{D_{\max}}{D} \qquad [27]$$

- the second method used the image processing software, ImageJ, to measure exactly the area with delamination, S, the white area in Figure 72b.



a b

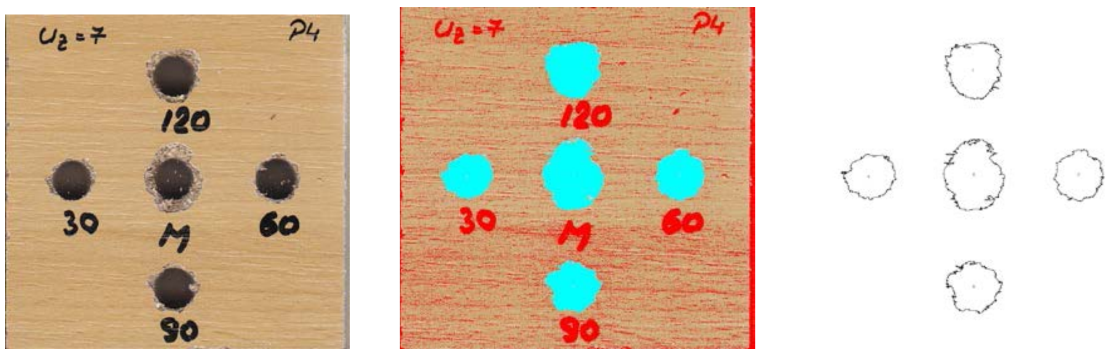
Figure 72 Evaluation of the particleboard delamination caused by drilling: a- by the delamination factor F_d; b- by the ImageJ image processing software (Ispas et al.2015).

Compared to the delamination factor, which approximates the zone with defect by taking into consideration the maximum diameter of a circle that circumscribes the defect, the second method is more precise, because it identifies exactly the damage around the holes. The method was previously used for wood species identification and the working principle was described in detail by Gurau et al.(2010). The software is able to detect image features, to select their contour and to return a mask image where only the items of interest are kept. In this study, they were holes with delamination surrounding them (blue areas in Figure 73b). Further, numerical data measuring their area was acquired in a spreadsheet.

The delaminated area was calculated for each hole as the difference between the hole area with defect measured with ImageJ and the processed hole area, calculated with the mean diameter D obtained from two calliper measurements D1 and D2 taken on perpendicular directions.

The mean values, standard deviation and coefficients of variation were calculated for both defect assessment parameters: the delamination factor F_d (Table 29 and Table 30) and the effective delamination area S (Table 31 and Table 32).

By comparing the delamination expressed by both parameters, delamination factor and effective delamination area, it can be observed a relative similar trend, which means that delamination factor is a close non-dimensional approximation of the defect and its evolution with processing parameters. However, if an exact measure of the delamination area is requested, then the effective delamination area is advantageous because it can give a dimensional quantification.



a b c

Figure 73 Exit side of a pre-laminated particleboard specimen drilled with five different tool geometries and 0.7 mm tooth bite: a- specimen scanned image; b- ImageJ detection of drilled areas including delaminations; c- contour detection of drilled holes with delaminations (Ispas et al.2015).

Whatever the specimen (hole) side, the biggest delaminations occurred when drilling with lip and spur drill bit (TLS), regardless of the used feed speed (exception: delaminations on entrance side produced when drilling with f_z = 0.1mm). At the same time, it can be seen that for the entrance side of the holes, the size of delaminations produced with this drill bit (TLS) was comparable to those produced by the other drills used. Not the same can be said about the delaminations on the exit side of holes. In this case, the effective delamination area produced by the TLS drill was, in some situations, more than 50 times larger that those produced by the other drills.

Another thing that can be noticed is that whichever the side of the holes there was a general trend (stronger for the entrance side and much weaker for the exit side) of delamination increase with the increase of the tooth bite (feed rate), observed by both defect parameters and all drill geometries. This result is in agreement with other results from literature (Valarmathi et al, 2013; Ispas et al, 2014). The most sensitive to the variation of the feed rate was T120, where the delamination size almost doubled at the exit side and it was 7 times larger at the entrance side for a tooth bite of 0.7mm compared to 0.1mm.

A very interesting thing, for all drills except TLS, the defect zone was larger at the entrance side of the drill compared to the exit side with the greatest amount for T60 (more than 11 times, at f_z=0.7mm), followed by T90 (almost 9 times) and then by the other tool geometries T120 and T30 (almost 8 times). For the TLS drill, the effect is opposite: bigger delaminations at the exit side of the holes (more than 16 times at f_z=0.1mm and increasingly smaller with the increasing of the feed speed). Therefore, considering the delamination occurred at the entrance side as well as at the exit side, a drill type T90 seems the best option for getting the best quality and for having the flexibility of choice for holes with or without limited depth. At the opposite, the drills types T120 and especially TLS seem to have worsened the drilling quality.

IN	f_z = 0.1mm			f_z = 0.3mm			f_z = 0.5mm			f_z = 0.7mm		
	mean	SD	cvar (%)	mean	SD	cvar (%)	mean	SD	cvar (%)	mean	SD	cvar (%)
T30	1.10	0.04	4.00	1.20	0.04	3.49	1.24	0.03	2.18	1.25	0.06	4.58
T60	1.14	0.04	3.14	1.22	0.04	3.56	1.27	0.07	5.74	1.28	0.05	4.04
T90	1.11	0.04	3.65	1.22	0.05	3.91	1.25	0.05	4.31	1.30	0.04	2.89
T120	1.09	0.02	2.19	1.26	0.06	4.44	1.28	0.06	4.35	1.32	0.06	4.41
TLS	1.14	0.06	4.88	1.31	0.05	3.53	1.34	0.04	3.33	1.35	0.04	2.97

Table 29 The mean values, standard deviations and coefficients of variation for the delamination factor F_d , at the entrance side of the specimens, for various feed rates and drill geometries (Ispas et al.2015).

OUT	f_z = 0.1mm			f_z = 0.3mm			f_z = 0.5mm			f_z = 0.7mm		
	mean	SD	cvar (%)	mean	SD	cvar (%)	mean	SD	cvar (%)	mean	SD	cvar (%)
T30	1.01	0.02	1.75	1.02	0.03	2.95	1.05	0.08	7.68	1.08	0.05	4.96
T60	1.00	0.03	3.01	1.02	0.04	3.68	1.10	0.09	8.43	1.10	0.08	7.28
T90	1.01	0.02	2.20	1.01	0.03	2.47	1.07	0.06	5.55	1.07	0.05	4.21
T120	1.07	0.10	8.91	1.11	0.11	10.06	1.06	0.09	8.91	1.08	0.07	6.45
TLS	1.70	0.12	7.30	1.82	0.17	9.09	1.78	0.27	15.26	1.70	0.22	13.01

Table 30 The mean values, standard deviations and coefficients of variation for the delamination factor F_d , at the exit side of the specimens, for various feed rates and drill geometries (Ispas et al.2015).

IN	f_z = 0.1mm			f_z = 0.3mm			f_z = 0.5mm			f_z = 0.7mm		
	mean	SD	cvar (%)	mean	SD	cvar (%)	mean	SD	cvar (%)	mean	SD	cvar (%)
T30	4.41	1.26	28.48	7.11	2.93	41.21	9.95	1.84	18.45	10.70	2.09	19.57
T60	5.41	1.06	19.62	7.81	1.92	24.58	11.54	3.65	31.64	14.99	3.43	22.88
T90	3.63	0.57	15.66	6.93	2.43	35.12	10.20	3.13	30.70	13.37	2.01	15.06
T120	2.22	0.91	40.88	9.42	2.77	29.41	13.18	3.71	28.18	15.68	3.23	20.63
TLS	3.75	1.05	28.08	12.68	4.61	36.39	17.38	2.75	15.85	22.83	4.01	17.58

Table 31 The mean values, standard deviations and coefficients of variation for the effective delamination area S, at the entrance side of the specimens, for various feed rates and drill geometries (Ispas et al.2015).

OUT	f_z = 0.1mm			f_z = 0.3mm			f_z = 0.5mm			f_z = 0.7mm		
	mean	SD	cvar (%)	mean	SD	cvar (%)	mean	SD	cvar (%)	mean	SD	cvar (%)
T30	1.04	0.31	29.59	1.98	1.51	75.99	1.77	0.84	47.53	1.37	0.86	62.69
T60	1.05	0.41	39.25	1.77	1.39	78.61	1.55	1.28	82.02	1.32	0.47	35.58
T90	1.26	0.50	39.32	1.68	1.00	59.71	1.38	0.93	66.98	1.51	0.49	32.07
T120	1.41	0.71	50.62	2.47	1.56	63.32	1.65	0.97	59.17	2.40	2.66	111.11
TLS	60.28	20.74	34.41	96.12	22.40	23.30	74.91	41.62	55.56	69.21	42.07	60.78

Table 32 The mean values, standard deviations and coefficients of variation for the effective delamination area S, at the exit side of the specimens, for various feed rates and drill geometries (Ispas et al.2015).

Conclusions

This study examined the delamination defect at drilling pre-laminated particleboards by means of two parameters: a non-dimensional one used also by other researchers, the delamination factor, and one measuring the effective area of defect with an image processing method.

Generally, the delamination increased with the increase of the tooth bite (feed rate) for all drill geometries. The defect zone was larger at the entrance side of the drill compared to the exit side with the greatest amount for the lip and spur drill, followed by the other drills.

The results showed an increase in the delamination defect with the increase in the drill tip angle, but the influence wasn't very clear for the 30°, 60° and 90° tip angle. If delamination and flexibility of hole depth is considered, a helical drill with 90° tip angle gave the best quality. The lip and spur drill and the drill with the greatest tip angle, 120°, do not seem appropriate for processing pre-laminated particleboards.

Further studies may complete these results for various rotation speeds and other types of drills to optimise the process quality at drilling pre-laminated particleboards.

Similar studies, published in journals in international databases, on the evaluation of surface quality at drilling particleboards with different tool parameters and processing variables were those of Ispas et al. (2013 and 2014).

The results of these studies **applying ImageJ for evaluating the surface quality at drilling particleboards were disseminated in 3 papers in international journals and 3 in international conferences**.

4.2 ImageJ-imaging method for wood identification in restoration purposes

This section will prove how ImageJ can be used as supporting tool, for species identification of samples detached from the structure of various objects subject to restoration.

Any restoration involving replacement of wood elements should be evaluated and well documented based on the original condition of the unit. This requires an initial macroscopic analysis of the wood part to identify its main anatomical features. However, identifying wood can be difficult because stains, finishing, biological deterioration and aging can change wood by modifying its original colour and look. Most woods exposed to sunlight and outdoor conditions for long time, will lose their characteristic colour and become much lighter while other woods can become darker due to exposure to light or treatments with oil, waxes and polishes (Hingley 1998).

Most of the time a careful macroscopic examination of a clean finished surface or a freshly sanded surface is considered as a typical solution of the problem. However, there are many cases when a microscopic investigation is needed and reference microscopic samples are employed to compare and to have an accurate identification of the piece (Macchioni et al 2011).

The most advanced techniques, such as X-ray phase contrast micro-tomography (Mayo et al 2009) enable the 3D-analysis throughout the volume of the wood without physical sectioning. However, as this technique and other tomographic methods are not readily available, the most commonly used wood identification technique would be classical transmission light microscopy through thin microtome sections at the cellular level where 2D image of the section can be developed. Even so, the samples size may be too small, given the value of an object and the requirement to use a hidden area for sample collection and this may lead to insufficient wood variation within the microslide. Otherwise, wood may be degraded by natural ageing, by biologic degradation or by the uneven finishing penetrating the material.

Computer image processing technologies, as additional tool, can be considered as an alternative,objective method to evaluate the section rather than relying on simple microscopic observation. Techniques for image processing, analysis and visualization of digital data have had a substantial development during the last two decades. This is specially the case with ImageJ, a program in the public domain, which has proved to be a most suitable package for processing, analysis and visualization of 2D and 3D data (Carrasco 2010)

ImageJ, an image processing program intended for medical microscopy, can be used for identification purposes (Gurau et al.2010). The method is useful for wood since it offers an objective quantitative way to separate and measure anatomical structure of the section so that statistical analysis of the data can be carried out.

The method of wood identification for restoration purposes was applied successfuly in several research papers of the author, **but the most representative was the following study published in an ISI journal-*Wood and Fiber Science* journal** (Gurau et al.2013b**) cited 6 times in ISI Web of Science and 15 times on Google Scholar.**

The method presented in this study was using ImageJ, as supporting tool, for species identification of samples detached from the structure of three furniture objects subject to restoration. Micrographs of known species, having similar anatomy with the targeted samples, were used as references for visual comparison. Image processing with ImageJ was employed to quantify the size, proportion and frequency *of samples main wood features. For species identification these values were further compared with data references from literature*.

Three pieces of wood furniture, namely two bent chairs and one table decorated with intarsia, dating from the middle of the twentieth century were subject to patching operations during an action of restoration.

In order to avoid any uncertainty regarding the species of origin, small wood samples of. app.20 x 8 x 10 mm were cut with a sharp chiesel out from hidden surfaces of those objects: the back side of the chairs legged frame, respectively the back side of the table top. The samples displayed all three main type of surfaces: longitudinal, radial and tangential. Other details about preparing the samples are detailed in Gurau et al. (2013b). Specimens were labeled with information regarding: the furniture object, the sampling location and date and the sample code. The codes used in this paper for easy reference to the samples under investigation are: „C1” and „C2” for the chair and „T” for the table.

The samples were then softened by boiling in water for about 4h, being further transferred into a mixture of glycerol and ethanol (1:4). Next, the samples were trimmed under a magnifying glass to precisely expose the transverse, radial and tangential surfaces. Sections were cut from each surface with a sliding microtome to 30-60 micron thickness. Ethanol solution was used to prevent surface tension attaching the sections to the knife. After this, sections were stained with safranine, washed with water and then mounted in glass slides using a mix of glycerol and water (1:1). By positioning the cover slip, the slides were allowed to cool and after 12 hours, the slides were cleaned and polished with a cloth and a little ethanol and then labelled.

From each slide several images were taken on each section at magnifications of 40x, 100x and 200x by means of an optical microscope BIOSTAR OPTECH B5 fitted with an image capture system. In order to make a reliable assessment of the species of origin the transversal sections were chosen so that they had the annual growth limit.

Although a visual examination can give some qualitative observations about the distribution and size of the anatomical cells, an image analysis program, ImageJ, was also used in order to have an objective analysis, consisting in a quantitative evaluation of the investigated parameters.

ImageJ identifies wood cells (eg. pores) as objects, it selects their contour and returns a mask image where only the objects (anatomical cells) of interest are kept. Together with the mask image it provides numerical data in a speadsheet about the measured objects such as: area and perimeter of each object, total and average area of objects, percentage and number of objects detected in an image.

Before any measuring, the image was calibrated and a scale was set based on a known unit of length, normally the scale bar in microns that accompanies the image (Line selection-Analyze-Set scale- Known distance-Unit of length). Next step was to convert the colour image into a grey scale. To ease the identification of the features in an image the contrast was enhanced (Process-Enhance contrast).

If the features of interest are wood pores, a threshold should be applied meant to retain in the image as much as possible only the pores lumens, (Image-Adjust-Threshold). Some of the lumens of other type of cells may also be retained, therefore a final threshold in μm^2 is applied, which will retain in the mask image only the pores lumens (Analyze-Analyze Particles). The threshold, which is user's decision, should correspond to the minimum size of the pores lumen, while every other features below this size are disregarded. Sometimes, smallest pores can be lost at thresholding if their size is in the fibers or parenchyma lumen range of variation. For example, this is the case for beech (*Fagus sylvatica*), where the reported size of the smallest pore diameters is of 8 μm, while the diameter of the largest fibers reach 11.2 μm (Wagenführ 2000).

Another influence factor in achieving a representative mask of objects is the degree of destruction of wood pores, which suffered deformation during cutting or whose cell wall detached towards the lumen. In this case, the real contour of the original vessel cannot be retrieved, the lumen appears divided and of smaller dimensions than initially.

The quality of filtering also depends on the image quality, on the degree of uniformity of the light spot: in areas with shades, the pores are fading and cannot be detected. This phenomenon was noticed more frequently with low magnification (40x).

By filtering, not only mask images containing the pores lumen were obtained, but numerical data, as previously described, was also acquired (Analyse-Analyse Particles). Data was transferred to an Excel sheet for further analysis where were calculated: the number of pores on mm^2, the approximated mean pores lumen diameter (μm), the approximated maximum pores lumen diameter (μm) and the percentage of total lumen pores area (%).

With regard to the calculation of the lumen diameter it was conventionally assumed that a lumen area is the one of a circle, although in reality pores have a rather oval shape with two axes of symmetry whose real values cannot be automatically calculated. The only facility in this sense of this program is to measure each axis with a manual command.

ImageJ was further used for assessing the size of rays (maximum and minimum width and maximum height) by manual selection (Line-Analyze-Measure). The measured lines and values were then added on the micrographs (Edit-Draw).

Other observations regarding the pores distribution and grouping, the presence of longitudinal parenchyma, the type and number of rays were visually performed directly on the micrographs.

Collection of micrographs from known species frequently used in restoration works was considered to select the images most resembling the characteristics of samples under investigation. They were included in the comparison as reference images. The measurement results with ImageJ were compared with key characteristics of those reference known species described and quantified in reliable literature reports.

Microscopic images of species for identification, their mask images and feature measurements with ImageJ were compared with reference micrographs from known species. Table 33 also displays the measurements for all three unknown species in comparison with reference cell data from literature.

Species Identification for the Samples „C1" and „C2"

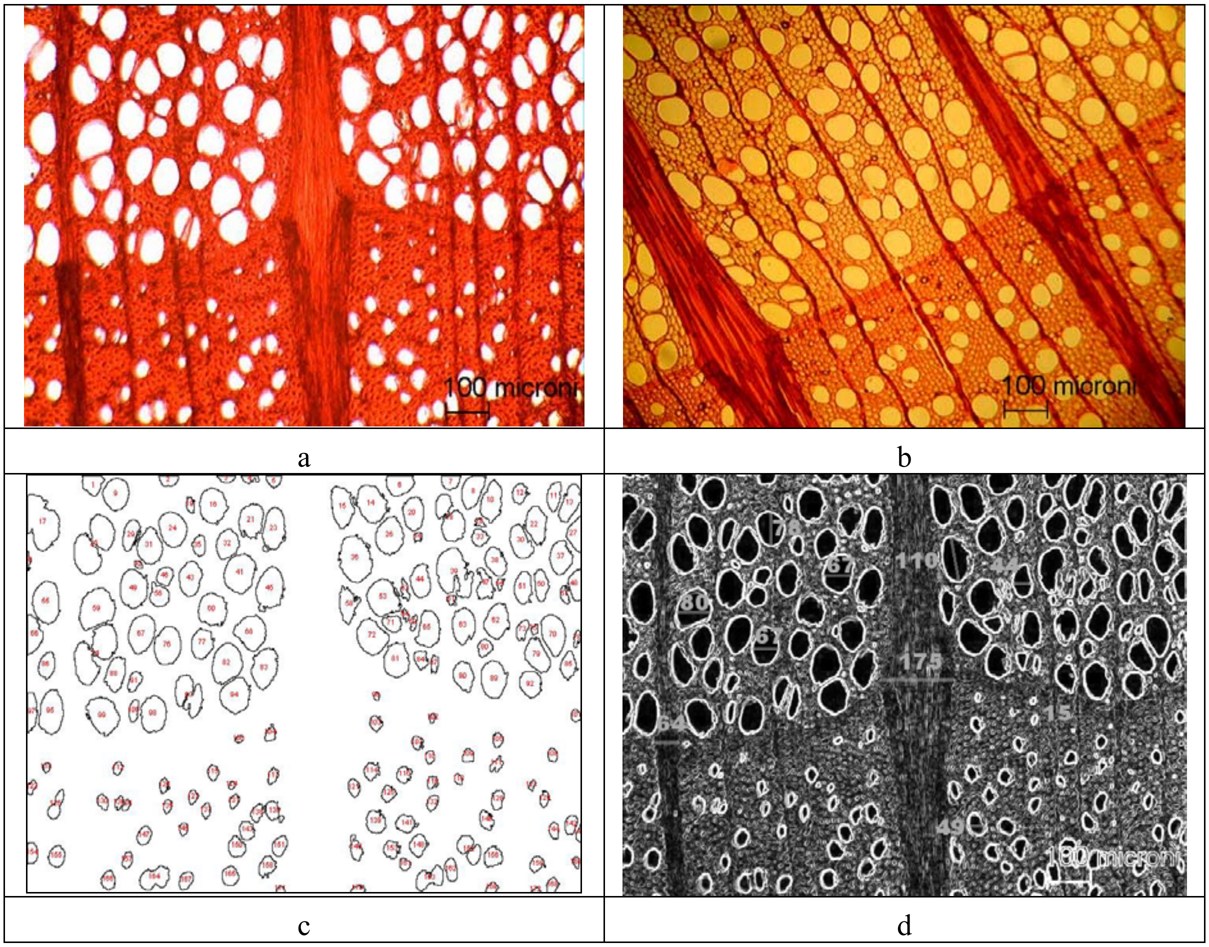
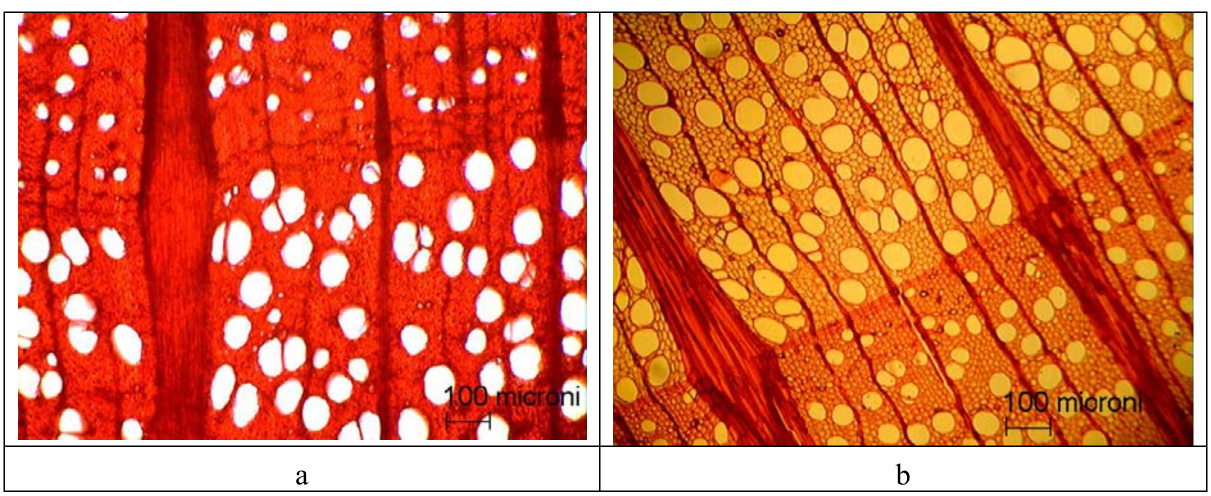
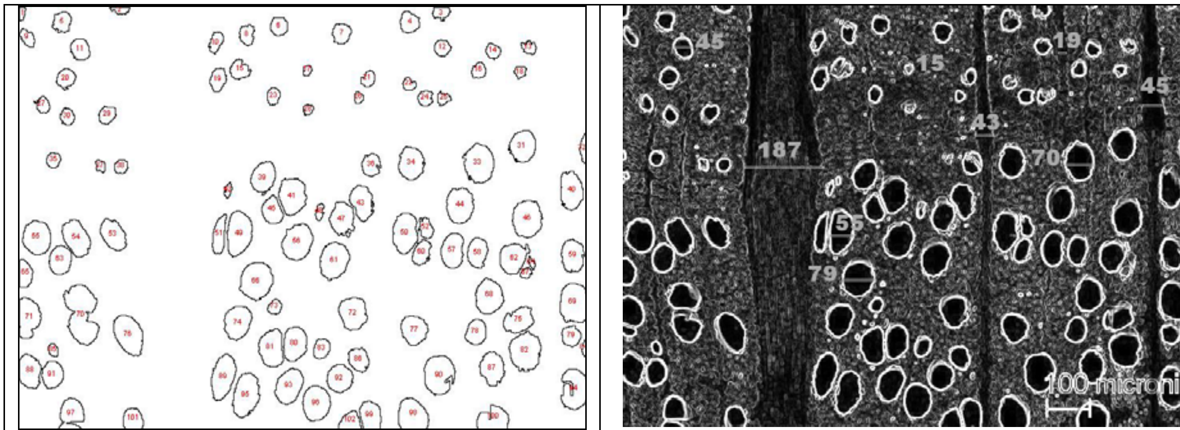


Figure 74 Cross sections, 100x magnification. a- investigated sample "C1"; b- reference sample (beech- *Fagus sylvatica*); c- "mask" image of the investigated sample "C1"; d- investigated sample "C1" with cell contour enhanced and measurements. Size of the investigated sample micrographs: 1289,09x965,45 (μm) (Gurau et al.2013b)





c	d

Figure 75 Cross sections, magnif. 100x. a- investigated sample “C2”; b- reference sample (beech-Fagus sylvatica); c- “mask” image of the investigated sample “C2”; d- investigated sample “C2” with cell contour enhanced and measurements. Size of the investigated sample micrograph: 1312,96 x 983,33 (μm) (Gurau et al.2013b)

As can be seen from Figure 74a and Figure 75a both types of samples come from a hardwood species due to the presence of pores, having diffuse structure, solitary or associated in small groups. The reference species closest to the appearance of the investigated micrographs seemed to be beech. Therefore the key characteristics of beech from known literature were assumed to be the term of comparison to see if the features measured with ImageJ fall within the expected range or not. ImageJ acts as an additional tool, meant to confirm or infirm an initial supposition, but which has the advantage of offering a quantitative information beyond the human perception that uses a simple visual examination. Nevertheless, it is not enough to look at a single characteristic in isolation, all the other features have to lead to the same species. For instance, the processing of mask images in Figure 74c and Figure 75c indicated app. **138** pores/mm^2 for the sample coded “C1” and **79** pores/mm^2 for the sample coded “C2”. These values were within the range reported in the literature for beech species, **80-125-160**/ mm^2 (Wagenführ 2000). It has to be mentioned, that this frequency of pores for both specimens, taken in isolation, may lead to other hardwoods as well (ex.lime), but the range of species gets narrower when other pores characteristics are also examined, such as: minimum, mean and maximum pores diameter, their proportion and distribution across the annual ring. Rays size and frequency, the occurrence and amount of longitudinal parenchyma and other species characteristics that can be distinguished and measured in an image will narrow even further the range of possibilities to the final decision.

The pores mean lumen diameter calculated from the “mask” images (Figure 74c and Figure 75c) were **49.5** μm, respectively **55.5** μm and the maximum lumen diameter measured from Figure 74d and Figure 75d was app. **80** μm on tangential direction. These values were closed to the mean, respectively maximum reported for beech **8-45-85** μm (Wagenführ 2000) with specification that the reports from literature have included the thickness of the cell walls and not only the lumen.

The vessels lumen proportion of **26.6**% estimated for the investigated sample in Figure 74a was close to the lower limit reported in the literature for the proportion of pores (including the cell walls), **24,6-39,5-**

52,5% (Wagenführ 2000). The threshold based on trials, which was found suitable for getting the mask images for both type of specimens was of 200 μm^2. This corresponds to a cell diameter of 16 μm, which is a little greater than the maximum size of beech fibres, 11.2μm (Wagenführ 2000). This means that smallest pores typical for beech and ranging from 8 μm (Wagenführ 2000) to 16 μm (the threshold) were not included in the evaluation. Their presence may have added to the lumen proportion.

If lime was given above as an example of species having pores frequency similar to beech and even a similar range of pores diameters (20-60-90 μm) according to Wagenführ 2000, their proportion is lower than for beech (17%) and rays are much narrower (10-20-30 μm). This excludes lime from any further comparison with the micrographs in this work.

In Figure 74a and Figure 75a can be observed uniseriated and pluriseriated rays, the latter being strongly widened at the annual growth limit. This is characteristic for beech species and is visible also on the reference micrographs in Figure 74b and Figure 75b. The largest ray width measured in Figure 74d was **175** μm and in Figure 75d was **187** μm, values close to the usual maxim limit of **200** μm from literature (Wagenführ 2000). Narrower rays visible in Figure 74d had values from **15-64** μm and in Figure 75d were of **19-45** μm similarly to the width range reported for uniseriated rays in beech, **20-60** μm.

The number of rays for the investigated sample: 2 pluriseriate rays/mm and **7** uniseriate rays/mm in Figure 74d and **3-4** pluriseriate rays/mm and app. **6** uniseriate rays/mm in Figure 75d had a good correspondence with beech species, **2-3-5** pluriseriate rays/mm and **3-6-9** uniseriate rays/mm (Wagenführ 2000).

Diffuse apotracheal parenchyma is visible in the upper limit of the annual ring for the investigated species in Figure 74a and Figure 75a as well as for the reference species, beech in Figure 74b and Figure 75b.

The initial assumption based on visual observation regarding the species identity was supported by measurements and features analysis generated with ImageJ. This led to the conclusion that the investigated samples, "C1" and "C2", indicate most probably a beech species.

Species Identification for the "T" Sample

Details about species idetification in this second case study are given in Gurau et al (2013b).

As the characteristics of the investigated sample were close to *Acer* species is reason to assume that this may be the species looked for.

The measuring results with ImageJ of all three samples under investigation are summarized in Table 33.

		Wagenführ (2000) Fagus sylvatica	Sample "C1"	Sample "C2"	Wagenführ (2000) Acer pseudoplatanus	Pescăruş (1982) Acer platanoides	Sample "T"
No.pores/mm^2		80-125-160	138	79	34-38-44	30-50	43
Mean diameter of lumen pores(μm)		8-**45**-85	49.5	55.5	25-**50**-70(110)	50	45.6
Max. diameter of lumen pores(μm)		8-45-**85**	80	80	25-50-**70(110)**	30-50-**70(110)**	70
Percentage of pores (%)		24.6-39.5-52.5	26.6	-	4-6.9-8.4	7	7.1
No.rays/mm	Unis.	3-6-9	7	6	6-9-14	9	8
	Pluris.	2-3-5	2	3-4			
Max.ray width (μm)		200	175	187	-	-	-
Min.ray width (μm)		20	15	19	-	-	-
Max.ray height (μm)		-	-	-	630(1000)	<600	500

Table 33 Summary of cell characteristics for the species under investigation compared to those from reference species. Obs. Values for pore size in the literature include the cell walls (Gurau et al.2013b)

The species investigated in this paper were found to be diffuse pores, however past experience has shown good results for other diffuse pores species such as poplar, lime and one ring porous species, walnut. Further work should address more wood species, including softwoods, to check the usefulness of the image processing method on various situations and understand its limitations.

Conclusions

Microscopic investigation for species identification is a requirement in any restoration work, but often the size of the micrograph does not cover enough wood variation or wood may be altered by ageing or biologic factors, which may render the identification difficult. This can be resolved by a microscopical investigation followed by image processing and analysis in order to extract and quantify relevant information that can be compared with reference species and identification keys.

A method of wood identification based on ImageJ was proposed in this study and was applied for species identification in case of three furniture objects needing restoration. The identification was performed on micrographs from microtomed samples, which were interpreted for their common, but also specific features and characteristics and compared with reference images and literature data.

The image analysis method could be extended for any wood species identification.

The contribution of the author on **wood identification for restoration purposes** was extended on several case studies, as for example, the wood species identification for a Bishop's throne, dated 1838, from the Berislăvesti hermitage in Vâlcea County (**Timar et al.2013-***European Journal of Science and Theology***-**ISI), or identification of the wooden species for two artisanal objects employed in the traditional processing of natural fibers, respectively a reel wheel and a winder (**Timar et al 2012-** *International Journal of Conservation Science*).

This section presented only one of the studies performed on **wood species identification for restoration** works. In total, were 8 studies on this subject **disseminated as: 2 papers in ISI journals, 4 papers in international databases and 2 international conference papers**

4.3 ImageJ-imaging method for microscopic analysis of secondary wood resource

This section will show how ImageJ can be used as supporting tool, for evaluating the microscopic characteristics of a less known material, the secondary wood resource.

Two of the most ignored secondary resources, the branches and the juvenile wood from forest thinnings, mainly used as firewood, are insufficiently known and exploited in spite of limited natural resources. They could be used in new added value products as an alternative to stem wood, provided their characteristics are known, including their microscopic details, which can give an indication about the material strength.

From the reports in the literature it is known that branches have narrower annual rings (Tsoumis 1968, Bowyer et al. 2003), smaller cell and lumen diameter (Brunden 1964, Tsoumis 1968, Taylor 1977, Hakkila 1989, Bowyer et al. 2003), smaller cell wall thickness (Hakkila 1989) and smaller cell length (Manwiller 1974, Taylor 1977, Vurdu and Bensend 1979, Hakkila 1989) than stem wood. The length of branch wood cells increases with branch diameter and this is probably because small branches contain proportionally more juvenile wood (Hakkila 1989); the fiber length increases from the pith to the bark with a greater percent than in stem wood (Vurdu and Bensend 1979). Branch wood is generally characterised by a higher percentage as volume of fibers and longitudinal parenchyma with hardwoods (Vurdu and Bensend 1980, Hakkila 1989). Rays are more numerous (Tsoumis 1968, Bowyer et al. 2003) and vessels are smaller and in a greater number (Tsoumis 1968, Vurdu and Bensend 1980) in branch wood than in stem wood.

If there are some reports from the literature regarding the microscopy of branch wood, those regarding the comparisons between characteristics of juvenile wood and mature wood in hardwoods are not numerous. Especially in the diffuse porous hardwoods, the differences in properties between juvenile and mature wood are considered quite small, so that they will not affect product quality (Zobel and Sprague 1998). The fibre length in the juvenile wood of hardwoods was found 2 times shorter than in the mature wood (Dadswell 1958 as cited by Zobel and Sprague 1998, Evans et al. 2000, Akgül and Tozluoġlu 2009). Vessels were smaller in juvenile wood than in the mature wood (Zobel 1981 as cited by Zobel and Sprague1998, Helinska-Raczkowska and Fabisiak 1999, Bowyer et al. 2003). Also, juvenile wood is characterised by a less pronounced latewood (Tsoumis 1968).

No reference was found with regard to a simultaneous comparison between branch wood, juvenile wood from thinnings and the mature stem wood of the same species.

The following study (**Gurau et al. 2010**) *analyses the microscopic structure of beech (Fagus sylvatica L.) from specimens of branch wood and juvenile wood from thinnings in relation with the microscopic structure of mature stem wood of the same species. Compared with a subjective visual examination of the micrographs, ImageJ was used, because it offers an objective quantitative method to separate, measure and statistical data process for some anatomical features of interest.*

To better understand the anatomical characteristics of branch wood and juvenile wood compared to those of mature stem wood microscopic sections were prepared of beech (*Fagus sylvatica* L.) as one of the most common species in Romania and due to its large availability. The material selection and the preparation of microscopic samples are detailed in Gurau et al.(2010).

From each slide were taken 2 images on each section at magnifications of 40x, 100x and 200x by means of an optical microscope BIOSTAR OPTECH B5 fitted with an image capture system. This meant a total of 4 images for each type of section and each type of material.

In order to make a reliable comparison between the microscopy of branch wood, juvenile wood from young trees and mature stem wood the microscopic images of the transversal sections were chosen to comprise the annual growth limit and approximately equal parts of latewood and earlywood. Although a visual examination can give straight forward qualitative comparison regarding the differences between anatomical cells of branch wood compared to stem wood, such as smaller and more numerous pores and greater number of rays in branch wood, it cannot be avoided a degree of subjectivity in situations when the size differences are small. This seem to be the case when comparing branch wood with juvenile wood from young trees, the size of pores looks quite similar.

In this sense, it was preferred the use of an image analysis software,ImageJ, in order to perform objective comparison with the advantaje of getting also a quantitative evaluation of the investigated parameters. The procedure of applying ImageJ was similar with the one described in section 4.2. Based on trials, a threshold of 150-200 μm^2, corresponding to a cell diameter of 14-16 μm was the limit found suitable to separate the pores from fibers and radial parenchyma with the compromise that pores lumena smaller than the threshold value were disregarded. Exception made some of the large longitudinal parenchyma cells, which were still retained in the evaluation, but their influence is rather negligible considering their reduced frequency of occurrence (4-5% according to Wagenführ 2000).

Another negative influence factor in achieving a representative mask of objects is the degree of distruction of wood pores, which suffered deformation during cutting or whose cell wall detached towards the lumen. In this case, the real contour of the original vessel cannot be retrieved, the lumen appears divided and of smaller dimensions than initially. This is the isolated case of some of the largest pores in the earlywood of the mature stem slides.

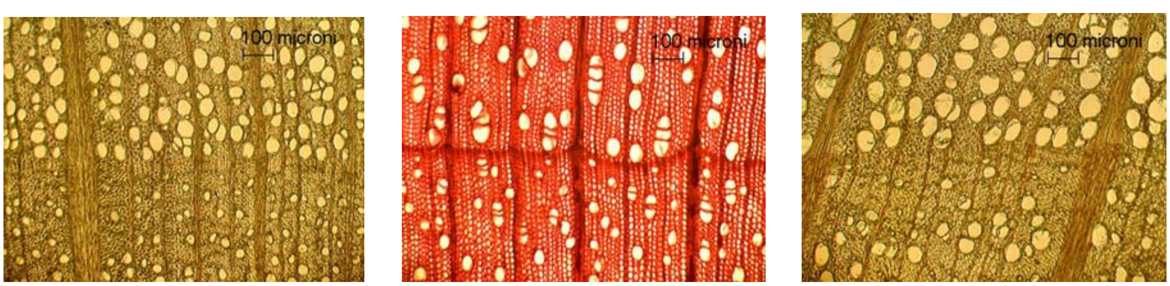
The quality of filtering also depends on the image quality, on the degree of uniformity of the light spot: in areas with shades, the pores are fading and cannot be detected. This phenomena was more frequent with low magnification (40x).

After filtering, the mask images containing only the pores lumena were visualised and compared with the original images, then numerical data of the type described above was acquired (Analyse-Analyse Particles). Data was transferred to an Excel sheet for further analysis where were calculated: the number of pores on mm^2, the mean lumen area (in μm^2), the approximated mean pores lumen diameter (μm), the approximated maximum pores lumen diameter (μm) and the percentage of total lumen pores area (%). Also, a mean value and the standard deviation for each variable was determined. With regard to the calculation of the lumen diameter it was conventionally assumed that a lumen area is the one of a circle, although in reality pores have a rather oval shape with two axes of simmetry whose real values cannot be automatically calculated. The only facility in this sense of this program is to measure each axis with a manual command, but this was found rather time consuming and less practical (Figure 76g,h,i).

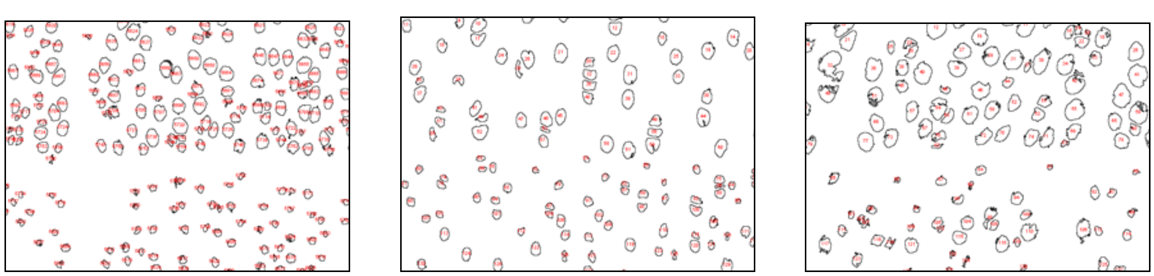
It was observed that at 40x magnification some information (anatomical features) is lost after the separation due to the fading affect, some of the lumena of the grouped pores appearing merged. At 200x, the separation was accurate, but the sampling was too small due to the high magnification. Among the three types of magnification 100x was preferred since it introduced the least bias and had an acceptable degree of representativity for the anatomical elements (Figure 76).

The results of image processing with ImageJ are presented in Table 34.

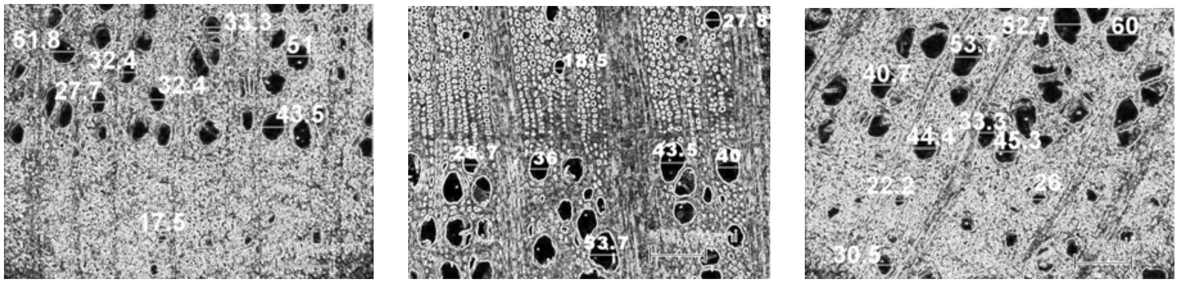
From the literature, the pores diameter of beech, including the cell wall thickness of app. 1.5-3 μm (Pescăruş 1982), ranges from the smallest in the latewood to the largest in the earlywood between 8-45-85μm (Wagenführ 2000). The approximated pores lumen diameters for the mature stem wood micrographs were in a range of 14-44-83μm, which are close to the values reported in the literature (Table 34). It has to be mentioned that the minimum value here corresponds to the threshold limit established for filtering and not to the real size of the smallest pores as was previously explained.



a b c



d e f



g h i

Figure 76 Image processing with ImageJ for beech branch wood (a,d,g), juvenile beech wood from young trees (b,e,h) and mature beech stem wood (c,f,i). a,b,c- original micrographs, magnification 100x; d,e,f- mask image with separated pores, magnification 100x; g,h,i-manual measurements of pores diameters, magnification 200x (Gurau et al. 2010)

The pores lumen mean diameters approximated for beech branch wood and juvenile wood were smaller than in the mature beech stem with about 30%, respectively 20%.

The pores size evaluated by their average area, actually representing a mean of the pores lumena from both regions of the annual ring, has indicated the smallest values for beech branch wood, which represented less than half of the values measured for beech mature stem wood. The pores from the juvenile beech wood had app. 30% larger openings (areas) than those from branch wood, but smaller compared to the mature stem wood with about 38%.

It was noticed a greater mean frequency of pores with about 62% in beech branch wood compared to the mature beech stem, which overpasses with about 18% the maximum limit reported in the literature for beech stem wood (80-125-160 pores/mm^2 according to Wagenführ 2000). The pores frequency in the mature beech stem ranged within the limits reported in the literature, staying close to the mean value of 125 pores/mm^2 (Wagenführ 2000), perhaps due to the fact that the area under investigation was balanced as far as the anatomy is concerned with approximately equal parts of earlywood and latewood. Juvenile wood from young trees had the smallest frequency of pores with app. 8% smaller than the mature beech stem.

The material porosity measured as percentage of the total pores lumen areas from the total surface has indicated minimum values for the juvenile beech wood, followed by beech branch wood and eventually mature beech stem wood.

Specimen	Pores/ mm^2			Mean area of pores lumena (μm^2)			Mean pores lumen diameter (μm)			Maximum pores lumen diameter (μm)			Percentage of total lumen pores area (%)		
	C	J	M	C	J	M	C	J	M	C	J	M	C	J	M
1	175	107	103	783	940	1547	31,6	34,6	44,4	54	55	83	13,7	10,1	16,1
2	238	116	126	676	907	1427	29,3	34	42,6	47	54,5	67	16,1	10,6	18
3	182	114	128	676	909	1223	29,4	34	39,5	51	49	67	12,3	10,7	15,6
4	162	91	110	626	818	1548	28,2	32,3	44,4	53	45,8	78	10,1	7,7	17
Mean	189	107	117	690	894	1436	30	34	43	51	51	74	13,1	9,8	16,7
Standard deviation	33,5	11,3	12,2	66,2	52,6	153,1	1,4	0,99	2,3	3,1	4,4	8,1	2,5	1,4	1,1
Percentage related to mature wood (%)	162	92	100	48	62	100	69	79	100	69	69	100	59	45	100

Table 34 Experimental data processing (Gurau et al. 2010)

Conclusions

The results have shown that pores lumena size and frequency for the mature stem specimens investigated were similar to those reported in the literature. Compared to the mature stem, but also with juvenile wood from thinning operations, the branch wood of beech has smaller and more numerous pores. The mean area of pores lumena in branch wood represents about a half the mean area of those from mature stem wood, while its pores mean frequency was about 60% greater.

The juvenile wood from thinning operations had smaller pores than the mature wood with a mean area of pores lumena almost 40% smaller. Among the three materials investigated the pores of the juvenile wood were the least numerous.

ImageJ analysis method proved to be an useful tool in the objective (quantitative) evaluation of the microscopic structural differences between the mature wood, juvenile wood and branch wood of the same species.

The study with **ImageJ** on the **microscopy of secondary wood resource** was disseminated in 1 paper in an international journal (Gurau et al. 2010 on branch wood) and 1 paper in international conference (Dumitrascu et al.2010 on wood from thin logs).

4.4 ImageJ-imaging method for evaluating the depth of penetration for wood consolidants

This section will show another application of ImageJ, originally explored by the author, to evaluate the depth of penetration for wood consolidants, in order to assess the quality of this operation.

Consolidation of degraded and frail wood by impregnation with synthetic and natural polymeric compounds in solution is one of the most important operations of active conservation of wooden cultural heritage. The effectiveness of such a treatment depends essentially on the consolidant retention, penetration and uniformity of distribution, aspects that could be cumulated in the term of impregnation level and practically influenced by many and various factors.

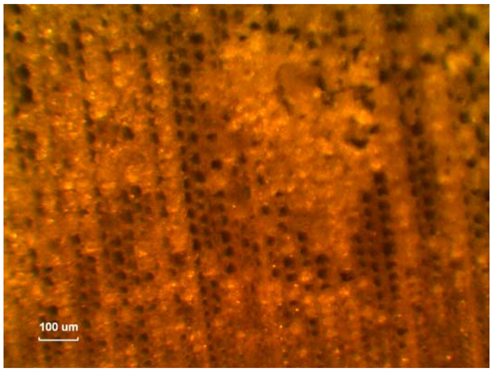
*The purpose of the following work (**Timar et al. 2010**) was to look at some practical possibilities of characterising the impregnation level achieved in some consolidation treatments with different solutions of a frequently employed synthetic polymer (Paraloid B72) and waxes (bee wax and modified paraffins as melts or in combination with linseed oil) using a simple optical microscopy technique in conjunction with an original method of samples preparation. In order to objectively appreciate the retention and penetration of consolidants into wood the method using ImageJ, a useful image processing software, was used to process the micrographs so that some quantitative estimations of the variation of the impregnation level with the penetration depth were obtained.*

Below, is presented a brief part of this study, mainly, the one showing the application of ImageJ for assessing the extent of consolidant penetration in wood.

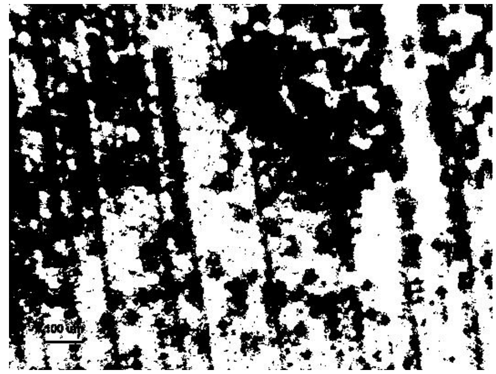
Small sound wooden samples and different consolidation products were employed in this study. The wooden samples were parallelepiped blocks of spruce wood (*Picea abies* Mill) with dimensions of (10x10x15)mm on the radial, tangential and longitudinal directions, respectively, cut from sound wood, conditioned at 20ºC and 50-55% RH, planned on the longitudinal faces and sanded with 150 grit size before treatment.The consolidation products were Paraloid B72 (an acrylic copolymer which is practically the most often used in the conservation of wood and other materials), bee wax and two types of wax modified paraffins.

The wooden samples, initially measured and weighed, were treated by total immersion for 15 minutes into the consolidation solutions/mixtures, squeezed to remove the excess of product, weighed to calculate the solution/product uptake and allowed to dry in the laboratory in normal conditions of temperature and RH (approximately 20ºC and 50-55% RH). The immersion treatment was done at room temperature (20ºC) for Paraloid B72 and on a water bath at around 80ºC for the wax and paraffin products.

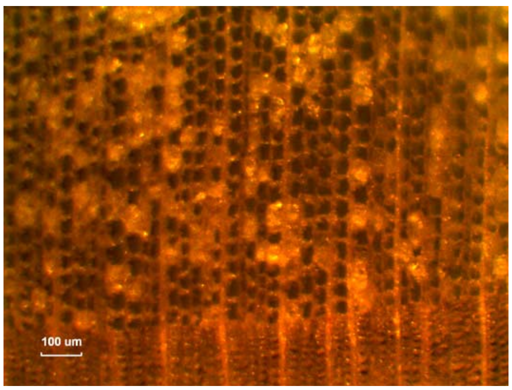
The treated samples were then weighed periodically until reaching a constant weight and the weight percent gain (WPG, in %) resulted from the consolidant retention was calculated at this point. Three replicate samples were prepared for each treating variant and a similar number of untreated samples were kept as controls.



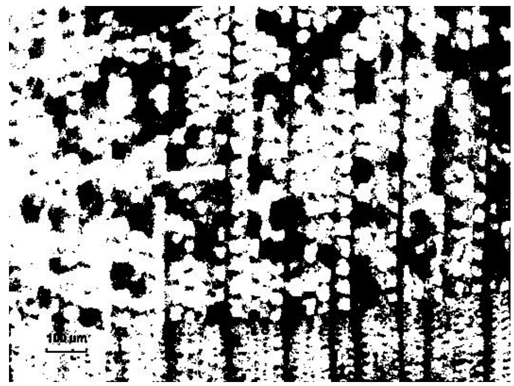
a-Micro-section 1.3 (depth~190µm), 80X



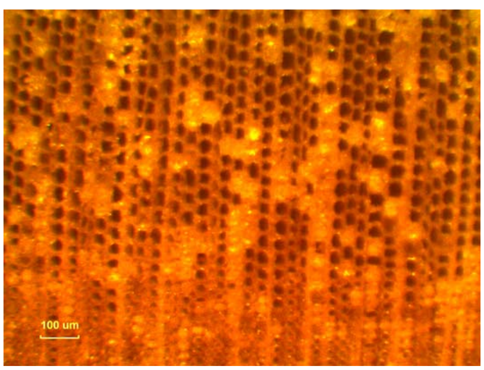
b-Mask image. Investigated area :1234.88 x 927.91mm^2; total impregnated area: 632666.292mm^2; impregnated area fraction: 55.2%.



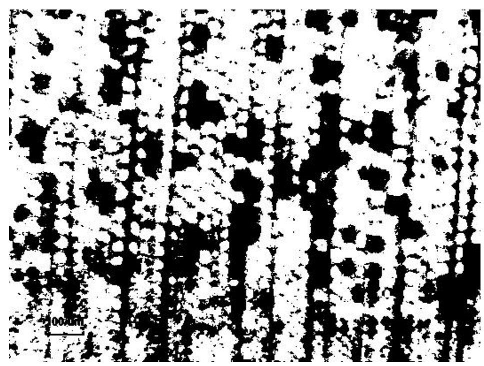
c-Micro section 2.3 (depth~280µm), 80X



d-Mask image. Investigated area : 1234.88 x 927.91 mm^2; total impregnated area: 486846.935 mm^2; impregnated area fraction: 42.5%



e-Micro section 3.3 (depth~370 µm) 80X



f-Mask image. Investigated area : 1234.88 x 927.91 mm^2; total impregnated area: 466852.343 mm^2; impregnated area fraction: 40.7%

Figure 77 Image processing and calculation of the percentage of consolidated area using ImageJ software: a,c,e - original micrographs of three successive micro-sections; b,d,f - the corresponding mask images and specific parameters (Timar et al. 2010)

To have an image of penetration and distribution of the consolidant into wood a series of thin crosssections of 30 - 60µm were cut with a microtome from the wooden samples previously plasticized by immersion in water at room temperature for 48h and trimmed with the microtome to get a clear cut surface.

To objectively asses and compare the penetration and retention of consolidants in wood in a different way than by means of a visual examination, the micro slides taken at various depths were analysed with ImageJ. For each micro slide was measured the total area covered by the substance and its area fraction.

In Figure 77 are presented comparatively the original microscopic images and their corresponding masks returned by ImageJ. Consolidant filled areas appear in black. The calculation results have shown a gradual decrease of filled areas from micro slide 1.3 to micro slide 3.3. The percentage area of the consolidant decreased from 55.2% on the micro- section 1.3, to 42.5% on the micro-section 2.3 and finally, to 40.7% for the micro-section 3.3, corresponding to the deepest area investigated. Consequently, it can be stated that the longitudinal penetration was deeper than 370μm.

Conclusions

The direct microscopic observation of consolidant retained in wood was easier for the consolidants with high solids content (waxes), which partly filled the lumens. With regard to the diluted Paraloid solutions, the lumens filling was not observed, instead the treated areas appeared very shiny and highly reflective. In brief, the simple optical microscopy technique applied in conjunction with ImageJ software could be characterised as an useful method to evaluate the quality of penetration for some wood consolidants.

The research results from chapter 4, where sections 4.2, 4.3 and 4.4 outlined the work performed by the author in the framework of the **project CNCSIS PN2 Idei(Ideas) 856/2009-"Development and implementation of an advanced scientific research methodology for sustainable wood (furniture) restoration-conservation and ecodesign**", were disseminated in 17 publications, among which:

- 2 papers in ISI Web of knowledge journals.The most cited in ISI web of Science was:
    - **GURAU,** L, TIMAR, M.C., POROJAN, M., IORAS, F. 2013. Image processing method as a supporting tool for wood species identification. ***Wood and Fibre Science***, July 2013, 45(3), p.1-11, ISSN 0735-6161 At the moment of writing, this paper had **5 citations (in ISI Web of Science)** and 15 citations in Google Scholar
- 9 Journal papers in other international databases
- 6 International conference papers
- part of the findings in section 4.3 were included in a PhD thesis defended in 2012 by Ramona Dumitrascu. The author of this habilitation thesis was member of the advisory board

5. CONCLUSIONS AND ORIGINAL CONTRIBUTIONS

Chapter 1. Although surface roughness can have a huge impact on finishing costs and the perceived quality of wood products, there is a lack of consensus on how to measure and evaluate wood surface roughness. One reason for this is that the presence of anatomical features can bias the measuring and evaluation of surface data. Consequently, the methods and recommendations given in general standards on measuring surface roughness do not apply well to wood surfaces. Therefore, the research pursued after 2005 (till present) and presented in chapter 1, has continued and complemented the doctoral research submitted in 2004 "**The roughness of sanded wood surfaces**" and has focussed on various components of wood surface metrology providing recommendations on how to best measure and evaluate surface roughness (it is referred along the habilitation thesis as "**the metrology method for wood surfaces**"). In brief, the recommendations are given in section 1.3. This metrology method gives specific recommendations regarding the selection of the measuring instrument (stylus), the length of evaluation (at least 40 mm), the measuring resolution (5 µm), removal of form error (with or without prior removal of wood pores), the use of the Robust Gaussian Regression Filter, appropriate cut-off length (2.5 mm), recommendation regarding the iterative filtering process and reduction of computation time, the best roughness parameter for describing the processing roughness (*Rk*) as well as a method to separate the processing roughness from anatomical roughness by using an Abbot-curve. It has to be mentioned, that *all metrology steps proposed in this research are available as MathCad algorithms written by the author*. ***It is for the first time that a metrology method for wood surfaces is proposed with the purpose to unify further approaches in this domain and make results between results obtained by different researchers reliable and comparable*.*These findings (algorithms), if automated in dedicated software can serve for optimisation of processing parameters in industry applications.*** In chapter 1, the metrology method was tested on oak, beech and spruce surfaces sanded with various grit sizes.

The research results from chapter 1 were disseminated, **as first author**, in **28 publications** (among which 10 papers in ISI Web of Science, 2 book chapters in international publishing houses) and were acknowledged by **138 citations in ISI Web of Science**. Detailed dissemination information is given at the end of chapter 1.

Chapter2. Once a metrology method for measuring and evaluating the quality of wood surfaces was established, it offered the multiple possibilities to apply this knowledge in various domains and materials and it is not limited to these (studies pursued especially after 2014 till present). The wood metrology method was used to evaluate the surface quality of wood, then wood modified by various thermal treatments, wood surface modified by plasma and by laser engraving. Further, the study was extended for wood based panels, as MDF and chipboard, but also wood plastic composites.***The analysis was thorough, it was based on the proposed wood metrology method, with multiple roughness parameters and, in this way, multiple aspects of the surface quality were observed, which were not discussed in previous literature publications.***

It was possible to see ***the effect in measuring the surface quality of the two wood growth areas: earlywood and latewood.*** The denser latewood was smoother and surface roughness seemed to be related to local wood density. An important conclusion from this was that measured surfaces should contain both earlywood and latewood, to be relevant for assessing surface quality of wood. ***Further analysis can include*** *the influence of tangential-radial cut, the influence of sapwood-heartwood, the influence of species type, the influence of moisture content, of wood defects (knots, sloped grain, others) on the surface roughness of wood.*

The ***studies on planing, milling and sanding thermally modified beech wood*** have shown that heat-treatment at temperatures of 200° C increases the surface roughness in comparison with the untreated wood and this effect is more pronounced with an increase in treatment duration. High heat treatment temperatures combined with long treatment durations cause a kind of surface plasticization and pull-out areas during processing. However, surface waviness, seems to decrease by thermal treatment and with the duration of the treatment.

The study on the EDS technique, was part of an international contract, where **the author was coordinator**, No. 15826/11.11.2016 "**Experimental research regarding the characteristics of beech (Fagus japonica) heat treated by EDS technology**" (2016-2017) and concluded between Transilvania University in Brasov and EDS Laboratory-Japan. Among other properties tested and concluded in section 2.2.4, the EDS treated beech wood (by smoking) had a homogenizing effect on the assortment with red heart. In EDS treated wood, the quality of the tangential surface after planing was slightly lower in the assortment without red heart and better in the assortment with red heart. The results were presented as 5 research reports. The results of the first report were disseminated in one journal paper in international database, while the other results are going to be published, too. ***In further work,*** *these studies can be extended on other species than beech, to evaluate the influence of species on the quality and other properties of thermally treated wood.*

The ***studies on the effect of laser engraving***, *the first of this kind in the literature*, on surfaces of beech and maple have shown that the surface roughness increased linearly with the laser power and decreased after a logarithmic correlation with the scanning speed. The laser is causing ridges on the surface which appear as push-up latewood bands as relate to earlywood as well as an ablation effect on wood as a level difference between the laser scanned area and the unprocessed wood. Those effects increase with the laser power and with a decrease in the scanning speed. The correlation curves of surface roughness and wood colour change can help when choosing the laser power-scanning speed combinations capable of giving the targeted colour change with minimum surface roughness. ***Further work can explore*** *the effect of laser on other species, the effect of more laser variables (scanning gap, increased powers) in order to optimize the quality of processing for aestetic applications.*

Plasma modification of wood is a relatively new approach. Zn/ZnO coatings deposited by cold plasma spraying on wood and polypropylene were investigated with regard to morphologic aspects as well as their impact on photodegradation of wood and possible sealing materials. Roughness measurements showed a slight roughness increase for particle-coated beech and a tendency of particles to increase the surface peaks as well as to reduce wood anatomical gaps, most probably by filling the wood pores to some extent. This was a good example of an interdisciplinary research where results coroborate for a better understanding of the surface morphology and material behaviour.

The surface metrology method was further applied on wood based panels and wood plastic composites. Their surface roughness is significant when panels are used as the substrate for overlays such as thin melamine paper or vinyl or, in the case of WPC, surfaces have to be smooth for a direct painting.

It was found ***that the surface quality of MDF*** manufactured from different species did not depend on the MDF density, but it was influenced by the type of species. A very low grinding gap distance, that establishes the size of the wood fibers, will not improve the surface quality of MDF panels.

No significant effect of particle thickness on the surface quality was found when investigating ***the surface quality of particleboards*** of different density and varied particle thickness in the core layer, The surface roughness and waviness of particleboards increased with a decrease in density.

By increasing the fluidity of polymers, ***the surface roughness of wood plastic composites*** decreased due to a better polymer penetration inside the wood cell cavities. At the extreme, the roughest surface was measured for WPC's where the wood flour percentage alone or in combination with mineral filler was the highest. As the amount of mineral filler was replaced with wood flour in the composition, the surface roughness of the WPCs increased. Reducing polymer content in favour of mineral filler, while keeping the same wood flour percentage has increased the surface roughness of WPC. For similar polymer and additives participation, more mineral filler complemented by less wood flour led to a slightly smoother surface. These results should be helpful to anticipate the effect on surface roughness of the percentage participation for each amount of the wood or mineral filler, polymer matrix, and additives in further development of WPC combinations.

Further work *can include the study of the influence on surface quality of more wood based panels variables, such as various species, densities, particle size as well as interdisciplinary research on various types of wood composites (wood in combination with various materials) in order to optimize their surface quality.*

The research results from chapter 2 were disseminated, in **14 publications (**9 papers in ISI Web of knowledge**)** to which can be added the contribution to one doctoral study on thermally treated wood as member of the PhD advisory board and to a second doctoral study on the laser effect on wood as surface quality consultant. Detailed dissemination information is given at the end of chapter 2. The author was **"main author" or "corresponding" author** to the vast majority of those publications.

Chapter 3. This chapter comprised another direction of research developed in parallel with the previous studies, from 2006-2016, ***about the secondary wood resource*** (***wood branches, wood from thinning operations, juvenile wood versus mature wood***), **with the purpose to find applications and add value to this ignored resource.** Inovative type of wood panels with increased aestetics were created, made of crosscut wood branches or from crosscut thin logs, in order to increase the value of this resource. The research on the characteristics and properties of the raw material was complemented with research on the physical and mechanical properties of those panels, as well as with investigations regarding the surface quality of those panels after sanding. This research was part of a **project granted by the CNCSIS (The National Council of Scientific Research in the Higher Education) type A 450/2006: "Eco-conception and eco-technology for furniture and other wood made products obtained from natural secondary resources" (2006-2008), where the author was active member**

In brief, maple and beech branch wood had similar strengths to stem wood of the same species, which makes them alternative raw materials. Maple and beech branches had higher density than stem wood, probably due to the smaller lumen diameter of fibers and vessels, while density of branch Scots pine was lower, perhaps due to the occurence of pith and the juvenile tissue around it. The values of the mechanical properties (MOE, MOR and compression parallel with the grain) of wood from thin trees of *Quercus petraea* Liebl. were very close to the values for mature trees. A comparative study of microscopic characteristics of juvenile wood of beech (*Fagus sylvatica* L.) and maple (*Acer platanoides* L.) obtained from young trunks and mature wood from mature trees of the same species has shown that pores of the juvenile wood were less numerous in beech and more numerous in maple than those in the mature wood and contained helical thickenings. Also, it was observed that wood from juvenile trunks presents relatively narrower rays compared to the mature wood and this was more obvious in maple.

The ***new type of panels manufactured from the secondary wood resource*** had lower stiffness and bending strength than other composite panels. This result is mainly attributed to the grain orientation, which was perpendicular to the panel surface rather than to the material. The use of such wood panels from secondary wood resource may be as small decorative furniture parts, which should avoid high bending stresses. The surface roughness of fir branch panels with crosscut grain were smaller than their equivalent parameters of fir branch panels with longitudinal grain, which brings an advantage to their surface quality.

For pusuing the research on secondary wood research, ***the author has used her experience in wood microscopy as well as in interpretation of wood physical and mechanical properties. Research was complemented with evaluation of surface quality of newly designed panels from secondary wood resource. Further work,*** *can extend the type of species under investigation from the category of secondary resource, including the lesser used species, in order to understand their properties and add value to their use.*

The research results from chapter 3 were disseminated, in **32 publications (**6 papers in ISI Web of knowledge**)**, 3 patents as co-author in ISI Web of Knowledge, to which can be added the contribution to two doctoral studies on secondary wood resource, as member of the PhD advisory board. Detailed dissemination information is given at the end of chapter 3. **The author, contributed as "first author" or as "corresponding author" in the majority of them**.

Chapter 4. This chapter represents another series of researches (2009-2015) developed in parallel with the ones in previous chapters. It was **an original approach to the evaluation of surfaces by using an imaging software -ImageJ**, freely available on the internet, developed at the National Institutes of Health in the United States of America. ***The author has experimented with this software on wood and wood based materials and managed to find useful and original applications.***

One of the applications of ImageJ was to evaluate the surface quality of wood based panels after being processed by drilling This operation is often causing defects appearing as pull-out zones of material around the drilled hole. ImageJ was a new and useful approach to measuring and evaluating this area of processing defect. It was analyzed the influence of the point angle of various drill types and of the feed speed on the processing quality of pre-laminated particleboard, evaluated by de size of delaminations, both, at the entrance side and the exit side of the drills. To assess the defect, the effective area of delamination was evaluated with the method of ImageJ. Generally, the delamination increased with the increase of the tooth bite (feed rate) for all drill geometries. The defect zone was larger at the entrance side of the drills compared to the exit side. The drills with the greatest tip angle, 120°, do not seem appropriate for processing pre-laminated particleboards. ***Further work*** *can be pursued to evaluate the quality of drilling for other wood based materials, such as particleboards or wood composites.*

ImageJ was also used as supporting tool, for species identification of samples detached from the structure of various objects subject to restoration. Micrographs of known species, having similar anatomy with the targeted samples, were used as references for visual comparison. Image processing with ImageJ was employed to quantify the size, proportion and frequency of main wood features. For species identification these values were further compared with data references from literature. Only one study was presented in this thesis, but, in total there were 8 studies on this subject disseminated as: 2 papers in ISI journals, 4 papers in international databases and 2 international conference papers. ***Further work*** *implies any microscopic investigation of any species of wood from objects requiring restoration, by using ImageJ.*

A similar application of ImageJ was employed for evaluating the microscopic characteristics of a less known material, the secondary wood resource, in comparison with wood from stem. Compared with a subjective visual examination of the micrographs, ***ImageJ was used, because it offers an objective quantitative method to separate, measure and statistical data process for some anatomical features of interest.*** Compared to the mature stem, but also with juvenile wood from thinning operations, the branch wood of beech had smaller and more numerous pores. The pores of the juvenile wood were the least numerous. ImageJ analysis method proved to be an useful tool in the objective (quantitative) evaluation of the microscopic structural differences between the mature wood, juvenile wood and branch wood of the same species. ***Further work*** *can examine the microscopic characteristics of secondary wood resource from other species than beech, in order to understand their characteristics in combination with their physical and mechanical properties for potential applications.*

Another application of ImageJ was to evaluate the depth of penetration for wood consolidants, in order to assess the quality of this operation. The deeper and wider the penetration, the most successful the operation. ImageJ was used to process the micrographs so that some quantitative estimations of the variation of the impregnation level with the penetration depth were obtained. The direct microscopic observation of consolidant retained in wood was easier for the consolidants with high solids content (waxes), which partly filled the lumens. With regard to the diluted Paraloid solutions, the lumens filling was not observed, instead the treated areas appeared very shiny and highly reflective. The longitudinal penetration was deeper than 370µm in case of treating spruce. ***Further work*** *can include a diversity of consolidants and wood species to determine if the consolidant depth of penetration is species dependent.*

The last three applications were performed by the author in the framework of the **project CNCSIS PN2 Idei(Ideas) 856/2009-"Development and implementation of an advanced scientific research methodology for sustainable wood (furniture) restoration-conservation and ecodesign"** where the author was active member.

The research results from chapter 4 were disseminated, in **23 publications (**2 papers in ISI Web of knowledge**),** to which can be added the contribution to one doctoral studies on the microscopy of secondary wood resource, as member of the PhD advisory board. Detailed dissemination information is given at the end of chapter 4. **The author, contributed as "first author" or as "corresponding author" in the majority of them**.

The author research contribution presented in this thesis was not exhaustive. Only the subjects somehow related to the thesis title were maintained. One such example is the study by **Timar *et al.* (2016)** on the comparative study of photodegradation of six wood species after UV exposure, published in ***Wood Science and Technology*** (**1.509 impact factor in 2016**) and **cited 16 times** in ISI Web of Science.

The overall research results from 2005-2019 were validated by **156 citations(without self-citation) in ISI Web of Science** (**h-index 7**). The most important are **29 papers in ISI Web of Science** (21 as first author and 2 as correspondent), 2 book chapters in international publishing houses (ISTE-Willy for example), 5 books-Ed.Transilvania Univ., 20 papers in journals indexed in international databases (11 as first author), 43 papers in international conferences (7 in international databases) and 3 patents in ISI Web of Science-Dervent.

<u>Ongoing and further work:</u>

Apart from the studies included in this habilitation thesis, there is also ongoing research, whose results were not yet published. One such example is about ***the influence of natural and artificial weathering on the surface roughness of various wood species***. Surface roughness serves as an indicator for the degradation stage of the surfaces subjected to weathering. These studies, facilitated by an internal research grant awarded through competition by the Transilvania University of Brasov, represent a joint international research with Ecole Superieure du Bois, Nantes, France, aiming to contribute to a PhD study (Julia Buchner-enrolled at ESB). Another ongoing study, with the same partners is ***investigating the effect of laser on wood*** as a continuation of the studies in chapter 2, section 2.3.

The author of this habilitation thesis **coordinates, as UTBv partner, two international projects**, which are ongoing at this moment of writing. They will contribute to develop the research and academic activities of the author on furniture creativity and innovative materials and technologies for furniture:

- DITRAMA – “Digital transformation manager: leading companies in Furniture value chain to implement their digital transformation strategy”, PN: 601011-EPP-1-2018-1-ES-EPPKA2-SSA,with 12 partners from 8 European countries, t**otal grant: 994094 euro; UTBv share:46175 euro**. Period of implementation:**01/01/2019-31/12/2021.** *The **wood furniture** manufacturing industry will offer **personalised smart products and services based on digital manufacturing systems** supplied by resource-efficient and sustainable industries with an immense **need for enough digitization talents and skills** securing a competitive transformation of the industry*.

- FACET- “Furniture sector Avant-garde Creativity and Entrepreneurship Training”, PN: 2018-1-IT01-KA202-006734, **total grant: 324163 euro; UTBv share: 25342 euro**. Period of implementation: **01/11/2018-04/30/2021**. FACET project will guide professionals through the idea creation and implementation process improving their **creativity** and entrepreneurship skills **as they work in projects**

Apart from the ideas of further work outlined in this concluding chapter, ***the possibilities are unlimited.*** Surface quality remains a subject of interest ***for any material based on wood, any processing, any wood treatment or modification process***. It is also ***open to interdisciplinary research, where wood combines with other materials***. By knowing the real values of surface roughness and by understanding the surface morphology, the processes can be optimized and costs will be reduced.

Not only surface quality will be envisaged by further studies. The author has proved abilities in researching wood physical and mechanical properties, in wood microscopy, but also in wood modification and treatments, knowledge which can be used and developed in joint research, and generate and supervise thorough PhD studies.

It is important that studies on surface roughness are facilitated by a performing instrument: a MarSurf XT20 manufactured by MAHR GMBH (Gottingen, Germany) at the university research institute (ICDT) which was acquired with the contribution of the author in the framework of the structural funds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, ctr. No 11/2009), which, virtually, requires no cost for measurements.

(B-II) THE EVOLUTION AND PLANS FOR CAREER DEVELOPMENT

1. PROFESSIONAL CAREER EVOLUTION

a. STUDIES

- **Academic studies**

1982 -1987	**Transilvania University Brasov**, *Facultatea de Industrializarea Lemnului/Faculty of Wood Industrialization*, specialization *Art Furniture* **- DIPLOMA OF ENGINEER** no. 6452/24.06 1987(series F, no.2402), in the field of *Forestry*, majoring in *Wood processing* (**grade of 10 in the Diploma Examination**)

- **Doctoral studies**

2000-2004	**Brunel University**, Great Britain, **DOCTOR OF PHILOSOPHY** awarded on the 25th of May 2004, equivalated in Romania by Doctor of Philosophy in ***Industrial Engineering*** domain- diploma no.8982/16.06.2005 (series G, no.0001219), issued by the Ministry of Research, Education and Youth

- **Other specializations and qualifications**

2000	post-graduate course " English for Technical and Business Purposes in Wood Industry" organised by CECECOS, "Transilvania" University Brasov- **Certificate of Language Proficiency**, no.190/30.01.2008, corresponding to level B2 of the Common European Framework of the Council of Europe
2000-2003	programming in MathCad 2000 Professional- Buckinghamshire Chilterns University College, UK
2002	training in C++ BORLAND 5
2008	"ISO 9000:2000:Lead auditor training course" BM TRADA ,UK- **Lead Auditor** certificate- (no. A17110). certified by IQA-IRCA

b. PROFESSIONAL AND ACADEMIC EXPERIENCE

The professional experience of the author of the habilitation thesis began in 1987, after graduating the Faculty of Wood Industrialization, through the following stages:

1987– 1990	IPL Gheorgheni (Wood processing company), Harghita county, as ***production engineer***
1990 – 1996	"MAGURA" Codlea (Wood processing company), Brasov county, as ***project engineer***

	and ***engineer responsible with quality*** of raw materials and furniture products
1996-1998	Self employed person- ***project engineering and design***
Oct 1998- Sept. 2005	Transilvania University Brasov, *Faculty of Wood Engineering*, ***university assistant***, position obtained through competition at the Department of Wood Technology
Oct 2005- Sept.2008	Transilvania University Brasov, *Faculty of Wood Engineering*, ***lecturer***, position obtained through competition at the Department of Wood Technology
Oct 2008- prezent	Transilvania University Brasov, *Faculty of Wood Engineering*, ***associated professor***, position obtained through competition at the Department of Wood Technology

Production experience in technological, product design and quality evaluation activities

In the eleven years of being involved in technological, product design and quality evaluation activities (1987 - 1998), the author of the habilitation thesis has enriched her professional experience by:

- taking responsabilities with the quality of raw material as well as of furniture products
- taking responsabilities with technological and product design, studying and analyzing the technical and technological documentation from the external clients and adapting them to the technical and technological conditions of the company;
- computer-aided design (Auto CAD) since 1995
- drawing up the technical and technological documentation for furniture manufacturing
- collaboration with a management team from abroad, representative of IKEA company, for 2 years, at the furniture factory Măgura Codlea S.A as engineer responsible with the quality of furniture

Academic experience. Teaching, students supervision

During 1996-1998, the author undertook lectures, as ***associated academic staff,*** at the Faculty of Wood Engineering, getting in touch with first academic duties and pusuing applications (projects and laboratory work) in disciplines as: "*Furniture manufacturing*", "*Furniture design*", "*Stiles and ornaments in furniture*".

In 1998 obtained through competition the position of ***university assistant*** at the Faculty of Wood Engineering, the Department of Wood Technology, when she took the application activities for new disciplines as "*Wood science*" (year I), "*Physical and mechanical properties of wood*"(year II), as well as "*Art furniture technology*".

During 2000-2004, the author interrupted the teaching activities and performed a ***doctoral study*** in the UK. She returned in Oct.2004 and resumed the teaching activities, promoted to ***lecturer*** position (2005) and began to teach new courses in English, for the new born program in English "*Wood Science and Technology*" of the faculty: „*Furniture manufacturing"-in English* (years IV and V), „*Art furniture manufacturing*"*-in English* (year IV), „*Design*"*-in English* (year III), „*Unconventional technologies*"*-in English* (year IV) and „*Furniture*" in Romanian language,

From the last academic promotion in 2008 to ***associated professor***, new courses, laboratoy and project work, in Romanian language, were developed, as **course leader**:

- for undergraduate programs: „*Unconventional technologies*", „*Study of wood properties*", „*Furniture technology*", „*Furniture design*"(the most recent).

-- for master programs: „*Furniture design and basics of ergonomics*", „*New trends in furniture design*", „*Technologies and innovative materials*"

Other academic performances:

- **coordinator of diploma and disertation projects**- in average, 5 students every year
- **yearly coordinator or member of the examination board** in diploma and disertation evaluations
- **yearly awards** received for **student research achievements** participating to ***the Students Scientific Research Sessions***, as research coordinator (https://www.unitbv.ro/studenti/evenimente-anuale/1216-scss.html)
- **yearly awards** received for student research achievements participating to **AFCO conference** (https://www.unitbv.ro/studenti/evenimente-anuale/2789-absolventi-in-fata-companiilor-afco.html)
- **coordination of research activities with students** and **dissemination of results** in the international research journal ProLigno, indexed by international databases (ProLigno 2010 6(4): 43-54; ProLigno 2012 8(2): 3-11 http://www.proligno.ro/ro/index.htm)
- **Faculty Erasmus Coordonator** organising students and teaching staff mobility, implementing 21 bilateral agreements with partner universities from Europe (2004-2012).
- **coordinator of the undergraduate study program**: ***Wood Products Engineering and Design*** (since 2011)- two re-accreditations (in 2014 and 2019)
- teaching activities as **visiting professor** at Technical University in Zvolen,Slovakia, Department of Manufacturing Technology and Quality Management by CEEPUS III Mobility Grant (15-20.02.2016)
- teaching activities as Erasmus **visiting professor** at École Supérieure du Bois, Nantes, France (5-9.09.2016) and Bucks New University, High Wycombe, UK (18-27.02.2017)
- **member of the doctorate tutorial panel** for 8 PhD thesis

Contribution to improve the research infrastructure:

- the author has contributed to the acquisition of a performing **equipment for metrology of surfaces (measurements of surface quality)**: a MarSurf XT20 instrument, manufactured by MAHR GMBH (Gottingen, Germany), located at the university research institute (ICDT). It was acquired in the framework of the structural funds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, ctr. No 11/2009). This equipment has served for research in the domain of expertise of the author. ***The doctoral students will have access to this performant equipment to carry out the doctoral research programs under the supervision of the author of this habilitation thesis***.

Abilities and competences:

- wood properties, metrology of wood surfaces,, furniture design, furniture technology, inovative materials and technologies for wood industry

Managerial competences:

- vice dean of the faculty (responsible with research) (from May 2012)
- coordinator of the international conference ICWSE („Wood Science and Engineering in the Third Millennium") in 2013, 2015, 2017, 2019.
- coordinator of the undergraduate study program: *Wood Products Engineering and Design* (since 2011)- two re-accreditations (in 2014 and 2019)
- coordinator of 2 international projects granted by competition (DITRAMA-46175 euro UTBv share and FACET-25342 euro UTBv share) and of 1 international contract (16109.41 euro).

c. DEVELOPMENT OF THE SCIENTIFIC CAREER

The scientific research of the author, began with the studies on the surface quality of sanded wood surfaces during the PhD period (2000-2004). Those studies were finalized with a PhD awarded by Brunel University, UK, in 2004, for the thesis "*The roughness of sanded wood surfaces*". After those initial studies, the research directions can be grouped into three main groups:

- **Studies continuing the PhD subject in the surface quality of wood surfaces from 2005 at present**. They were developed as a set of recommendations for wood surface metrology and were tested on wood (after various processing, thermal treatments, plasma treatment, laser engraving) and wood based products (MDF, chipboard and wood plastic composites).
- **Studies about the characteristics, properties and quality of the secondary wood resource** (wood branches, wood from thinning operations, juvenile wood versus mature wood) and its application in value-added products **(2006-2016)-**wood microscopy, physical and mechanical properties, surface quality of the raw material and of inovative panels with crosscut grain
- **third research direction (2009-2015)** was to explore, for the first time, the potential in **evaluating the various aspects of the wood surface morphology of using an imaging**

software-ImageJ: wood species identification for restoration purposes, microscopy evaluation of secondary wood resource,, evaluation of surface quality and processing defects, evaluation of wood consolidants depth of penetration

The research results, their scientific relevance and impact are presented synthetically below.

Publications:

- publication of **29 papers in ISI Web of Science** (21 as first author and 2 as correspondent).:
  - 25 papers in ISI Web of Science in journals ***ranked as top journals*** according to CNCSIS criteria (**red zone for the majority**), 1 review paper with impact factor 3.548- Gurau and Irle (2017).
  - 4 papers in ISI Proceedings
- publication of **20 papers in journals indexed in international databases** (11 as first author), respectively CABI, DOAJ, DRJI, EBSCO Publishing Ltd. Academic Search Complete, INDEX COPERNICUS, Google Scholar;
- publication of 43 papers in **international conferences** (**7 in international databases**) and of 6 in national conferences
- publication of **2 book chapters in international publishing houses** (ISTE-Willy and NOVA Science Publishers) as first author and of **1 book**
- publication of **5 books** (2 as sole author)-Ed.Transilvania University
- recognition of **3 patents in Web of Science-Dervent (co-author)**

Projects,contracts, other grants as manager-Capacity to coordinate research teams:

- coordination as UTBv **project manager of two (2) international projects** granted through international competition:
  - DITRAMA – "Digital transformation manager: leading companies in Furniture value chain to implement their digital transformation strategy", PN: 601011-EPP-1-2018-1-ES-EPPKA2-SSA,with 12 partners from 8 European countries, t**otal grant: 994094 euro; UTBv share:46175 euro**. Period of implementation:**01/01/2019-31/12/2021.**
  - FACET- "Furniture sector Avant-garde Creativity and Entrepreneurship Training", PN: 2018-1-IT01-KA202-006734, **total grant: 324163 euro; UTBv share: 25342 euro**. Period of implementation: **01/11/2018-04/30/2021**.
- coordination as **UTBv partner in other (1) research international project financed by The Federal Ministry of Education and Research, Germany**:
  - International research project: „Networking of Wood Research Centers of the Danube Region to improve the educational, scientific and economic efficiency and infrastructure of the Regions due to a strengthened competitiveness of wood material and products-Danube Wood Region" (79.317 euro total project grant- financial coordination of mobility and workshops, exclusively of the German coordinator, UTBv- 0 funds)

- coordination as **project manager** of one (1) international research contract with Japan:
  - International contract No 15826/11.11.2016 “Experimental research regarding the characteristics of beech (Fagus sylvatica) heat treated by EDS technology/Cercetări experimentale asupra caracteristicilor materialului lemnos din specia Fag, tratat termic prin procedeul EDS” (with Japan) (**Total UTBv: 16109.41 euro**)
- 2 **research grants** (2500 euro each) awarded through competition by Transilvania University Brasov- for performing **research activities** at Ecole Superieure du Bois, Nantes, France (2-15.10.2016 and 9-18.11.2018).

Projects,contracts, other grants as member:

- member in 4 other international research projects:
  - International project 186/25.07.2006: “Designers’saturday: thinking with your hands. designing with your hands” (**43160 euro**) (2006-2007)
  - International project 5480/14.04.2011: “Window and wall” (**14000 euro** UTBv share) (2011)
  - International project 2682/23.02.2012 “Inside-Outside-in between” (**14000 euro** UTBv share) (2012)
  - International project CEEPUS Sk-0310-0815/2008: “Non traditional processes in production technologies and integration of the study and research in the Eastern and Central Europe universities” (**10000 euro**) (2008-2016)
- member in 4 **national projects awarded by national competition**:
  - Project granted by the CNCSIS (The National Council of Scientific Research in the Higher Education) type A1339/2004 “Scientific excellence network in the woodworking industry to integrate romania in the EU in 2007” (2004-2006). **Grant value: 136000 RON**.
  - Project granted by the CNCSIS (The National Council of Scientific Research in the Higher Education) type A 450/2006: “Eco-conception and eco-technology for furniture and other wood made products obtained from natural secondary resources” (2006-2008). **Grant value: 136000 RON**.
  - Project PN2 IDEI(IDEAS) 146/2007 “Modelling to sustainable promotion of wooden products and technologies with impact on the environment quality” (2007-2010). **Grant value: 784705 RON**.
  - Project PN2 IDEI(IDEAS) 856/2009 “Development and implementation of an advanced scientific research methodology for sustainable wood (furniture) restoration-conservation and ecodesign” (2009). **Grant value: 94473.65 RON**.
- member in one (1) national contract:

- o Research contract C176/6.07.2006 signed with The National Wood Institute Bucharest: “Wood protection according to the using domain for an efficient use and competitiveness of wood products” (2006-2007). **Value: 50000 RON**

The previous as well as the on-going research projects, in which the author was involved as project coordinator or as member, have led to the consolidation of ***a strong research team*** with members of the faculty, as well as with international connections, which represents the ideal environment for the further ***PhD students to develop their studies, receive proper supervision and guidance***.

Scientific recognition and impact of the research activity:

- **156 citations in ISI Web of Science (h-index 7)** and **507 citations in Google Scholar (h-index 16)**
- **Reviewer to 20 scientific journals, among which 17 ISI journals (yearly reviews certified by PUBLONS):**

- *Wood Science and Technology*, **ISI journal,** Journal of the International Academy of Wood Science, SPRINGER, New York, USA, ISSN 0043-7719
- *Wood and Fiber Science*, **ISI journal,** Soc Wood Sci Technol, Madison, USA, ISSN 0735-6161
- *European Journal of Wood and Wood Products* (Holz als Roh- und Werkstoff), **ISI journal,** SPRINGER, New York, USA, ISSN: 0018-3768 (print version), ISSN: 1436-736X (electronic version)
- *BioResources,* **ISI journal,** North Carolina State Univ Dept Wood & Paper Sci, Raleigh, USA, ISSN: 1930-2126
- *Journal of Adhesion Science and Technology*, **ISI journal,** ISSN 0169-4243 (Print), 1568-5616 (Online)
- *Wood Material Science and Engineering*, **ISI journal,** Taylor & Francis Ltd, Abingdon, England, ISSN: 1748-0272 (Print), 1748-0280 (Online)
- **Associated editor** to “*International Journal of Surface Engineering and interdisciplinary Materials Science*” (IJSEIMS)-in **international database** (SCOPUS), IGI Global, Hershey, USA, https://www.igi-global.com/journal/international-journal-surface-engineering-interdisciplinary/59713 ISSN: 2166-7225
- *The International Journal of Manufacturing, Materials, and Mechanical Engineering* (IJMMME), **ISI journal,** IGI Global, Hershey, USA, ISSN: 2156-1680, EISSN: 2156-1672
- *Scientific Research and Essays*, in **international database**, Academic journals, ISSN 1992-2248, http://www.academicjournals.org/journal/SRE,.
- *International Journal of Conservation Science*, **ISI journal,** Univ Alexandru Ioan Cuza Iasi, Arheoinvest Interdisciplinary Platform, Lab Sci Inves & Conservation, Iasi, Romania, Print ISSN: 2067-533X; Online ISSN: 2067-8223
- *Bulletin of the Transilvania University of Brasov*, in **international database** (SCOPUS https://ores.su/en/journals/bulletin-of-the-transilvania-university-of-brasov-series-ii-forestry-wood-industry-agricultural-food-engineering/,), Transilvania University Press, Brasov, Romania, SERIES II-WOOD INDUSTRY , ISSN 2065-2135 (Print), ISSN 2065-2143 (CD-ROM)
- **Member of the scientific committee***, ProLigno*, in **international database** (EBSCO, CABI, DOAJ, DRJI), Transilvania University Press Brasov, online ISSN 2069-7430; ISSN-L 1841-4737,
- *Computers and Electronics in Agriculture*- **revista ISI**, Elsevier Sci Ltd, Oxford, England, ISSN: 0168-1699
- *Drvna Industrija*, **ISI journal,**, Zagreb Univ, Fac Forestry, Zagreb, Croatia, ISSN 0012-6772 (print), ISSN 1847-1153 (Online)
- *Maderas Ciencia Y Technologia*, **ISI journal,** Univ Bio-Bio, Wood Engineering Dept, Concepcion, Chile, ISSN 0718-221X
- *Annals of Forest Science*, **ISI journal,**, Springer France, Paris, France, ISSN: 1286-4560

- *International Wood Products Journal,* **ISI journal**, TAYLOR & FRANCIS LTD, Abingdon, England,ISSN: 2042-6445
- *Turkish Journal of Agriculture and Forestry,* **ISI journal,**, Tubitak Scientific & Technical Research Council, Ankara, Turkey, ISSN: 1300-011X
- *Acta Facultatis Xylologiae Zvolen,* **ISI journal,**, Technicka Univ Zvolene, Zvolen, Slovakia, ISSN: 1336-3824
- *African Journal of Agricultural Research-AJAR,* **ISI journal,**, Academic Journals,, Nigeria, ISSN: 1991-637X

- **Member of the scientific committee, chairwoman in international conferences**
- **Organizer and proceedings editor** of the international conference ICWSE ("Wood Science and Engineering in the Third Millennium") in 2013, 2015, 2017, 2019
- **scientific referee** to one PhD defence-Faculty of Wood Engineering
- **International Opponent** in the PhD thesis defence (domain of Wood Science and Engineering) "*Studies on Industrial-Scale Thermal Modification of Wood*" presented by Mr. Ola Dagbro at Lulea University of Technology, Division of Wood Science and Engineering, Department of Engineering Sciences and Mathematics, Skelleftea Sweden (16.06.2016)
- **Member of the National Council for the Attestation of Academic Titles, Diplomas and Certificates (CNADTCU),** panel of "Industrial engineering and management" (28.03.2011-6.09.2012)
- **Member of the Scientific Council** of the Transilvania University (from Oct.2012)
- **Member of the Editorial Council** of the Transilvania University Publishing House (from Dec.2012)

Fulfillment of the criteria corresponding to the necessary minimum and mandatory CNADTCU standards for the commission "Engineering of plant and animal resources":

CNADTCU criteria		**Done**	**Minimum required**	
Criteria A1 "Didactic and professional activity"		**178.85 points**	**100 points**	
Criteria 1.1.*"Books and book chapters in specialty books"*	books	6	2	
	book chapters	2		
	First author	4	2	
	Published after the last promotion	6	1	
Criteria A2 "Research activity"		**1360.43points**	**260 points**	
Criteria 2.1."*Articles in extenso in ISI Thomson Reuters and proceedings indexed Thomson Reuters*"	ISI journals	25	4	8
	ISI proceedings	4		
	Main/correspondent author-ISI journals	20	2	4
	Main/correspondent author-ISI proceedings	3		
	Published after the last promotion	25	3	
Criteria 2.2."*Articles in journals and scientific proceedings indexed in other international databases*"(BDI)	BDI journals	20	15	
	BDI proceedings	7		
Criteria 2.3."*Intellectual*	Patents (as co-author)	3	-	

property, patents"				
Criteria 2.4."*Grants/projects won by competition, including research projects/consultancy* (minimum value 10000 euro)"	Director/responsible/partner-2 international projects, 1 international research contract		3	2
	Member	international	4	-
		national	5	
Criteria A3 "Recognition and activity impact"			**1311.11points**	**60 points**
TOTAL			**2850.39points**	**420 points**

2. CAREER DEVELOPMENT PLANS

a. DIDACTIC ACTIVITY

For the author of the present thesis, a major objective in the development of the professional career is **to improve the performances in the didactic activity**, by applying and perfecting communication skills and competences, transferring knowledge to students, masters, doctoral students. In this sense, the author of the habilitation thesis has the following goals:

- *introduce, where applicable, the research results in the didactic material (course support, applications)*
- *curricular development by implementing the knowledge from the two new projects (DITRAMA and FACET) and the results from their research. Involvment of students in the activities of these two projects*
- *emphasize the practical and applicative aspect of the information, in order to create the bridges between the acquired knowledge and the economic environment*
- *use of modern and interactive methods of training and teaching*
- *coordinate students and masters in the elaboration of their diploma and dissertation projects, inserting elements of research, in order to stimulate them for pusuing further research and studies in doctoral stages*
- *further publication of books and teaching material*
- *launch research projects involving students, masters, doctoral students;*
- *continue to improve the study program "Wood Products Engineering and Design ", as coordinator, by taking into account the observations and proposals of the students, maintain its accreditation and increase its degree of attractiveness to students*.

b. SCIENTIFIC ACTIVITY

As far as the scientific activity is concerned, the plans are:

- *to attract funds through national and international programs, to enhance both scientific and didactic research;*

- *to initiate and develop research teams with young researchers from all programs of study (undergraduate, master, doctoral), attracting them in interesting and up-to-date subjects, in scientific research projects.*
- *supervision of PhD researchers, coordinating them to respond to the real needs in the sector, linking research with practical/industrial applicability*
- *to continue participation as consultant in PhD advisory panels*
- *efficient use of research infrastructure from the university institute, in its multiple variety, in interdisciplinary projects, sharing ideas and experience with other university departments*
- *strenghtening further the international research cooperation,* ***facilitating access of PhD students to international laboratories*** *to enhance and complement experiences. In this sense, the international network,,****Networking of Wood Research Centers of the Danube Region to improve the educational, scientific and economic efficiency and infrastructure of the Regions due to a strengthened competitiveness of wood material and products- Danube Wood Region****" (2017-2019), where the author is* ***UTBv responsible****, has created a catalogue with research infrastructure and devices from each of the 10 partners, allowing exchange of staff and access to equipment, to optimize and strengthen joint research. This collaboration will continue in joint projects, seeking for EU funds*
- *to continue publishing the scientific results in high impact factor ISI journals,as well as in journals indexed in international databases*
- *to pursue presentations in international conferences,review papers in international high ranked journals, in order to increase the international visibility;*

Future research ideas for PhD supervision

Future research, can issue from the subjects opened by the studies in this thesis, but will not be limited to these and will be mainly addressed to doctorate students.

The metrology method for wood surfaces, proposed in this thesis with the purpose to unify further approaches in this domain, ***can be further automated in dedicated software*** and serve for optimisation of processing parameters in industry applications.

Apart from the research studies outlined in this thesis, ***the possibilities are unlimited***. By knowing the real values of surface roughness and by understanding the surface morphology, ***the processes can be optimized and costs will be reduced***. Further research can be pursued:

- *to evaluate the surface roughness for other types of processing with the purpose of understanding the influence of process variables on the surface quality and processing optimisation (eg. milling, planing, sawing, turning, others). Identification of improper selection of tool and technological parameters for the species being machined and optimization of their selection*
- *to evaluate the surface roughness for different types of materials based on wood (chipboard, MDF, other wood based composites), optimize their composition and processability for increasing their surface quality*

- *to evaluate the surface roughness of wood after various treatments (superficial or in depth treatments), in order to see the effect they have on the surface quality (thermal treatments, plasma treatments, preservation treatments, other treatments) and improve wood properties (stability, durability,adhesion)*
- *to identify the surface quality after various surface coating in finishing applications to optimize the process and reduce the costs*
- *to evaluate the influence of surface roughness on wood adhesion and strength of joints*
- *to examine the effect of laser variables (laser power, scanning speed,scanning gap) on various wood species in order to optimize the quality of processing by engraving for aestetic applications.*
- *explore the influence of natural and artificial weathering on the surface roughness of various wood species and of the effect of wood preservatives. Surface roughness serves as an indicator for the degradation stage of the surfaces subjected to weathering.*

Other subjects of research could be those:

- *to further explore the properties of the secondary wood resource (a larger range of wood species) in order to increase their value and find new products and design ideas for industrial applications*
- *to further use of the ImageJ method to evaluate the surface defects at processing wood based panels (MDF, particleboards, wood composites) and optimization of process parameters*
- *for exploring the creativity potential in furniture manufacturing by integration of wood waste materials and search for their industrial validation*

(B-III) BIBLIOGRAPHY

(B-III) BIBLIOGRAPHY

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