



## Classificazione e caratteristiche del materiale legno

Prof. Dr. Jan-Willem van de Kuilen

*Professore Ordinario  
Wood Technology - TU Munich  
Biobased Structures and Materials – TU Delft*



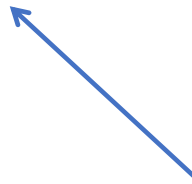
29/04/2021



# CONFERENCE TRACK TOUR 2021



Sumitomo forestry, Tokyo, 350 m  
70 Floors, Est. 185.000 m<sup>3</sup> of CLT  
Completion in 2041



Progettazione

BIM

Sicurezza

Affidabilità

Resistenza

Assistenza tecnica

Risorse (disponibili)

Prezzi / Costi

Sostenibilità



Durabilità

Produzione

Trasporto / Montaggio

Sito di costruzione

Riciclo / Circolarità

Estetica

Prestazione

Preferenze sociale / personale

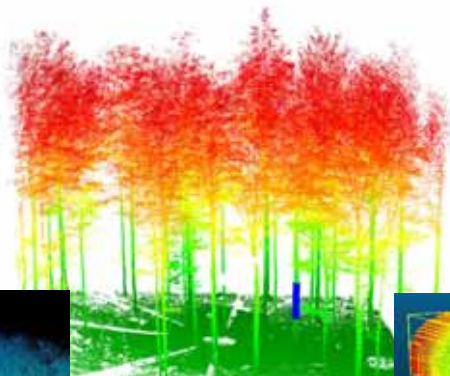


Hotel Jakarta, Amsterdam, 32 m  
2+8 Floors, CLT – 3D modules  
Completed in 2018

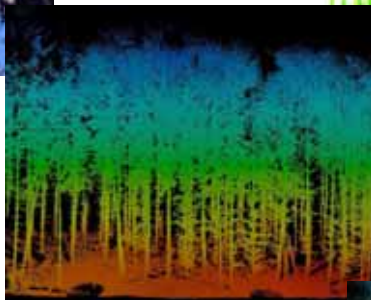
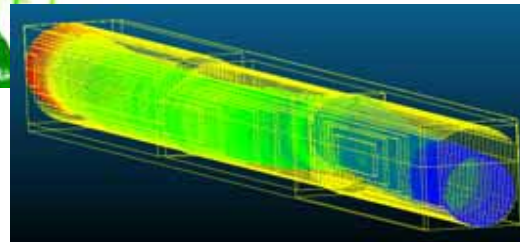




# CONFERENCE TRACK TOUR 2021



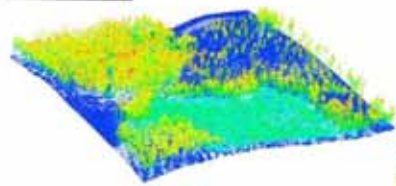
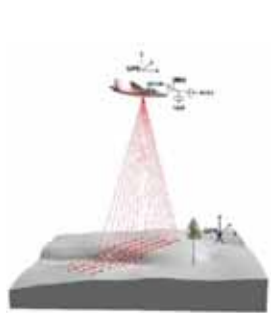
La filiera...  
(almeno una piccola parte...)



Scopo:  
automatizzazione completamente del  
intera filiera del legno, per produrre  
prodotti per l'ingegneria strutturale  
con il massimo valore aggiunto



Aerial surveillance  
Ground surveillance  
Terrestrial laser scanner (TLS)  
Stereophotography



Tree shapes (Diameter, Branch angles)  
Stem quality: shape / taper  
curvature, length, roundness



## Forest scanning – Scansione laser (Google trees)

### 3D-Scanning nelle foreste

- Analisi forestale (quantità / qualità)
- Qualità dei tronchi
- Qualità interna (?)

### Come?

- LIDAR (Light + Radar)
- Terrestrial laserscanning
- Stereofotografia

### Risultato: Immagini forestali di alta risoluzione

- Processi decisionali
- Mercato del legname
- Clienti nella filiera del legno
- Studi ambientali, biodiversità, sequestro del carbonio

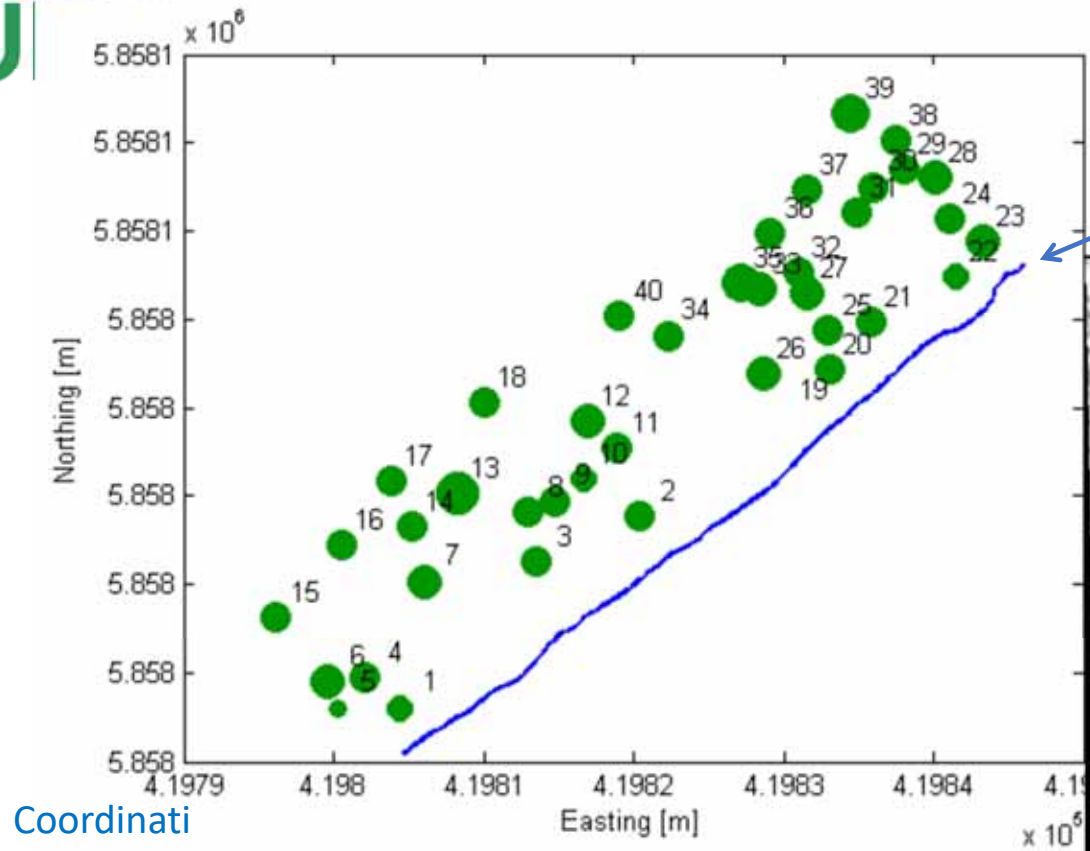


Douglasia in Bavaria, 360° scan

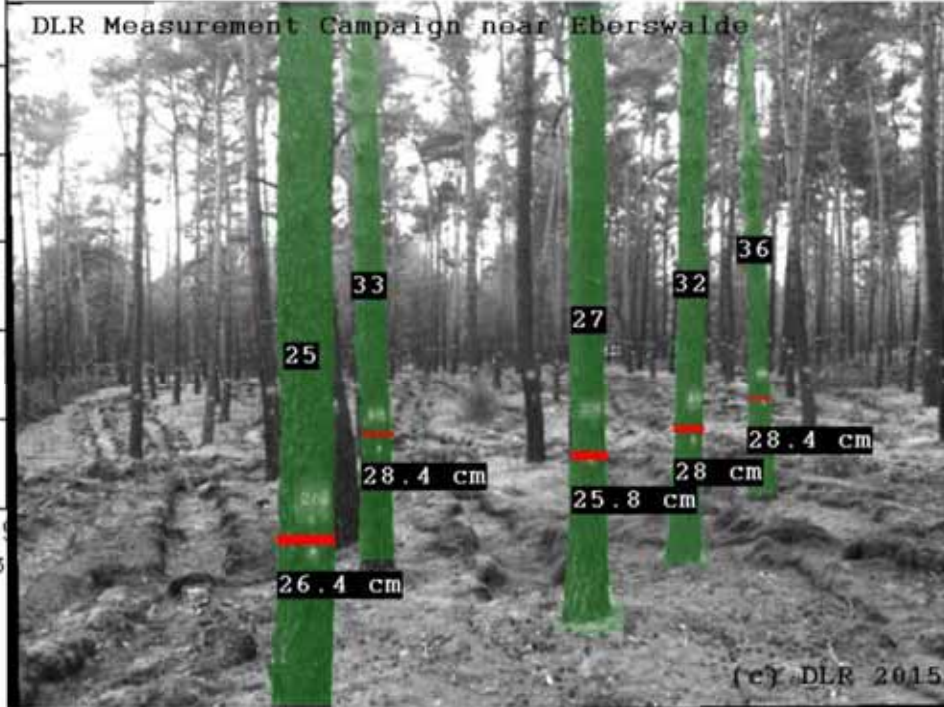




Google trees!



Scansione laser,  
direttamente dalla  
strada forestale.



Courtesy DLR



## Forest scanning for wood quality

Ogni albero è registrato

Tronchi, Lunghezza, Spessore.

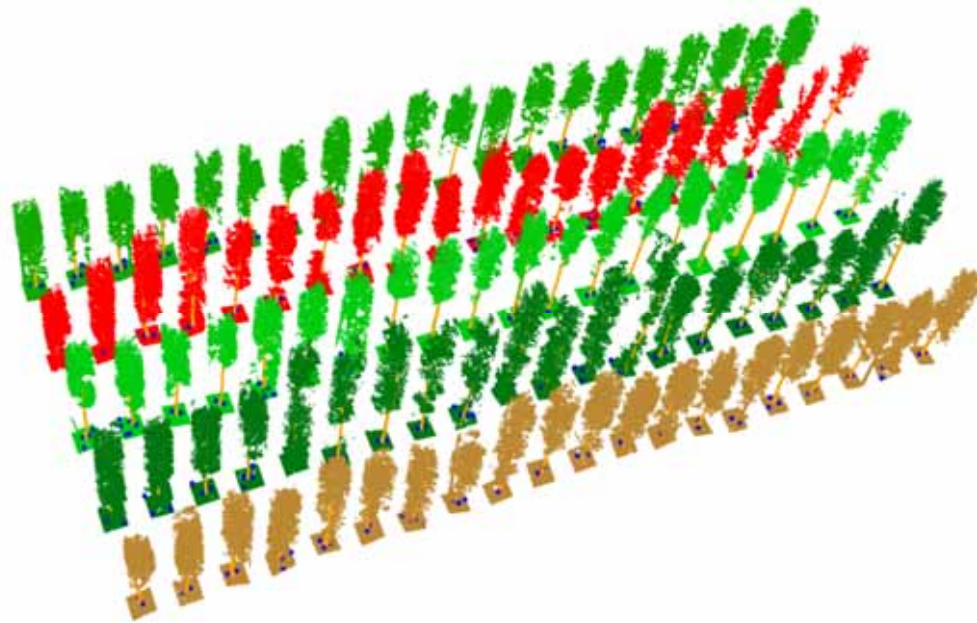
Previsione della nodosità e qualità del legno sulla base dei rami (diametro, angolo).



5mm – 2500 m  
Riegl - scanner



## 3D Tree scanning in (mixed) forests



Faggio in vari tipi di foreste:

- Querce
- Abete
- Faggio
- Douglasia
- Pini

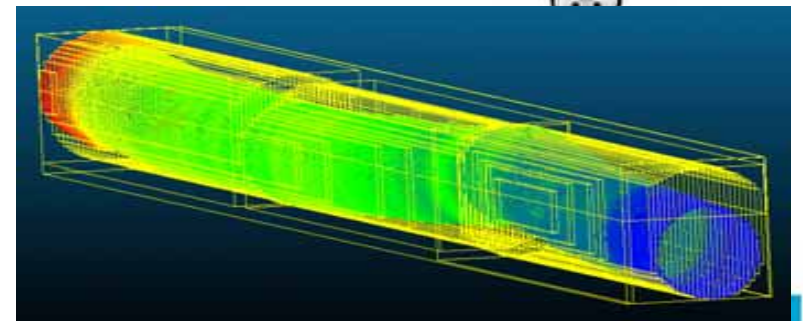
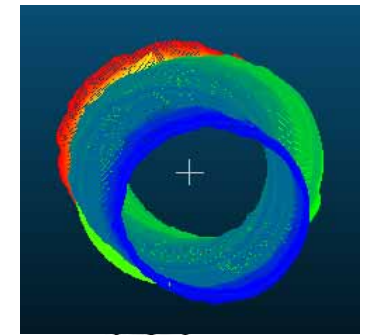
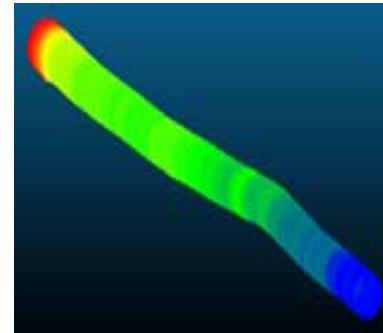
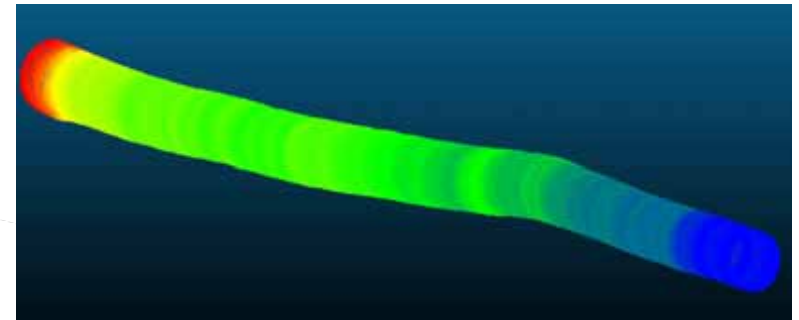
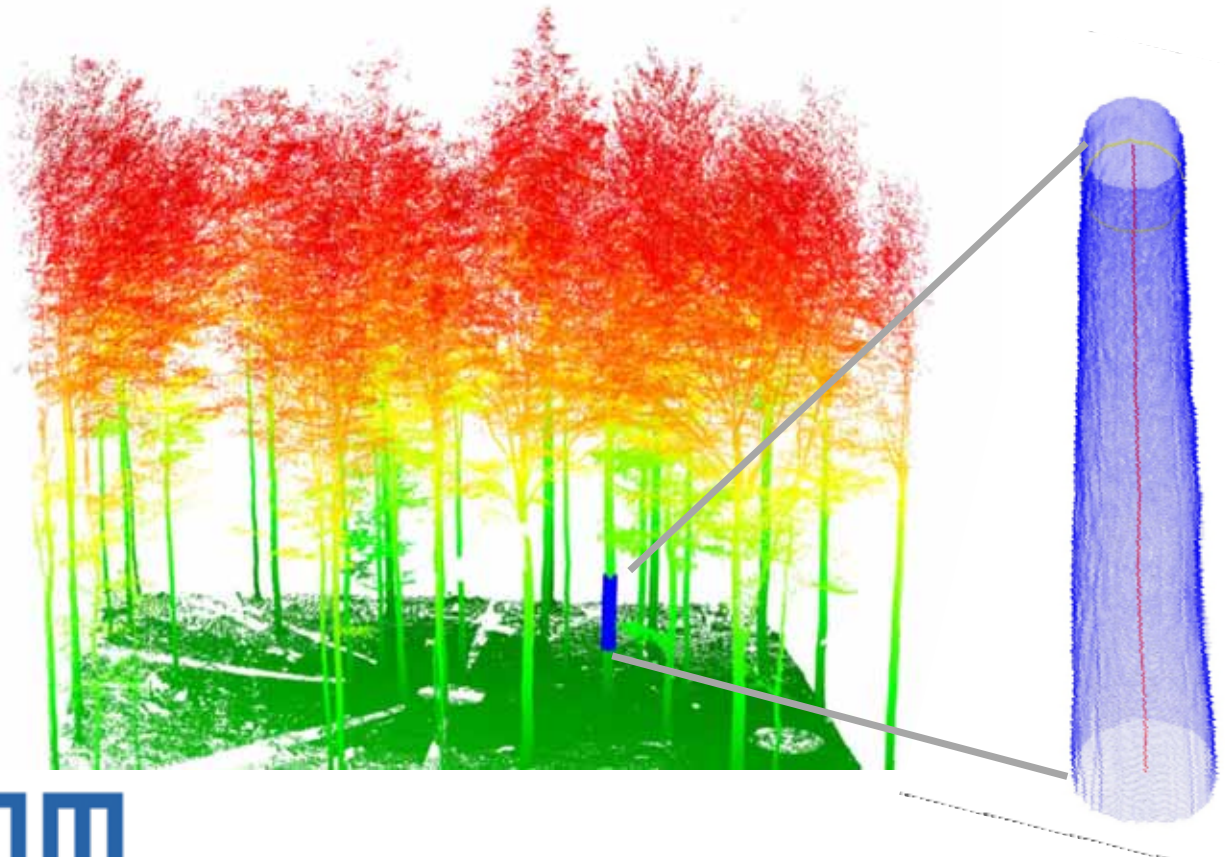
- Analisi delle foreste e la loro crescita
- La relazione tra foreste e la qualità del legno
- Capire la forma e la qualità dei tronchi
- Capire come crescono gli alberi (di faggio) in foreste miste
- Selezionare alberi per la filiera del legno

- Lunghezza
- Dimensioni molto più variabili
- Spigolo, Qualità della superficie, Dimensione, Tipo della sega, ecc.

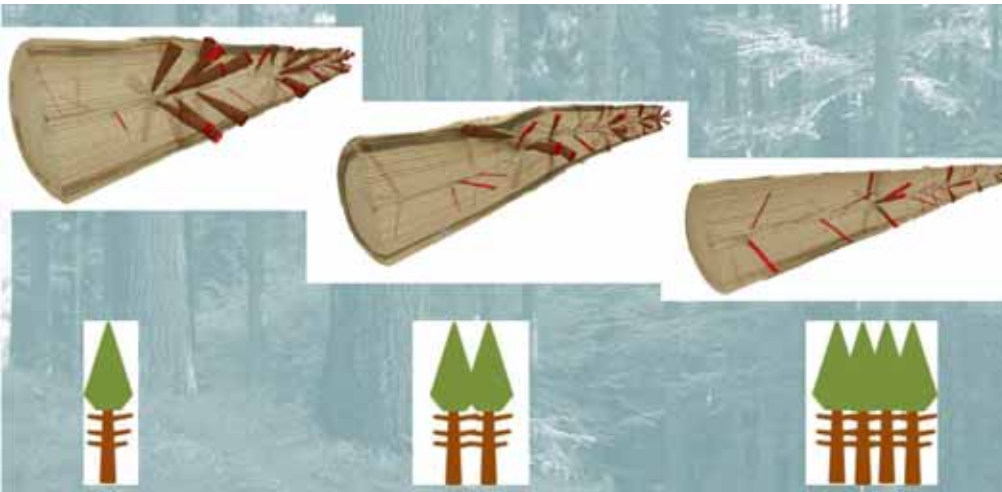




3D-Scansione Laser  
Classificazione automatica dei tronchi



# CONFERENCE TRACK TOUR 2021



1000/ha

2000/ha

4000/ha

Intensità: la qualità del legno: volume/ha – qualità/ha

Forestale: pagato a m<sup>3</sup> (Volume),

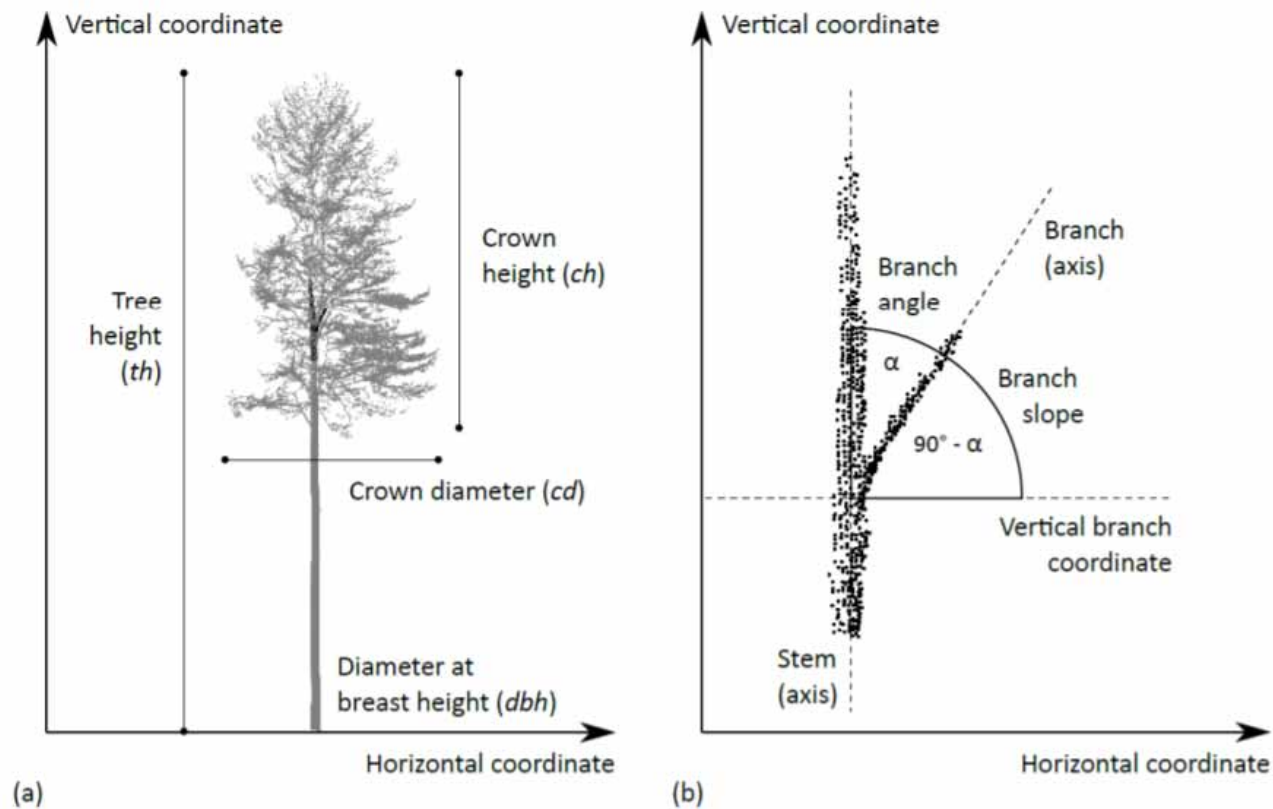
Segheria: pagato a m<sup>3</sup> (Qualità del legno – Classe di resistenza)



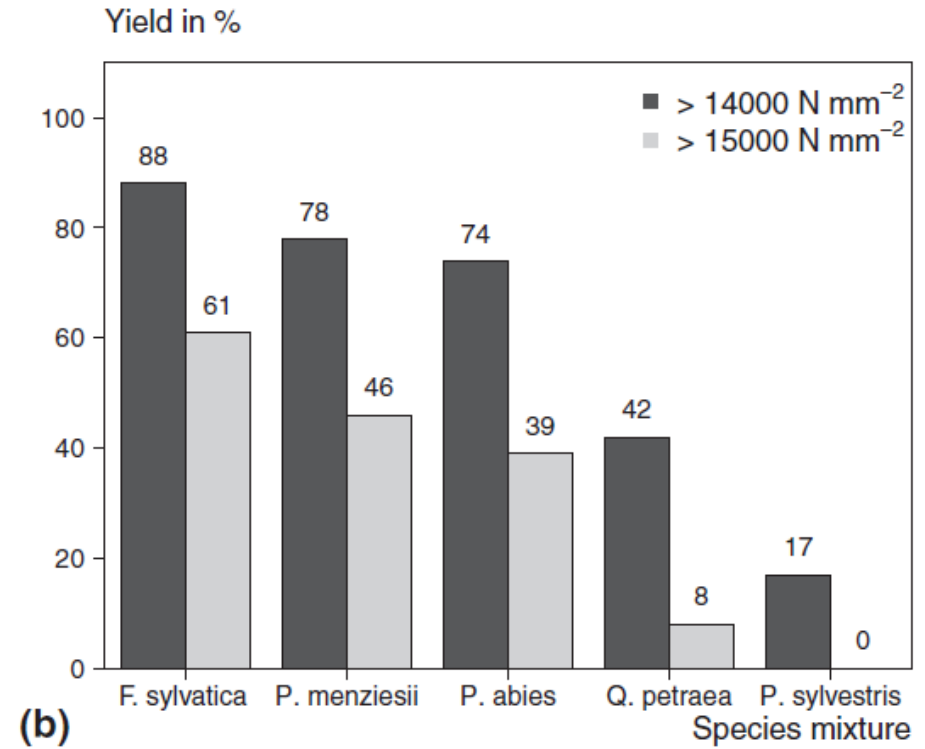
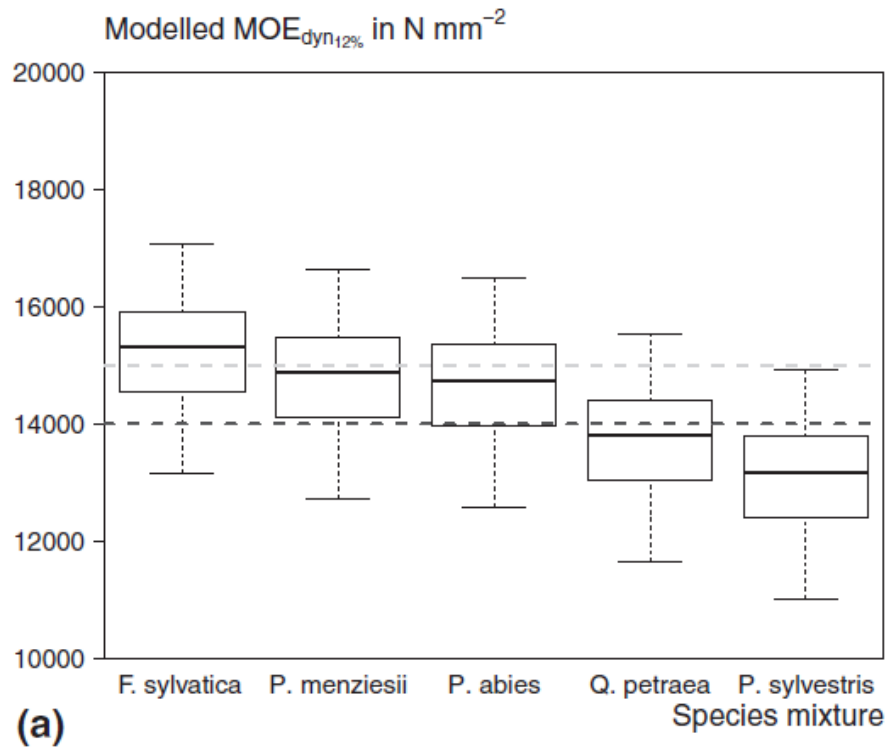
Misurazione del Modulo di Elasticità die tronchi.







Proiezione e previsione della qualità del legno (nodosità) interna

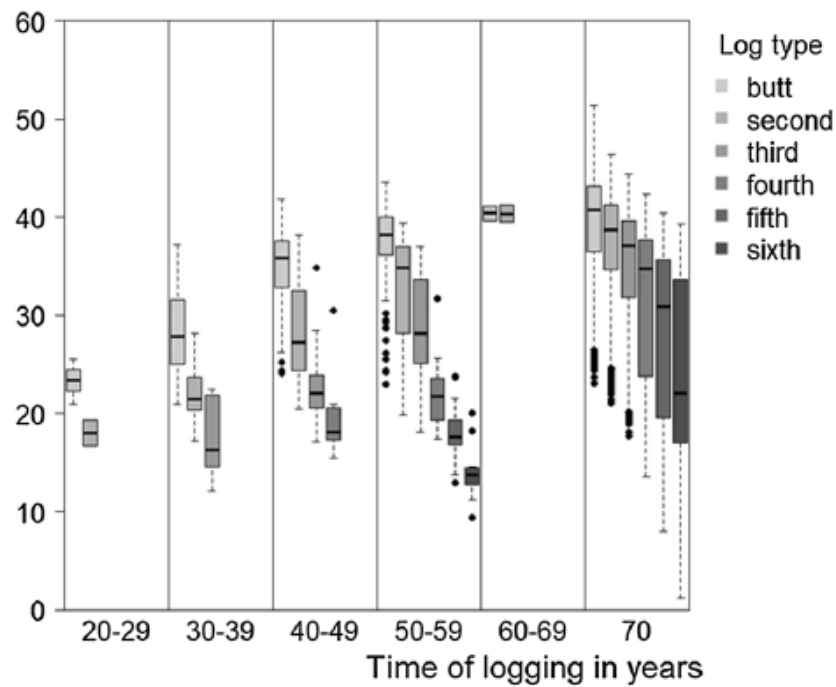


Variazione della MoE a base del tipo forestale



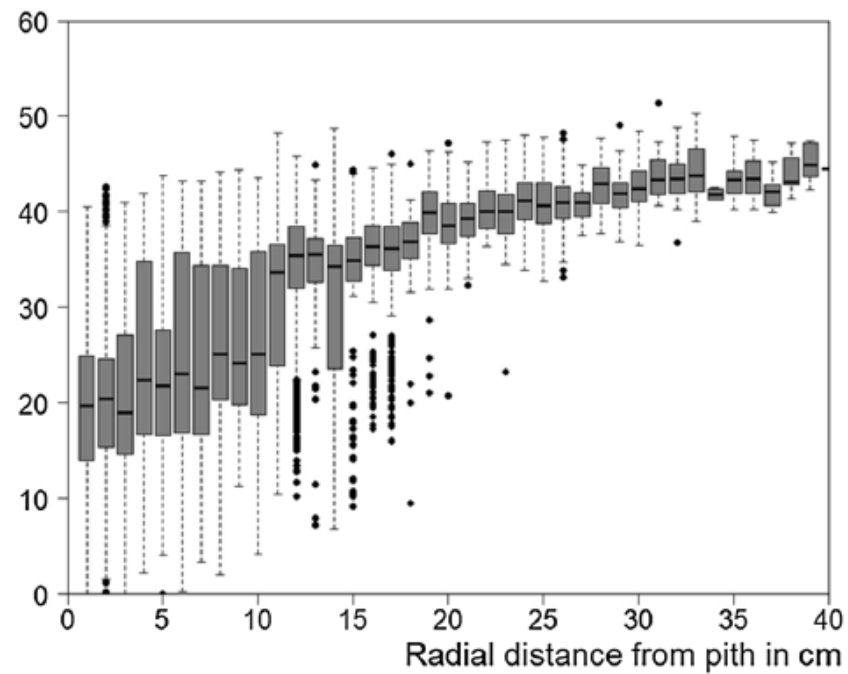
(a)

Indicating bending strength  $N\ mm^{-2}$

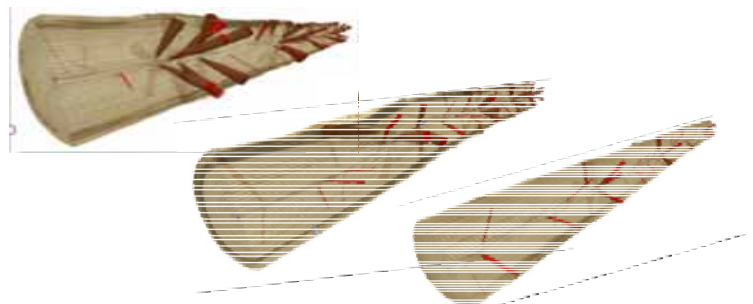


(b)

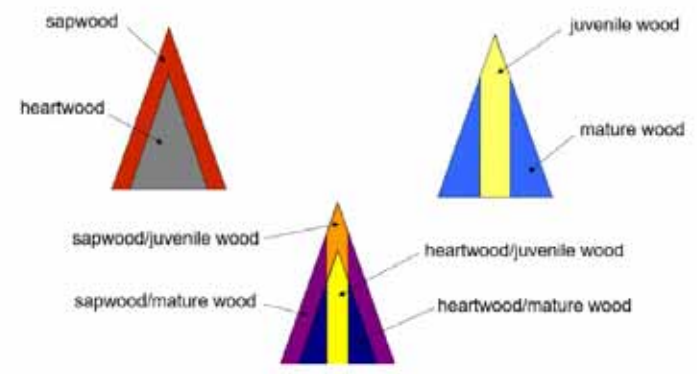
Indicating bending strength in  $N\ mm^{-2}$



# CONFERENCE TRACK TOUR 2021



1000/ha    2000/ha    4000/ha  
Densità: alberi/ha



Trasformazione dei tronchi in tavole  
Misurazione delle caratteristiche  
Classificazione delle tavole  
Classe di resistenza seconda le  
Norme Europee

Tecnologie per la classificazione delle  
tavole per scopo 'strutturale'

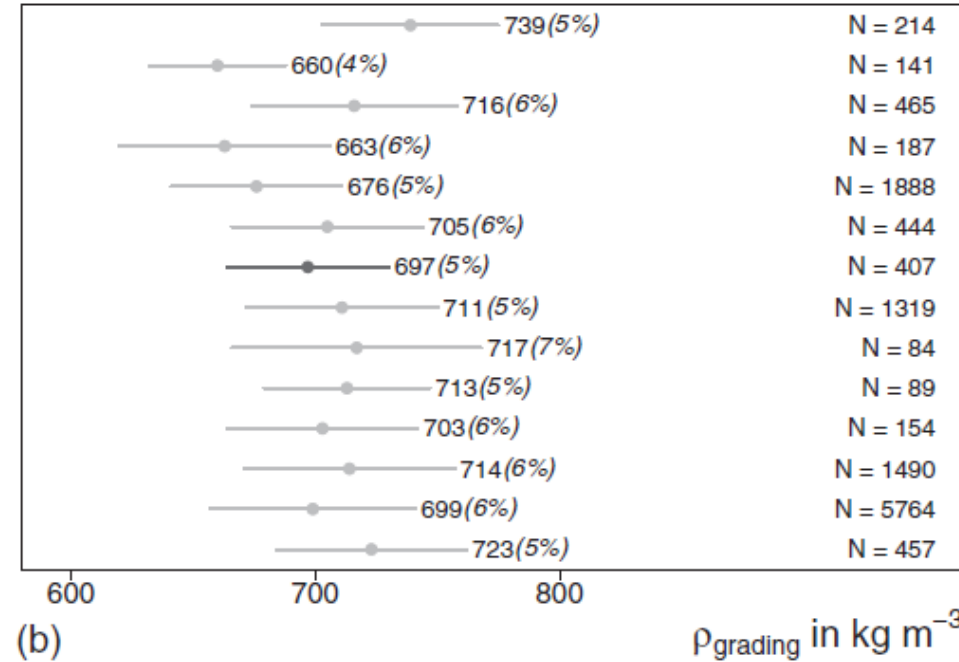
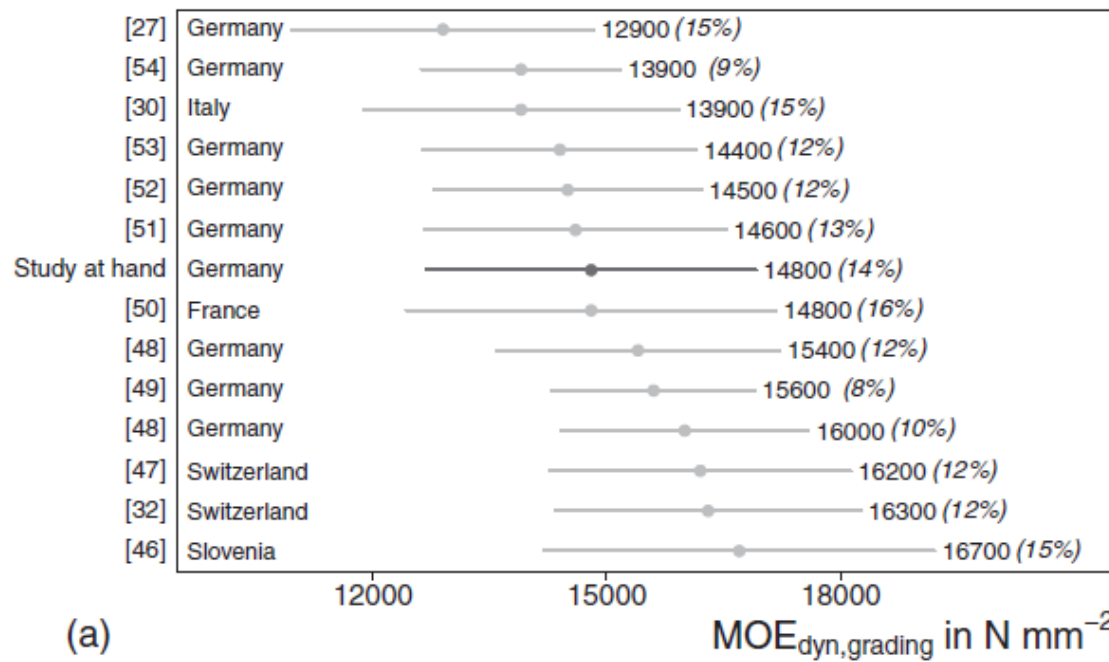
- classificazione a vista
- classificazione a macchina
- classificazione 'virtuale'



elft







Faggio: variazione die 'qualità': MoE e Densità



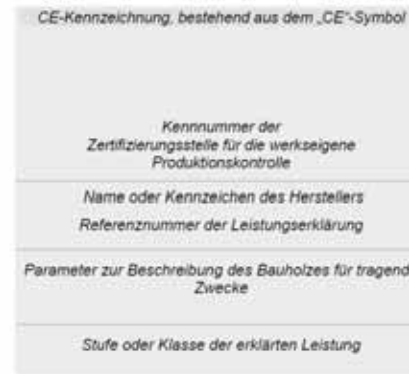
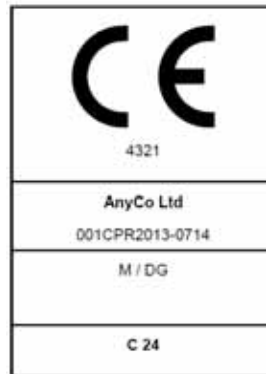
Legno strutturale: EN 14081

Legno lamellare: EN 14080

Classi di resistenza: EN 338:

Coniferi: C-Classes, T-Classes

Latifoglie: D-Classes, DT-classes (Proposta)

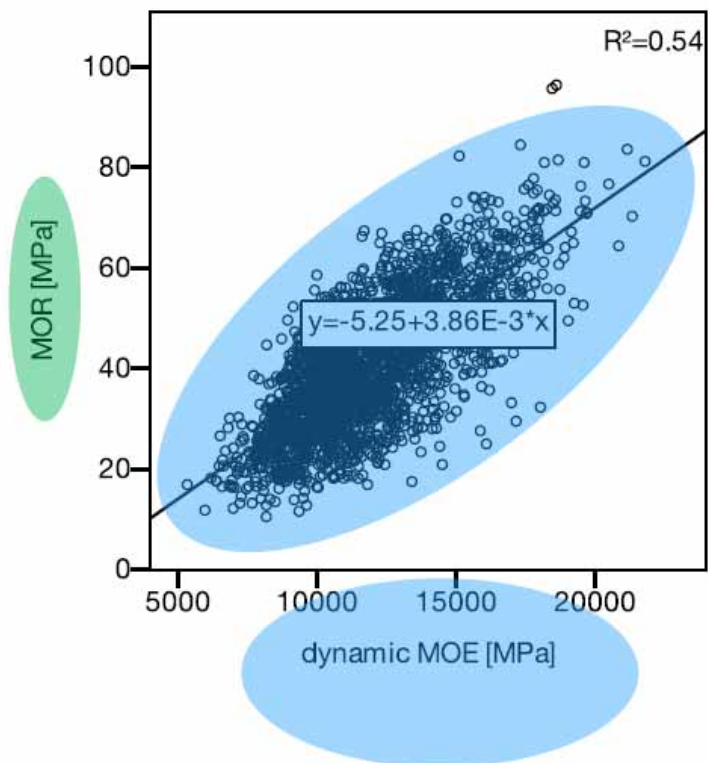
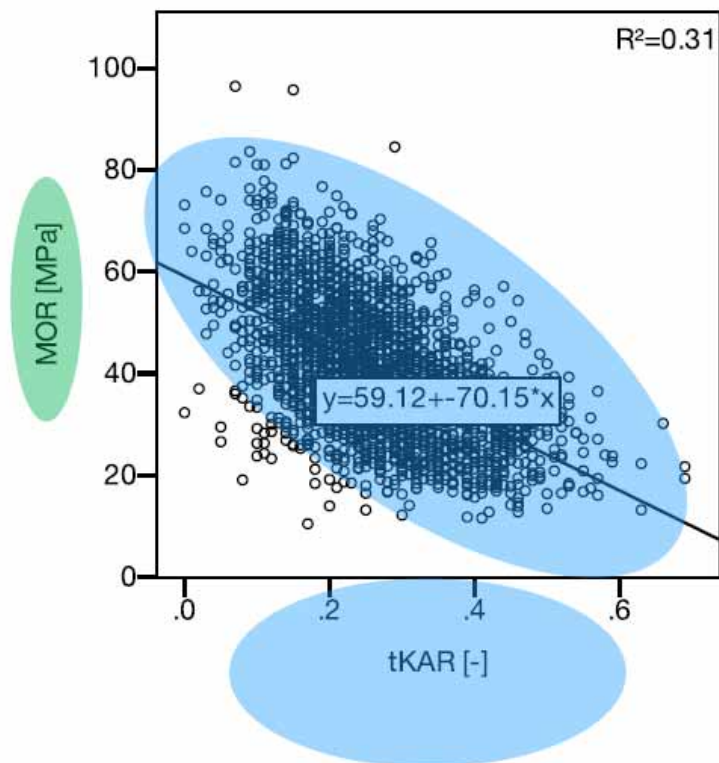


‘Tensile classes’ per legno lamellare (conifere)

Property		T11	T14	T18	T21	T24	T28	T30
Strength properties [N/mm <sup>2</sup> ]	$f_{t,0,k}$	11.0	14.0	18.0	21.0	24.0	28.0	30.0
Stiffness properties [kN/mm <sup>2</sup> ]	$E_{t,0,mean}$	9.0	11.0	12.0	13.0	13.5	15.0	15.5
Density [kg/m <sup>3</sup> ]	$\rho_k$	320	350	380	390	400	420	430



Lo scopo della classificazione del legno strutturale





Classificazione a vista a base dei nodi (p.e. DIN 4074 / UNI 11035)

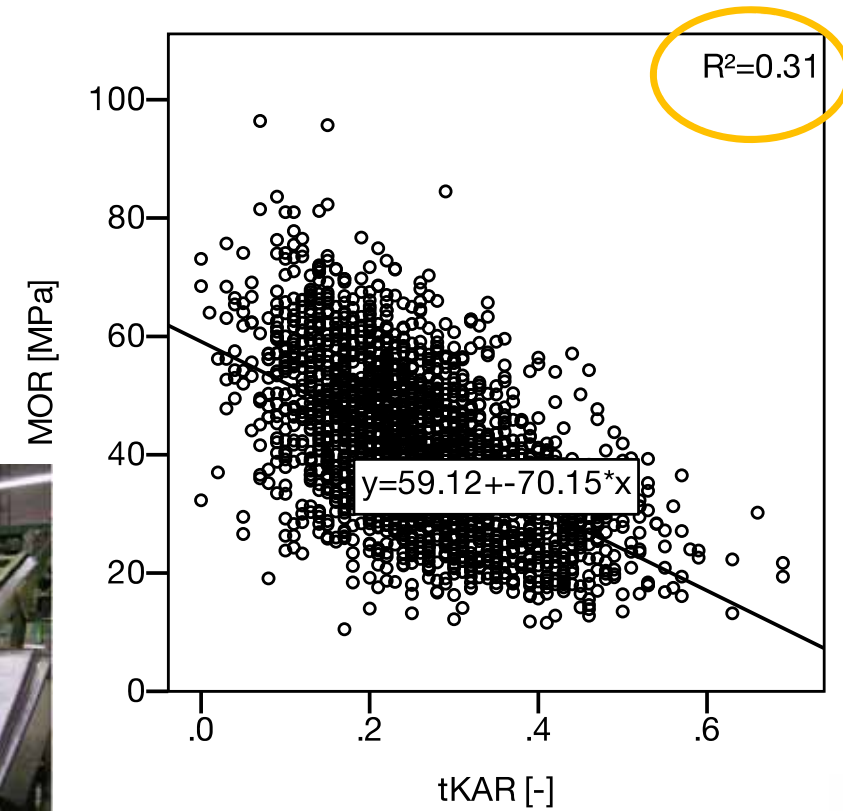
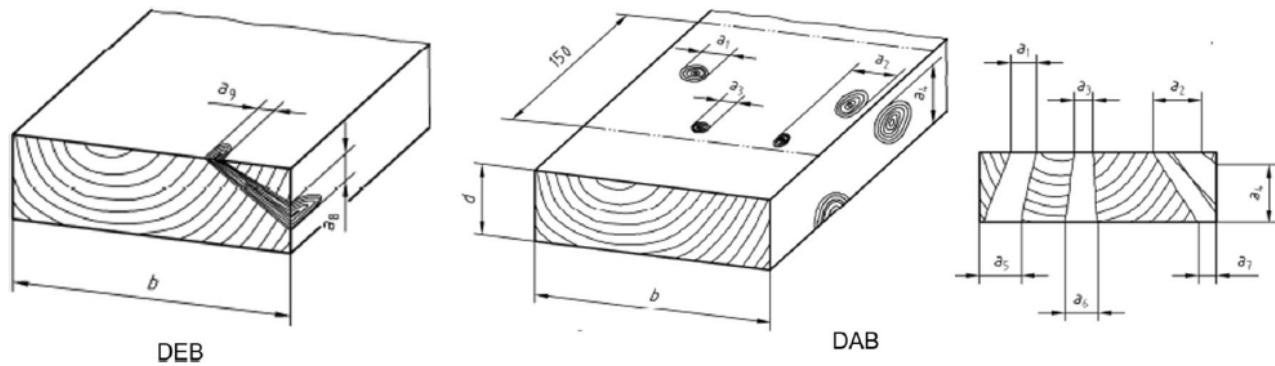


Table 1 — Strength classes for softwood based on edgewise bending tests – strength, stiffness and density values

	Class	C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
<b>Strength properties in N/mm<sup>2</sup></b>													
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50
Tension parallel	$f_{t0,k}$	7,2	8,5	10	11,5	13	14,5	16,5	19	22,5	26	30	33,5
Tension perpendicular	$f_{t90,k}$	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
Compression parallel	$f_{c0,k}$	16	17	18	19	20	21	22	24	25	27	29	30
Compression perpendicular	$f_{c90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,5	2,7	2,7	2,8	2,9	3,0
Shear	$f_{v,k}$	3,0	3,2	3,4	3,6	3,8	4,0	4,0	4,0	4,0	4,0	4,0	4,0
<b>Stiffness properties in kN/mm<sup>2</sup></b>													
Mean modulus of elasticity parallel bending	$E_{m,0,mean}$	7,0	8,0	9,0	9,5	10,0	11,0	11,5	12,0	13,0	14,0	15,0	16,0
5 percentile modulus of elasticity parallel bending	$E_{m,0,k}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,1	10,7
Mean modulus of elasticity perpendicular	$E_{m,90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40	0,43	0,47	0,50	0,53
Mean shear modulus	$G_{mean}$	0,44	0,50	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00
<b>Density in kg/m<sup>3</sup></b>													
5 percentile density	$\rho_k$	290	310	320	330	340	350	360	380	390	400	410	430
Mean density	$\rho_{mean}$	350	370	380	400	410	420	430	460	470	480	490	520
NOTE 1 Values given above for tension strength, compression strength, shear strength, char. modulus of elasticity in bending, mean modulus of elasticity perpendicular to grain and mean shear modulus have been calculated using the equations given in EN 384.													
NOTE 2 The tension strength values are conservatively estimated since grading is done for bending strength.													
NOTE 3 The tabulated properties are compatible with timber at moisture content consistent with a temperature of 20 °C and a relative humidity of 65 %, which corresponds to a moisture content of 12 % for most species.													
NOTE 4 Characteristic values for shear strength are given for timber without fissures, according to EN 408.													
NOTE 5 These classes may also be used for hardwoods with similar strength and density profiles such as e.g. poplar or chestnut.													
NOTE 6 The edgewise bending strength may also be used in the case of flatwise bending.													

## Multi-objective optimization: yield / strength Computerized visual grading

- Combination of boundaries for the grading criteria that maximizes the objectives:
- Maximum yield to the visual grades
- Desired characteristic properties for the visual grade

- Both objectives are expressed as a function of the grading parameters:

$$f_{yield} = f(x_{up,m}^{s13}, x_{up,m}^{s10})$$

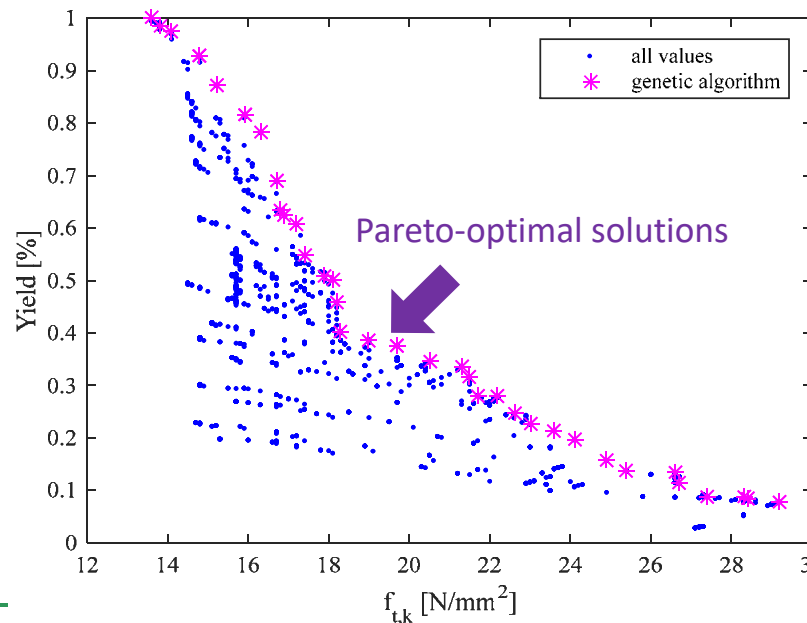
$$f_{strength} = f(x_{up,m}^{s13}, x_{up,m}^{s10})$$

- Grading to S13 and S10

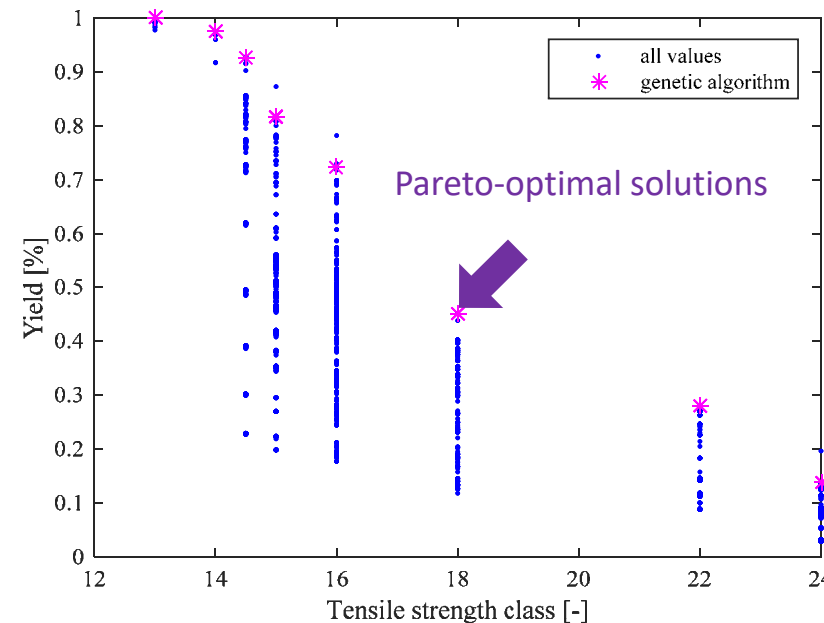


## Bi-dimensional optimization:

- Optimization of yield and characteristic strength of a single class (S13, S10+)

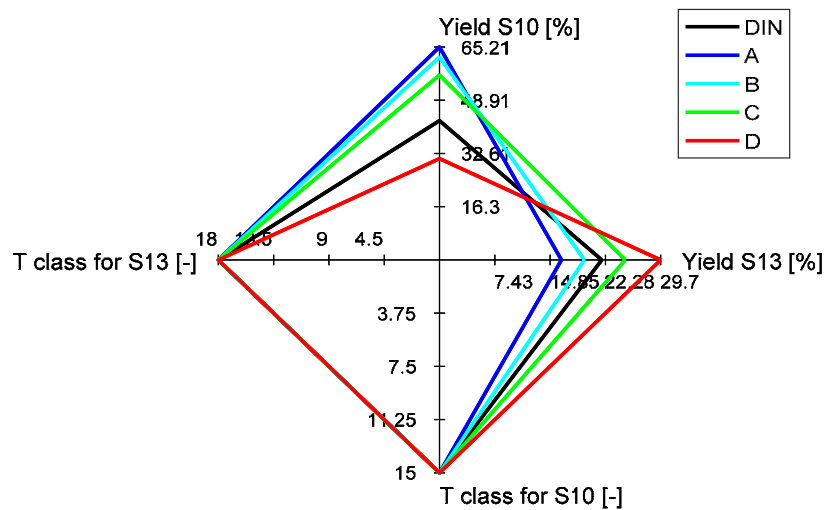


- Optimization of yield and strength class assignment of a single class (S13, S10+)

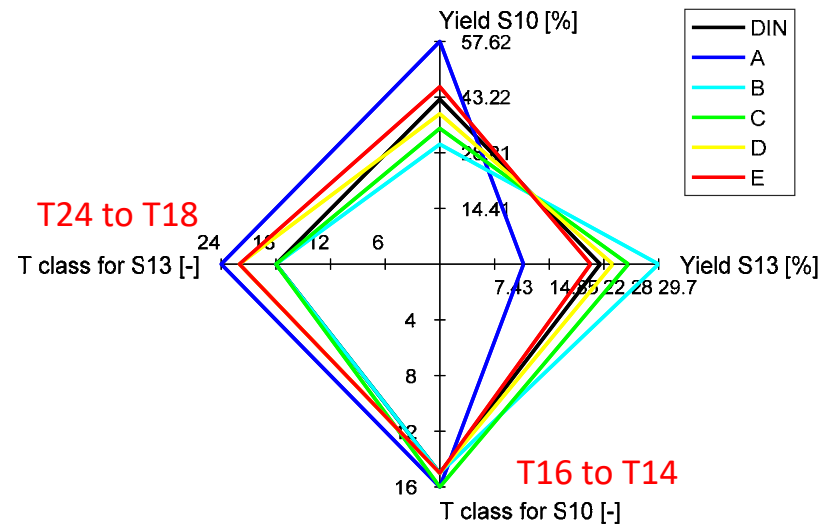


## Multidimensional optimization

**Assignment** to the strength classes (S13 to T18, S10 to T15) remains **constant**, Yield varies



**Total yield** to S13 and S10 remains **constant**.  
 Assignment to the strength classes varies



## Optimizing the visual boundaries of Norway spruce

Boundary values of the grading criteria for Norway spruce graded with selected boundary combinations

Grade	Solution	SK	KC	E	Pith
S13	DIN	0.2	0.333	0.333	0
	A	0.2	0.4	0.2	1
	B	0.4	0.4	0.2	1
	C	0.2	0.3	0.6	1
	D	0.2	0.3	0.4	0
S10	DIN	0.333	0.5	0.666	1
	A	1	0.5	1	1
	B	1	0.5	1	1
	C	0.3	0.4	1	1
	D	1	0.4	1	1

SK = Single knot  
KC = Knot cluster  
E = Edge knot

The same material can be graded, but using variable boundaries: improved yield!

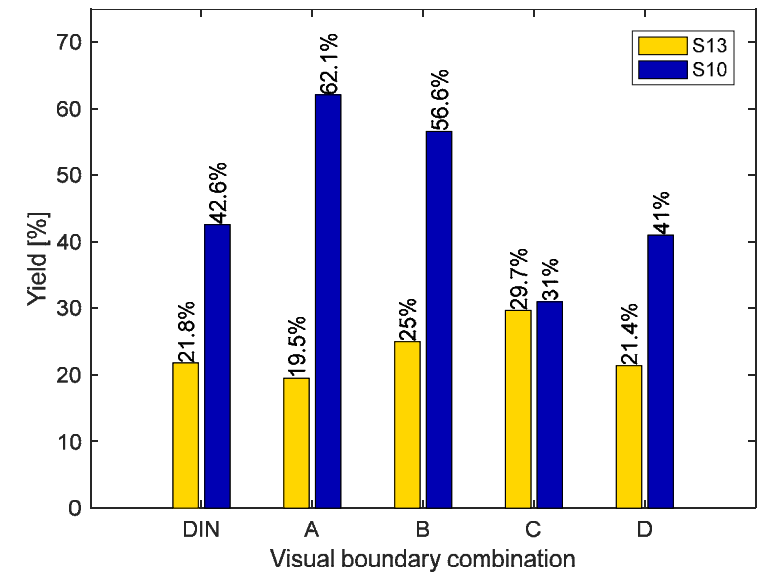


## Optimizing the visual boundaries of Norway spruce

Characteristic properties and strength classes

Grade	Solution	N	$\rho_k$ [kg/m <sup>3</sup> ]	$E_{0,mean}$ [N/mm <sup>2</sup> ]	$f_{t,k}$ [N/mm <sup>2</sup> ]	T class
S13	DIN	330	380	13750	23.4	T18
	A	295	380	13600	21.7	T18
	B	378	380	13200	18.5	T18
	C	450	380	13400	20.6	T18
	D	324	390	13900	23.6	T22
S10	DIN	646	370	11500	15.4	T15
	A	941	370	11500	15.2	T15
	B	858	360	11500	15.3	T15
	C	470	370	11600	15.0	T15
	D	621	360	11700	15.5	T15

Yield to the visual grades S13 and S10





Faggio



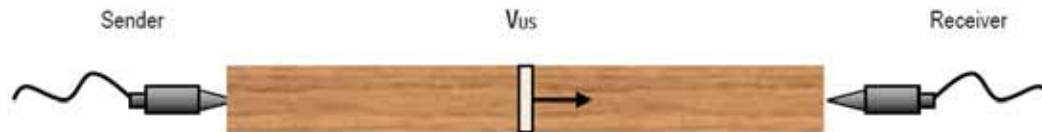
Acero

Classificazione a macchina:  
 Tecnologie per quantificare

- Nodi
- Fibratura
- Midollo
- Fissure
  
- Ultrasuono
- Vibrazioni
- Laserscanning
- 'virtual' grading

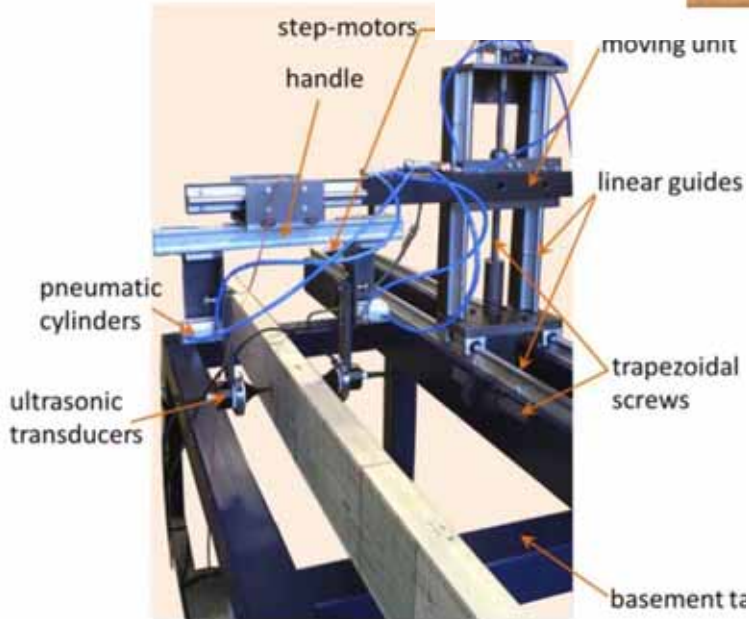
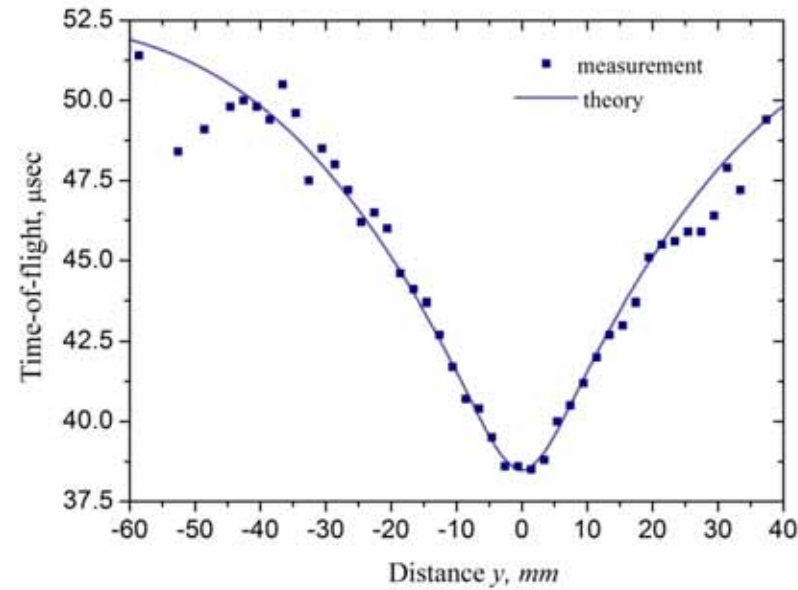


Abete

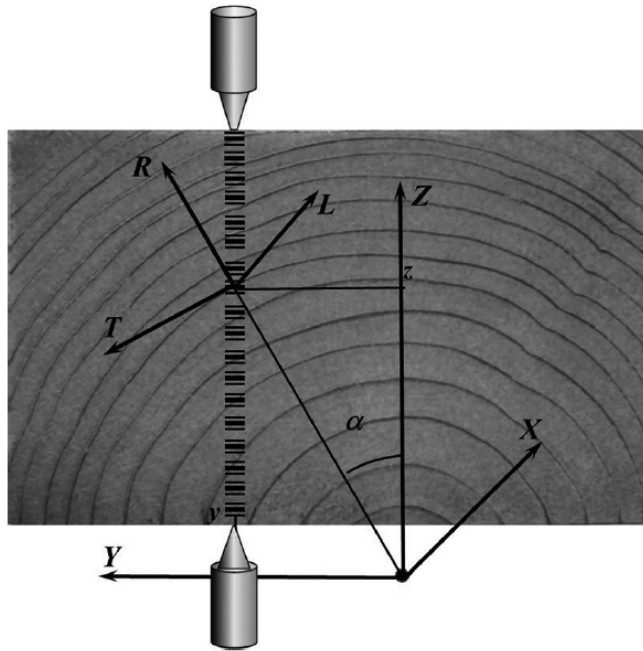


## Ultrasuono

- parallelo alla fibratura
- perpendicolare alla fibratura



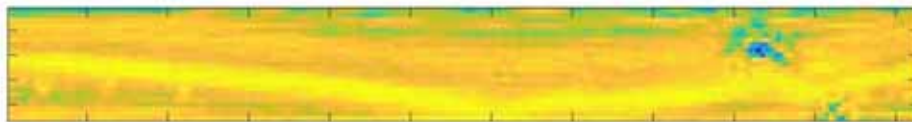
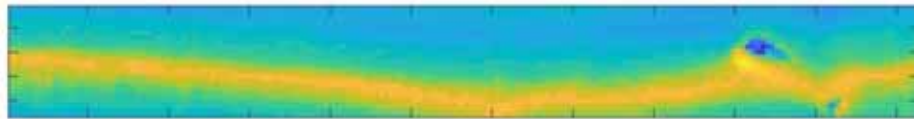
(a)



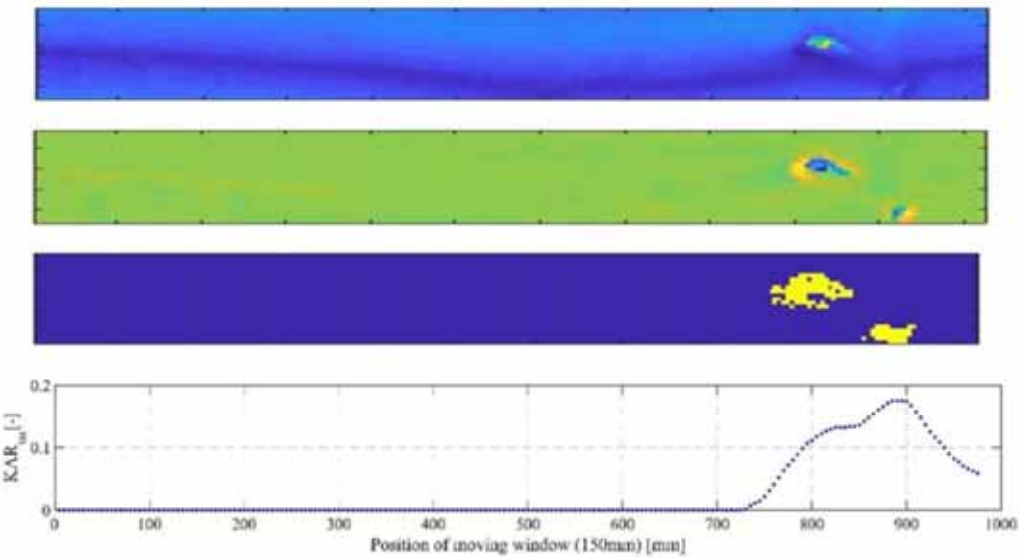


## Ultrasuono

Frassino



Ultrasuono

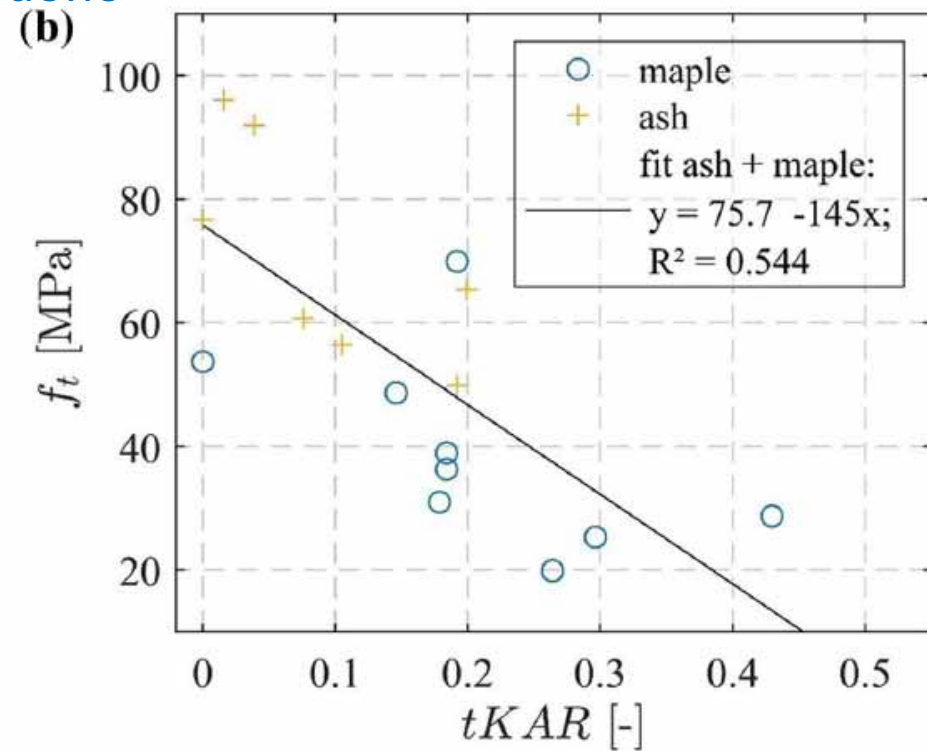
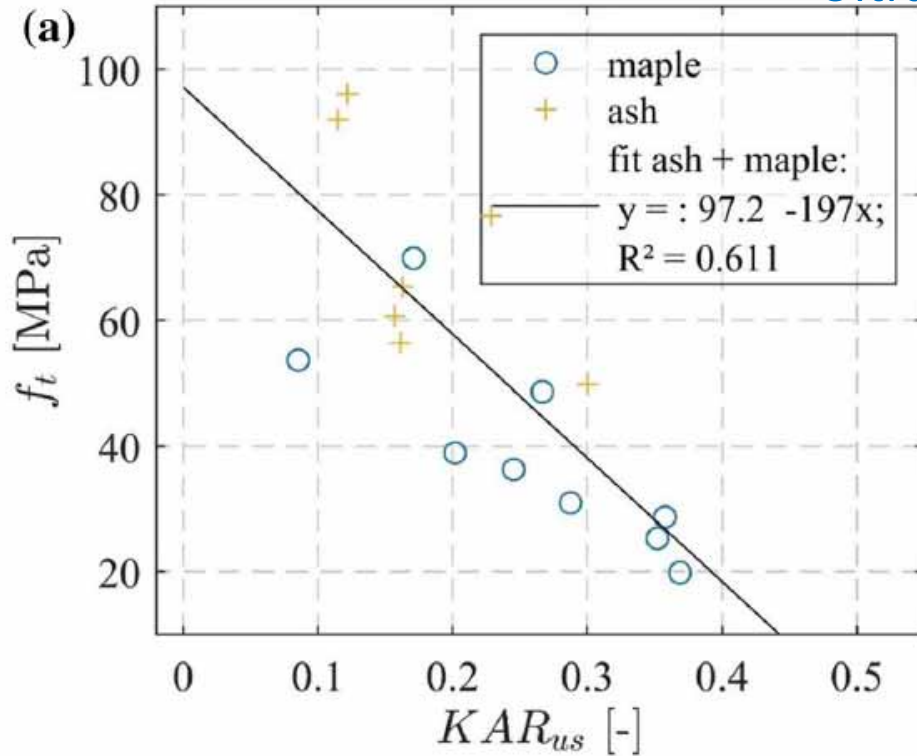


(a) ToF image      (c) Segmented objects in ToF image  
 (b) ToF image with filtered RT-Profile      (d) Knottiness profile



Tavola di frassino con rottura

Ultrasuono

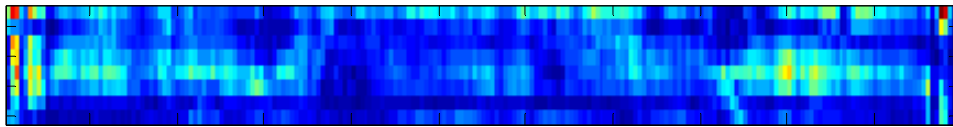


Nodosità a base di ultrasuono (sinistra) e la classificazione a vista (destra)

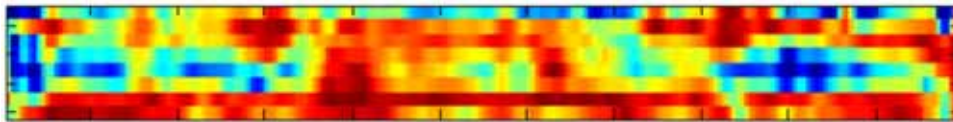


## Ultrasuono

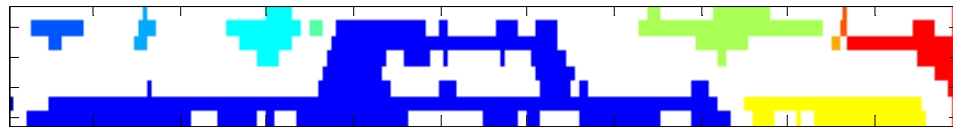
Original image



Processed image



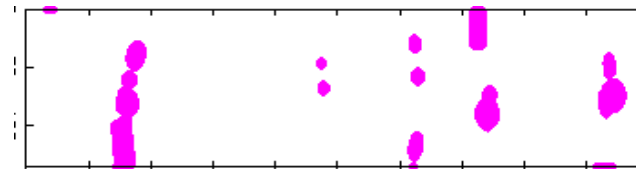
Segmented image



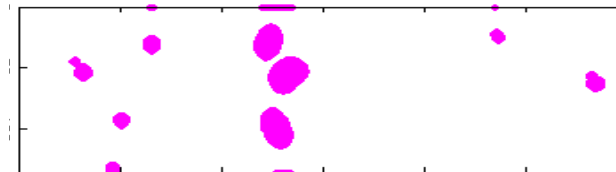
Segmented image – class 2



- Profilo dei nodi
- Immagine ultrasuono vs. 2D immagine di nodosità
- Prove distruttive (Tensione, Flessione)



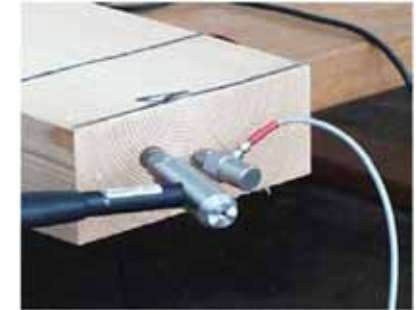
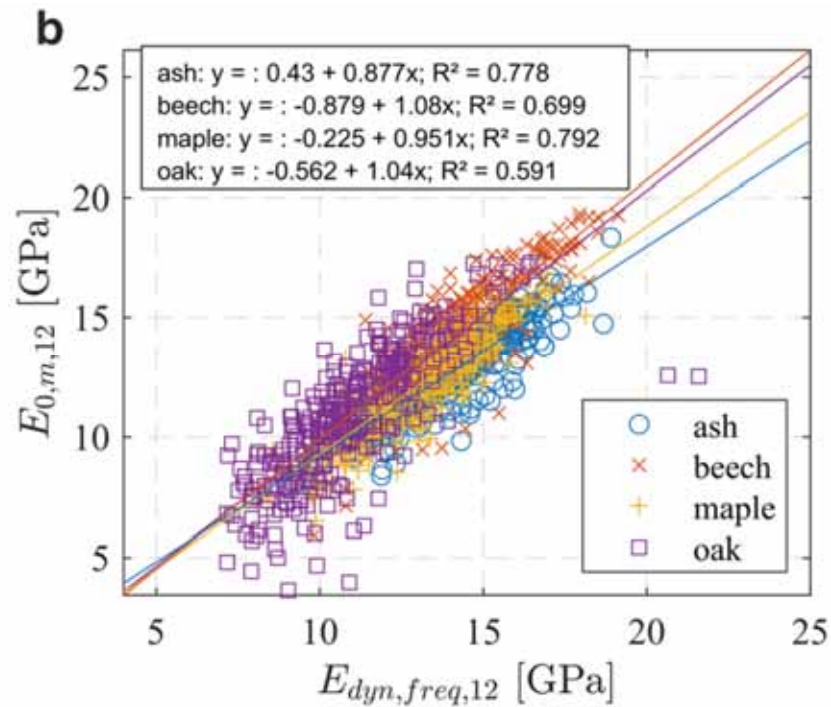
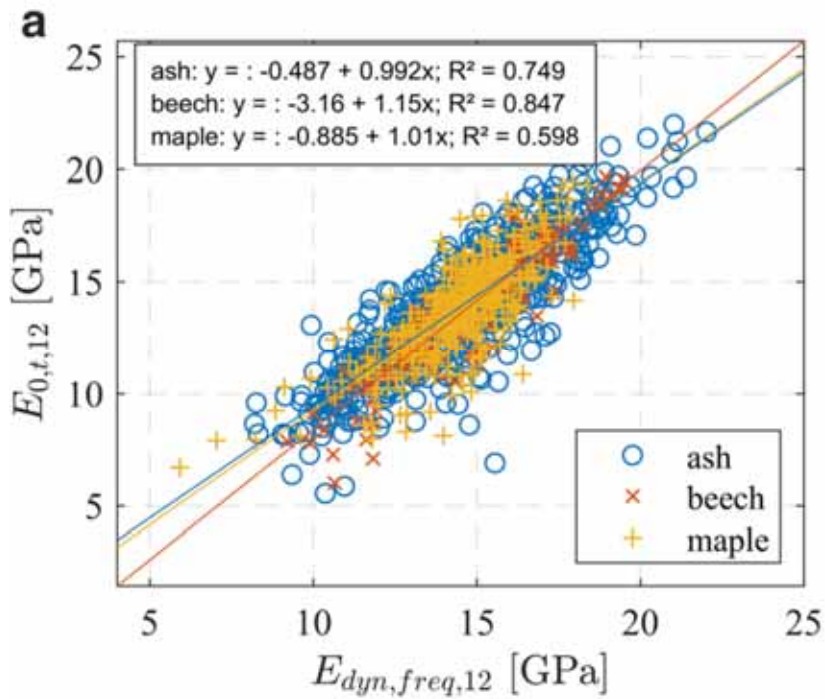
Sample 4003



Sample 4050

- Relazione tra nodosità e resistenza: CLASSIFICAZIONE

Vibrazioni



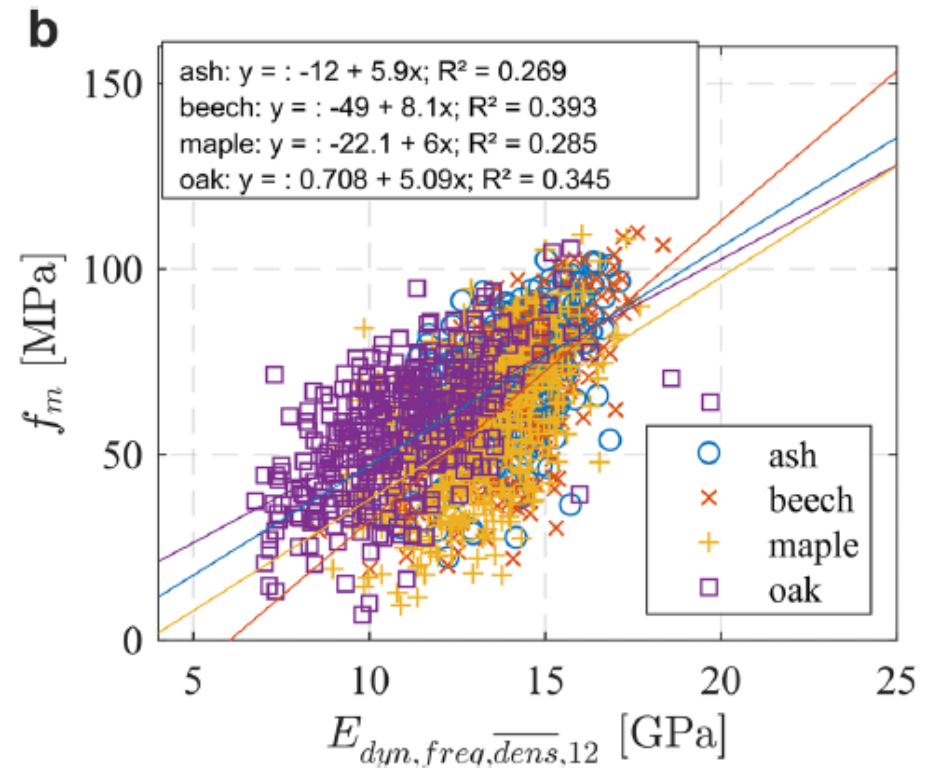
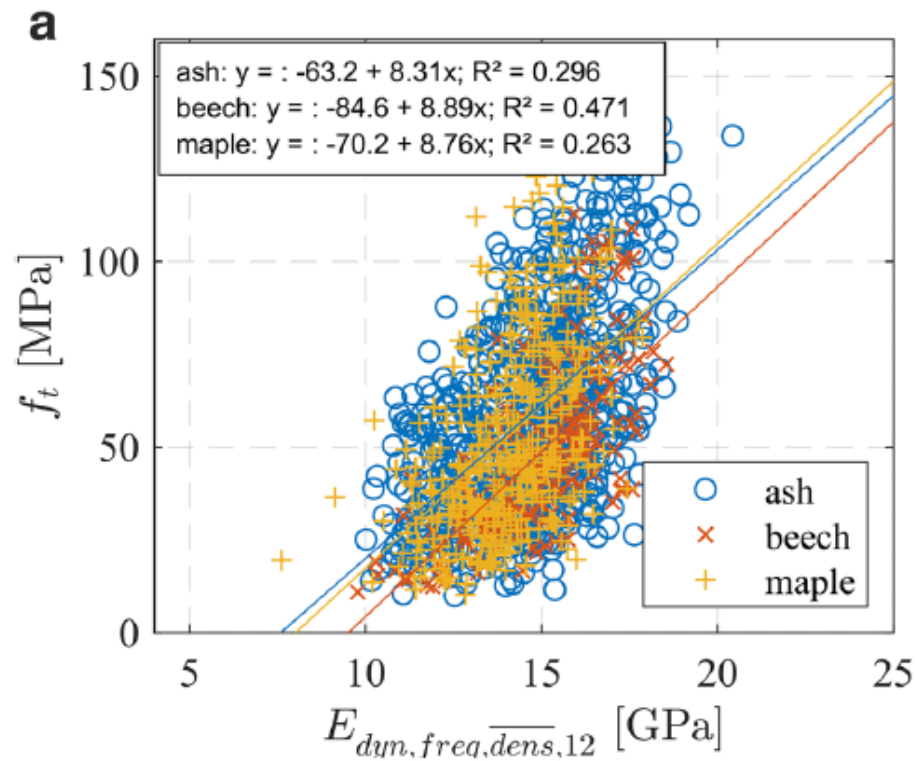
a)



b)r (MiCROTEC)

Vibration method: a) in laboratory using an accelerometer  
 b) contact-free in-line using a laser interferometer (MiCROTEC)

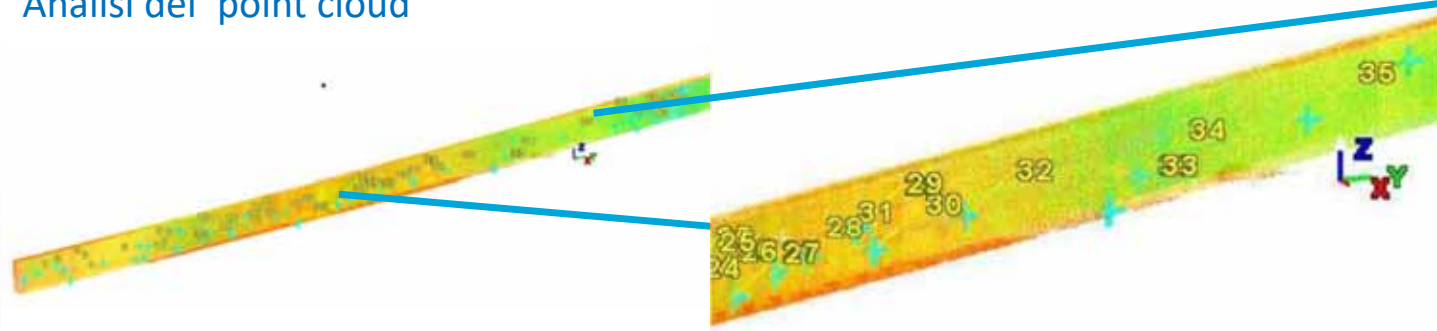
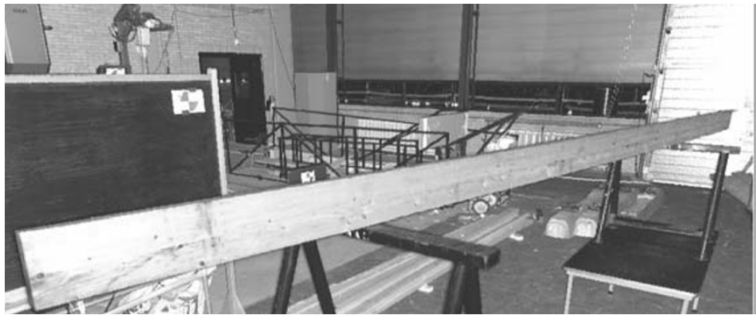
## Vibrazioni



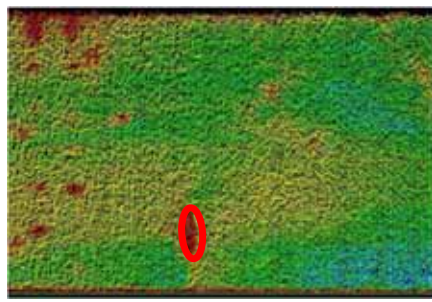
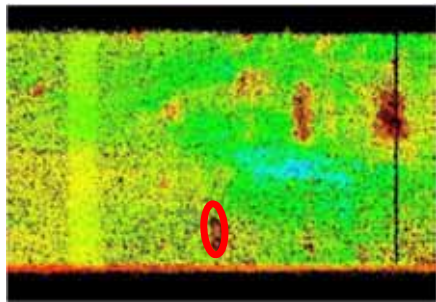
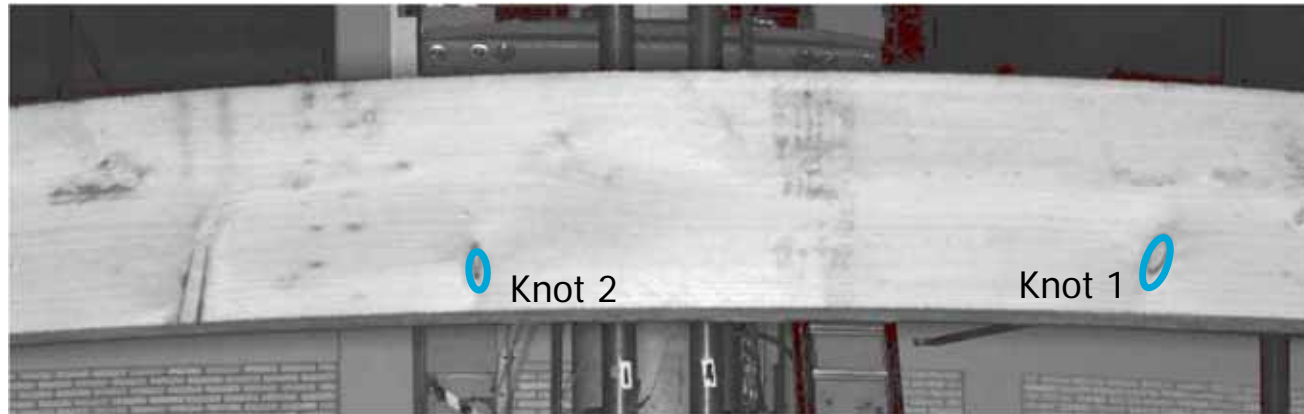


## Scansione laser

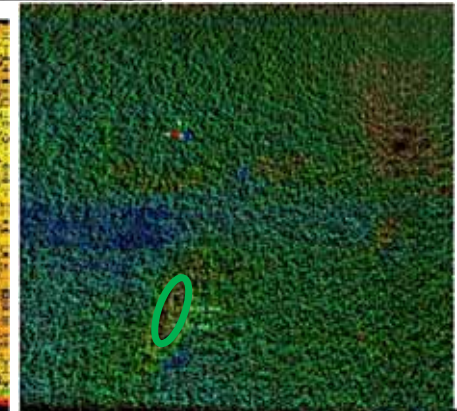
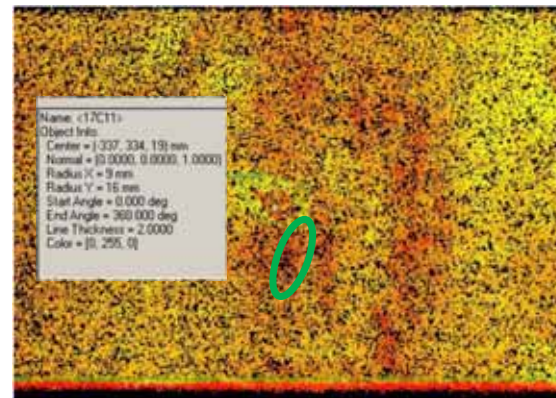
### Analisi del 'point cloud'



Analysis of the point clouds with algorithms  
Automatic **crack** and **knot** detection.

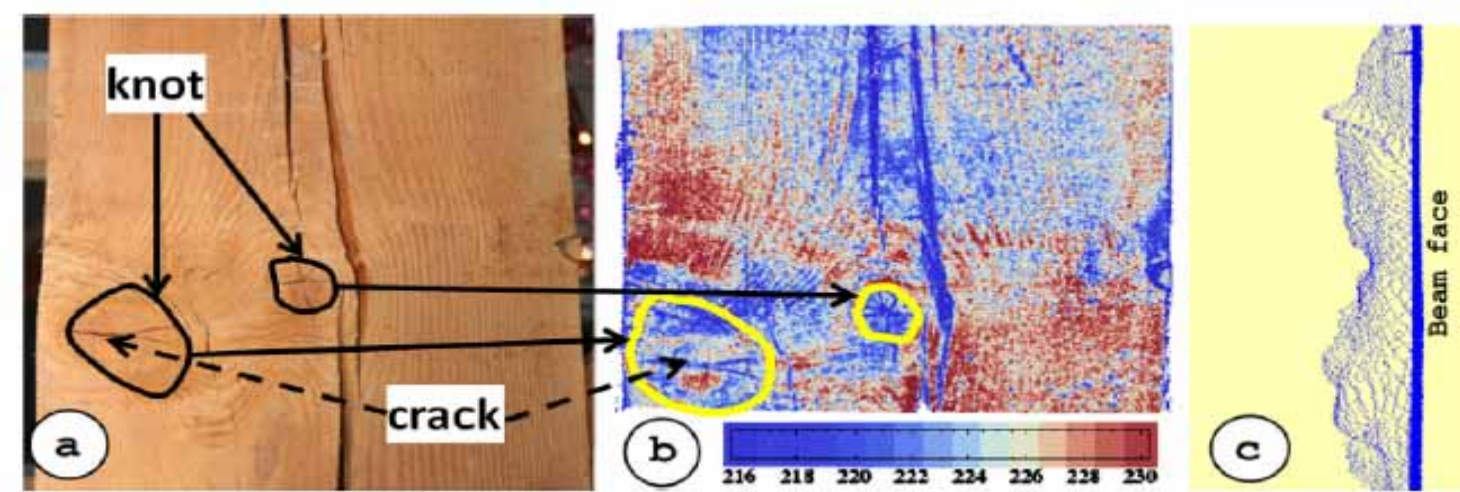


Front face / Back face Knot 2



Front face / Back face Knot 1

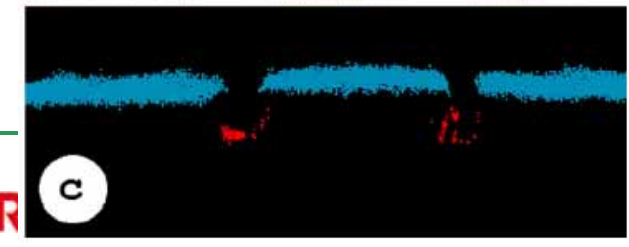
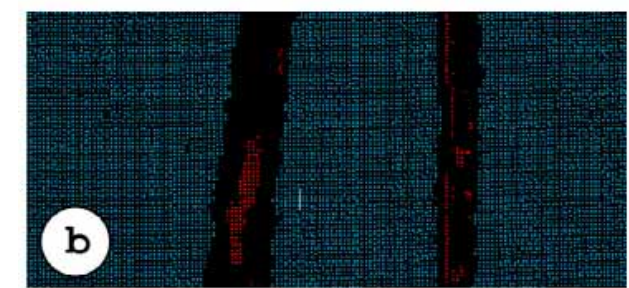
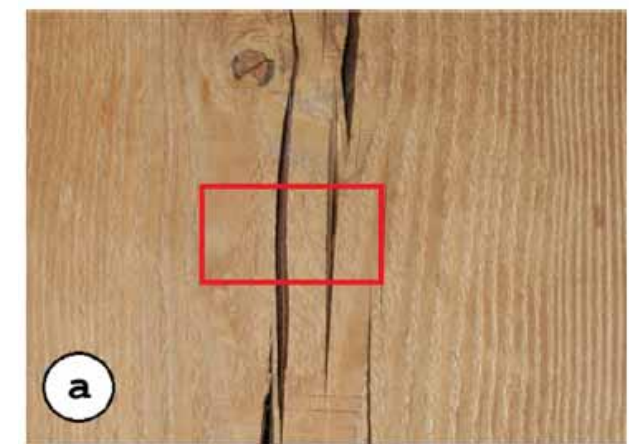




Scansione laser per analizzare e 'classificare':

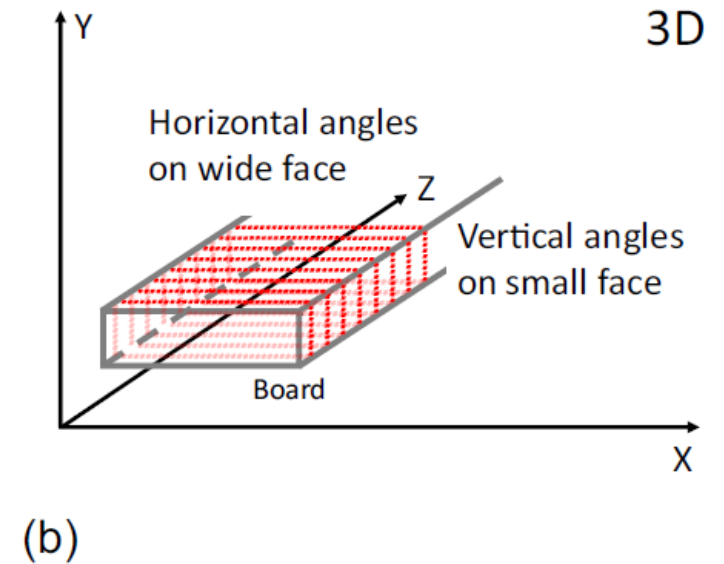
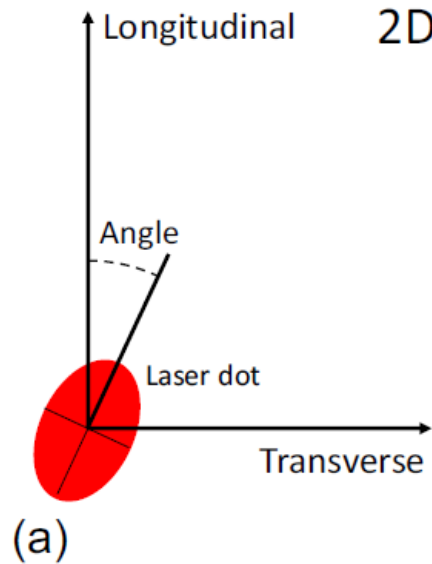
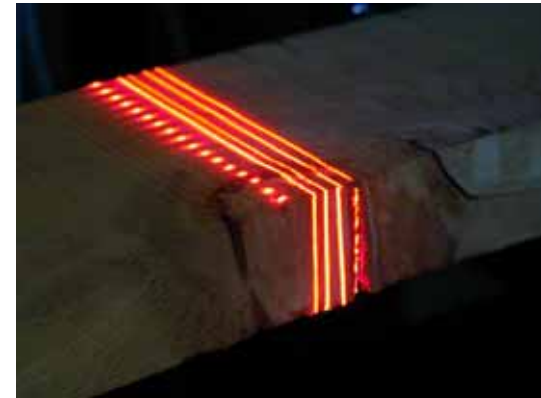
- alberi
- strutture
- tavole: nodi, fessure, fibratura (tracheid effect)

a,b,c: algoritmo →  
 Profondità ≥ threshold: fessure



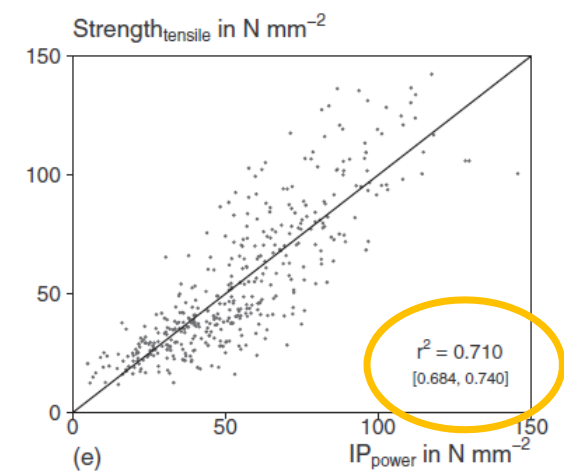
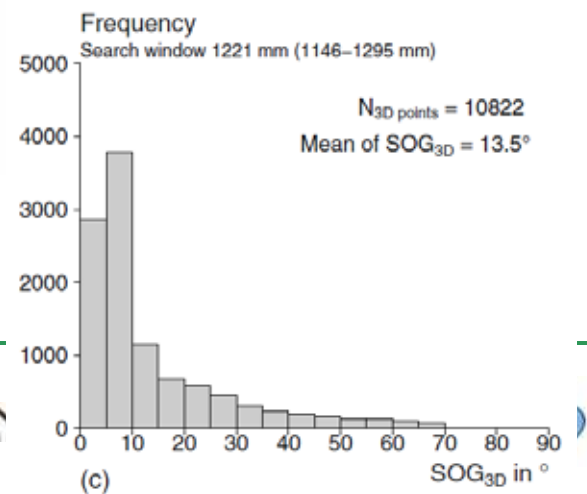
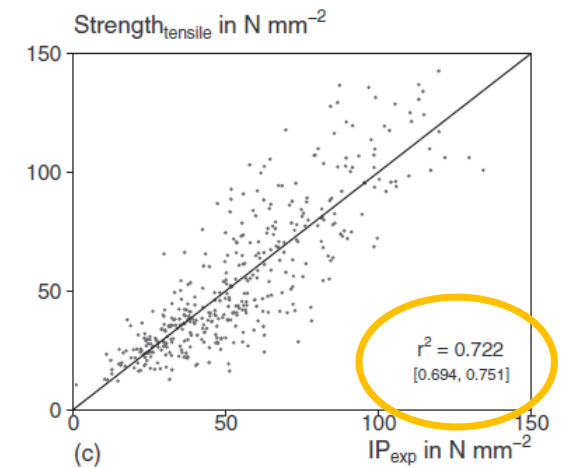
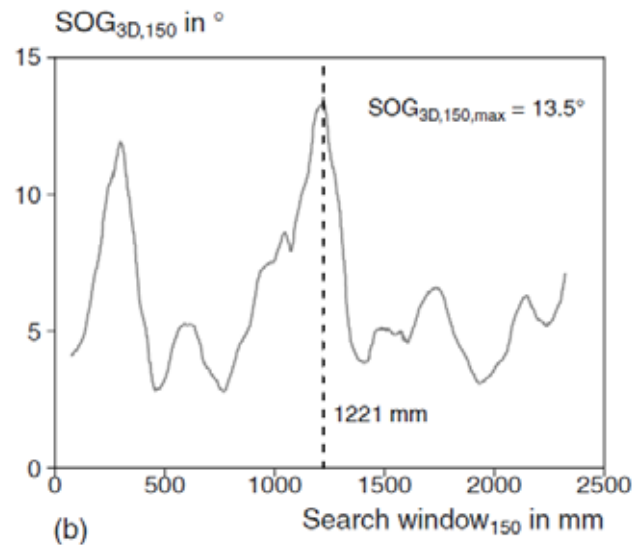
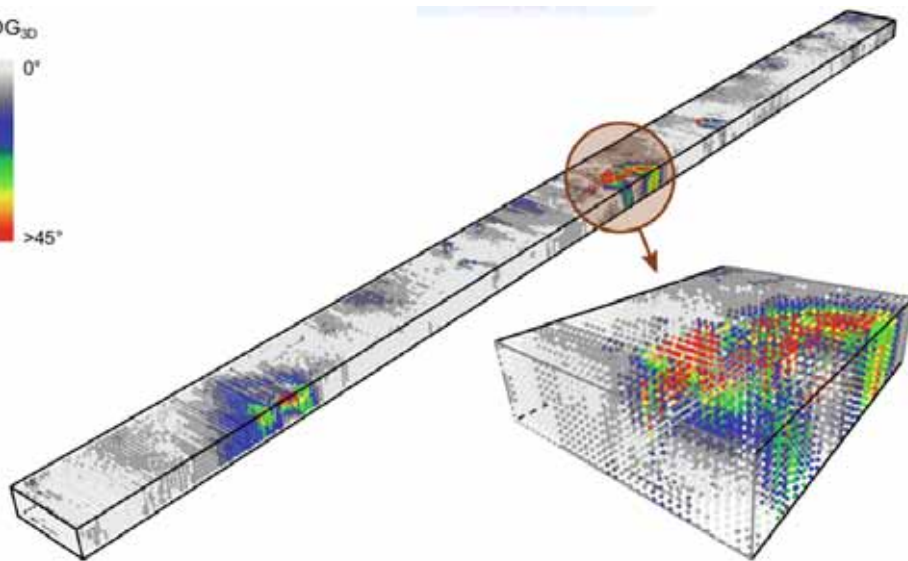
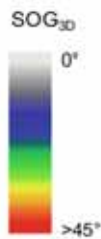


Scansione laser delle superficie del legno



l'angolo del laser dot (ellissoidale) ↔ fibratura

## Scansione laser delle superficie del legno

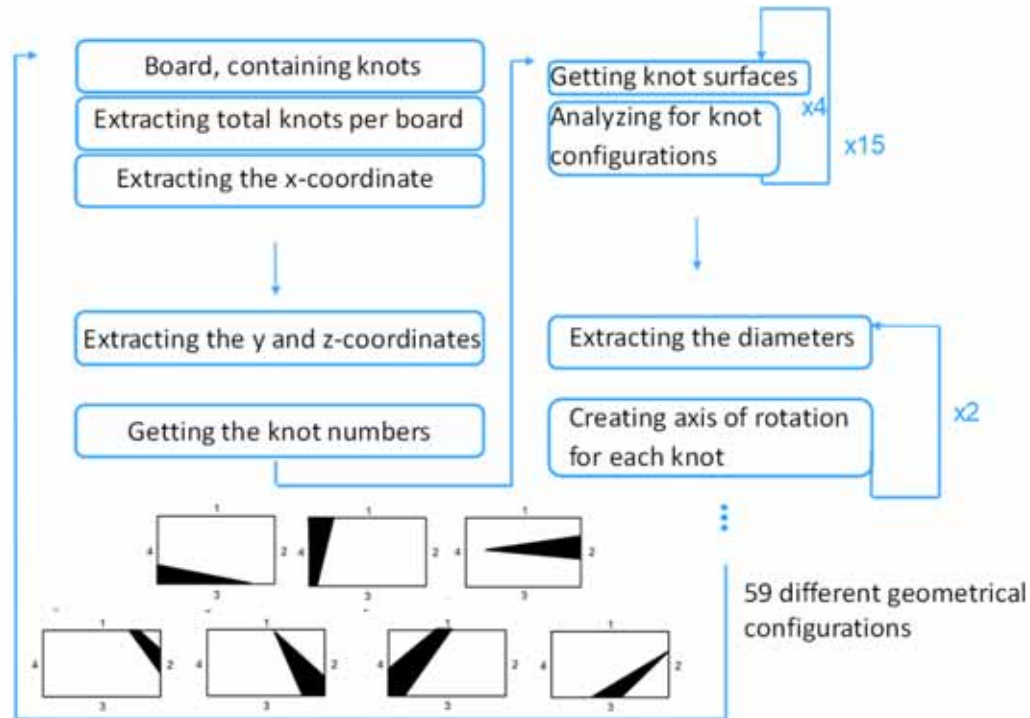


Il futuro della classificazione: 'virtual' grading

Surface image: nodes or fibre direction

Scansione delle superficie del legno:

- camera
- laser
- infrarosso
- ultrasuono
- ....



$$T \subseteq R^3$$

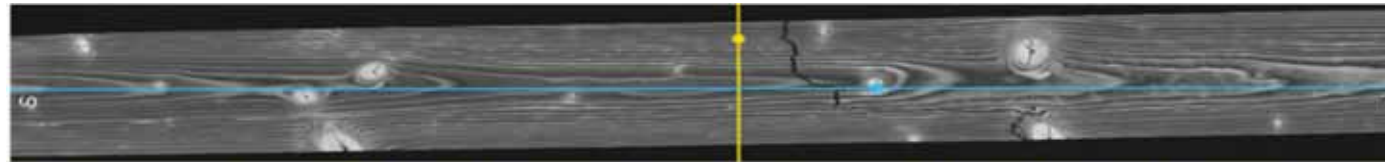
$$T = \{1 \leq x \leq 4; 1 \leq y \leq L; 1 \leq z \leq N\}$$

$$\iiint_T f(x, y, z) dx dy dz$$

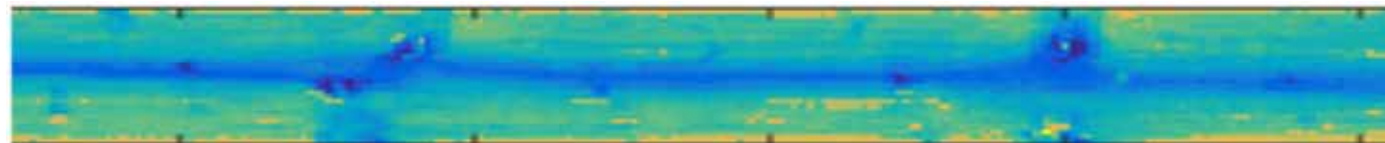




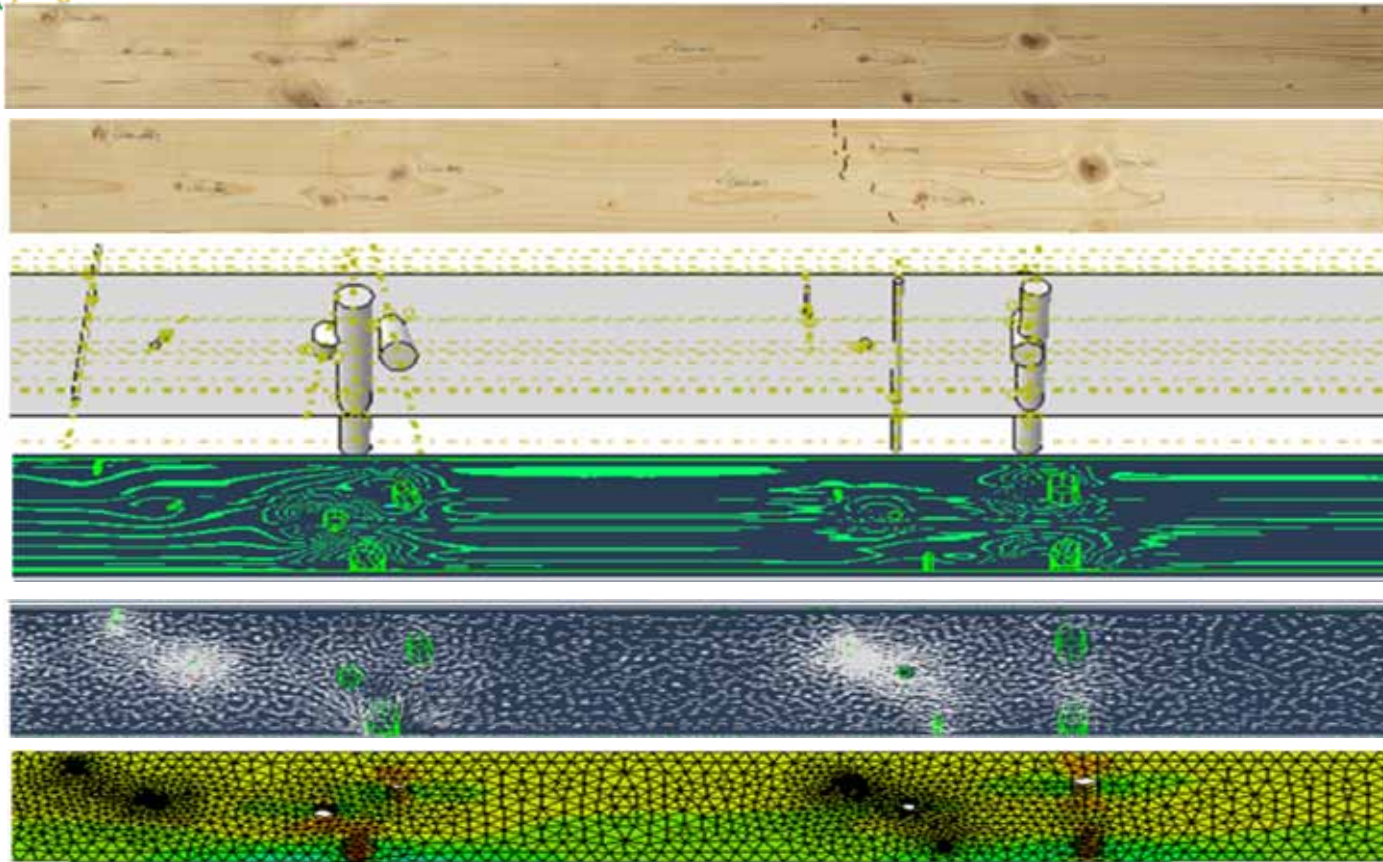
Image



Raggi - X



Ultrasuono



Image

Generazione dei nodi  
in 3D

Generazione della  
fibratura (CFD)

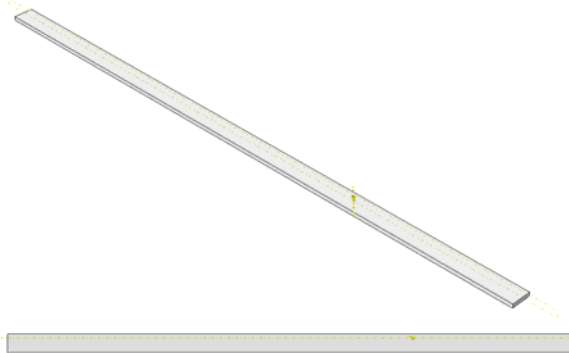
Generazione della  
fibratura max. (SOG)

Generazione FEM 3D

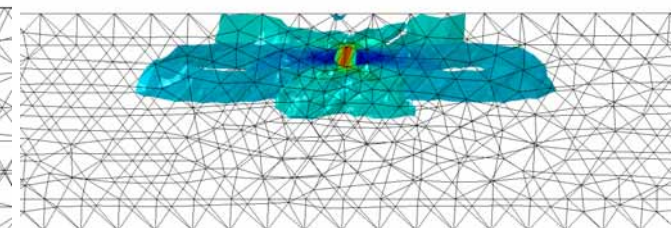
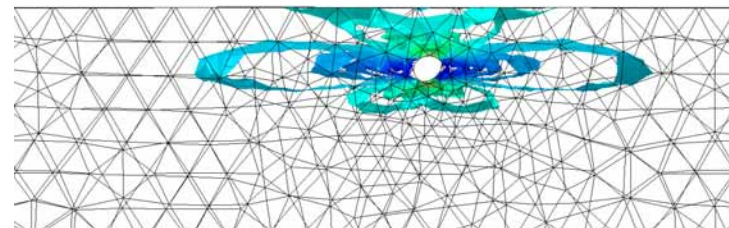
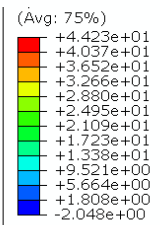


## Calcoli FEM:

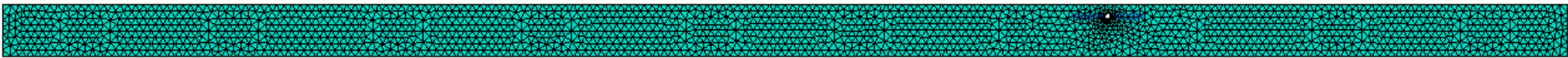
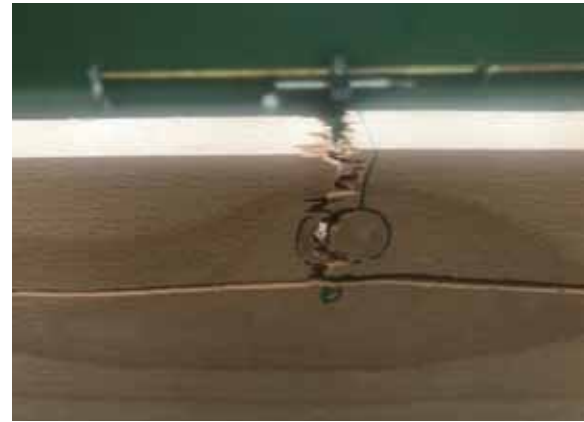
- generazione nuovi parametri
- Stress Concentration Factors (SCFs)
- Rottura
- Modulo Elastico Dinamico



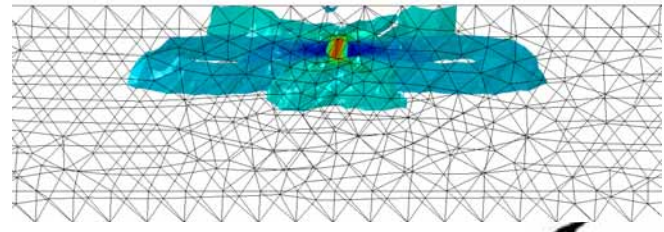
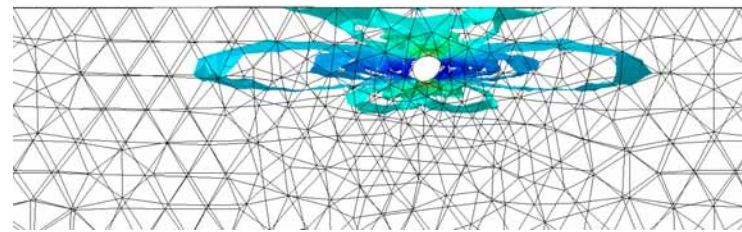
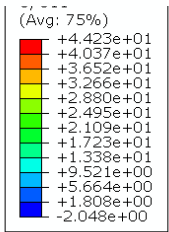
ODB: Solid.odb Abaqus/Standard 3DEXPERIENCE R2018x  
 Step: loading  
 Increment 11: Step Time = 1.000  
 Primary Var: S, S11  
 Deformed Var: U Deformation Scale Factor: +1.000e+01







ODB: Solid.odb Abaqus/Standard 3DEXPERIENCE R2018x  
 Step: loading  
 Increment 11; Step Time = 1.000  
 Primary Var: S, S11  
 Deformed Var: U Deformation Scale Factor: +1.000e+01

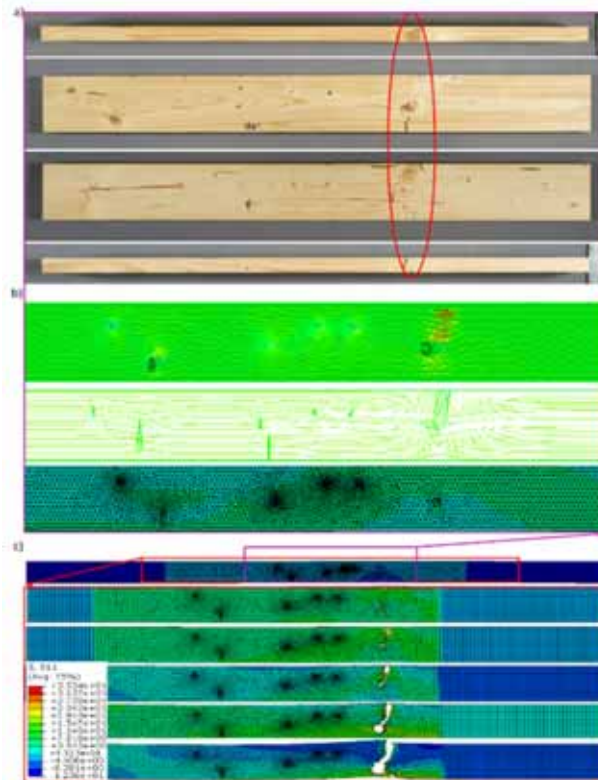


Stress Concentration Factors



Calcoli FEM:

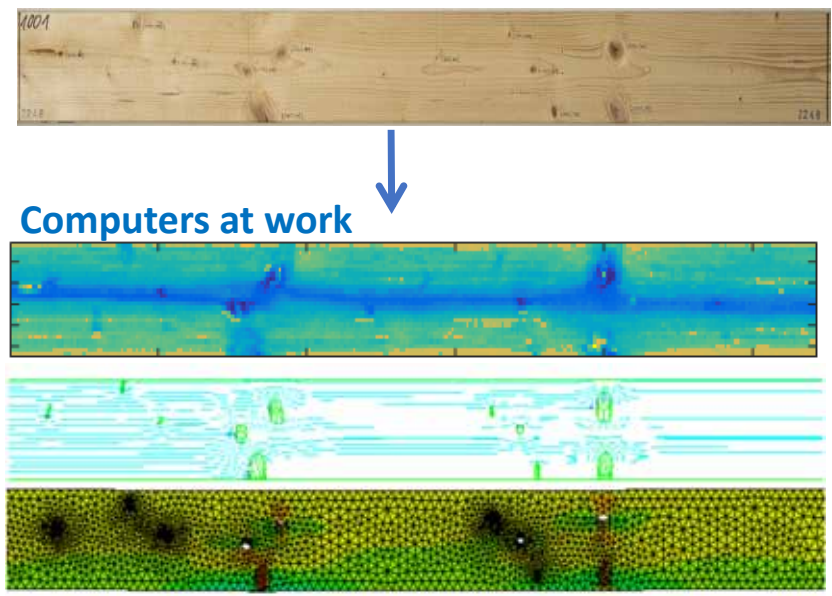
- generazione nuovi parametri
- Stress Concentration Factors (SCFs)
- Rottura
- Modulo Elastico Dinamico



Visual grading / Machine grading / Virtual grading **TU Delft**

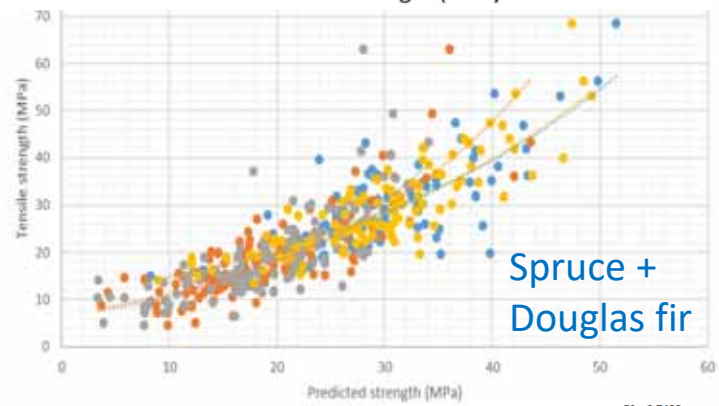
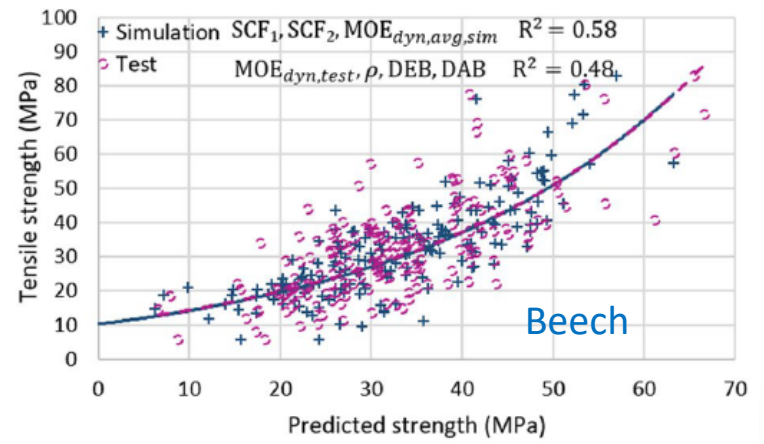
Virtual grading

Virtual grading



Computers at work

- Image based 'knot' identification
  - Fibre deviation modelling
  - 3D Stress model
  - Stress wave analysis
- Strength prediction

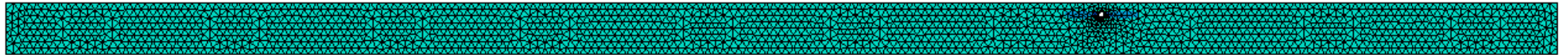
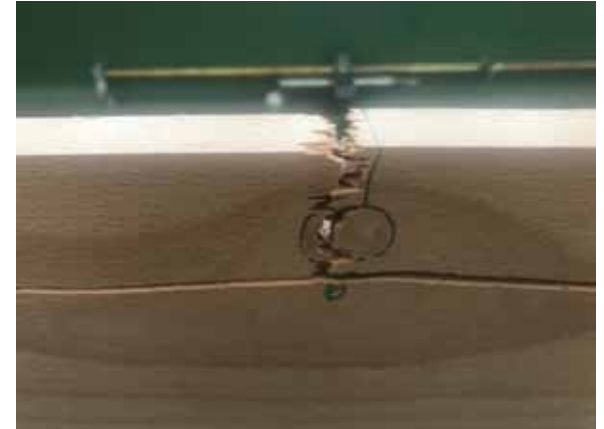


• All tested parameters (MOE\_dyn, TKAR, DEB, DAB, density) for spruce R<sup>2</sup> = 0.6036  
 • All tested parameters (MOE\_dyn, TKAR, DEB, DAB, density) for douglas fir R<sup>2</sup> = 0.6445  
 • Par1 and Par3 for spruce R<sup>2</sup> = 0.7492  
 • Par1, Par2 and Par3 for douglas fir R<sup>2</sup> = 0.6611

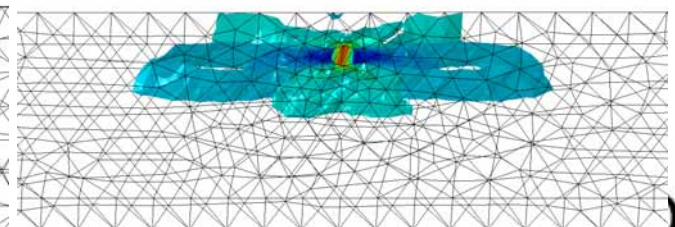
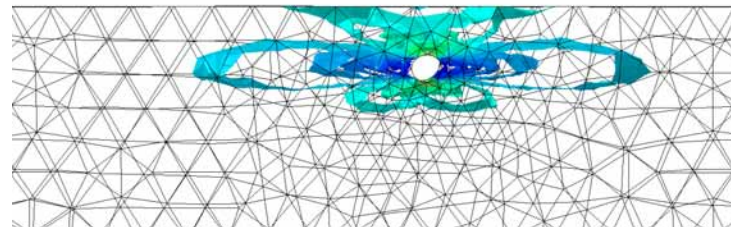
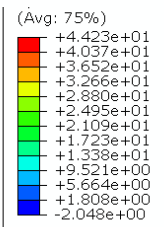




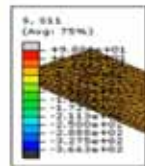
# CONFERENCE TRACK TOUR 2021



ODB: Solid.odb Abaqus/Standard 3DEXPERIENCE R2018x  
 Step: loading  
 Increment 11: Step Time = 1.000  
 Primary Var: S, S11  
 Deformed Var: U Deformation Scale Factor: +1.000e+01

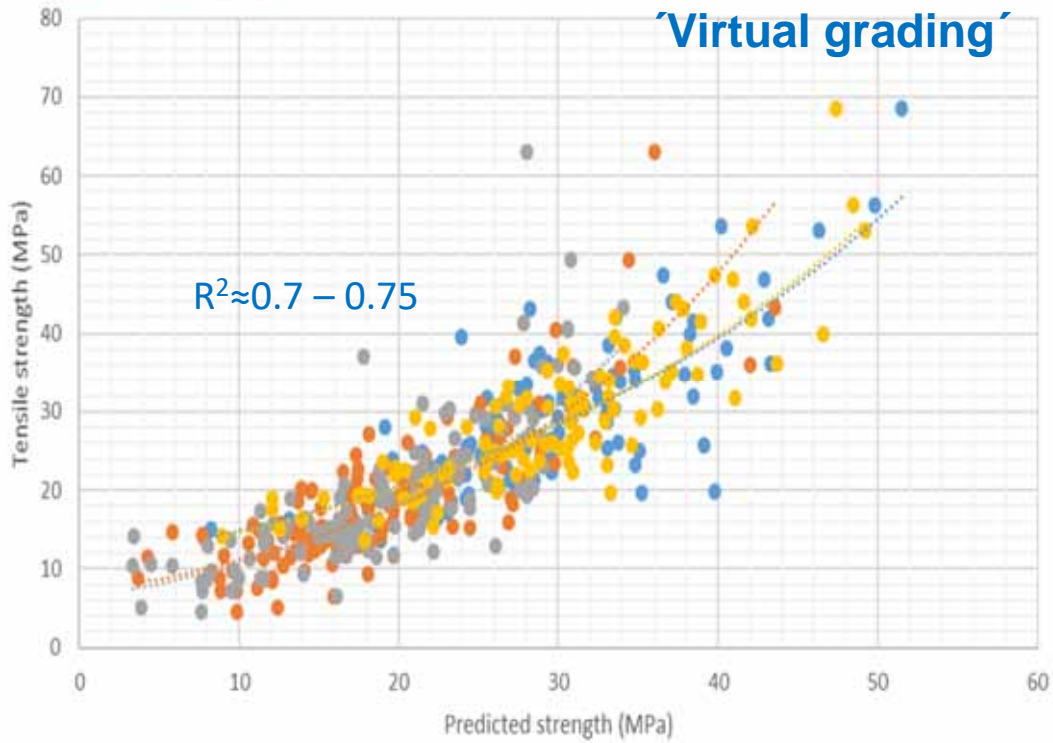


# CONFERENCE TRACK TOUR 2021



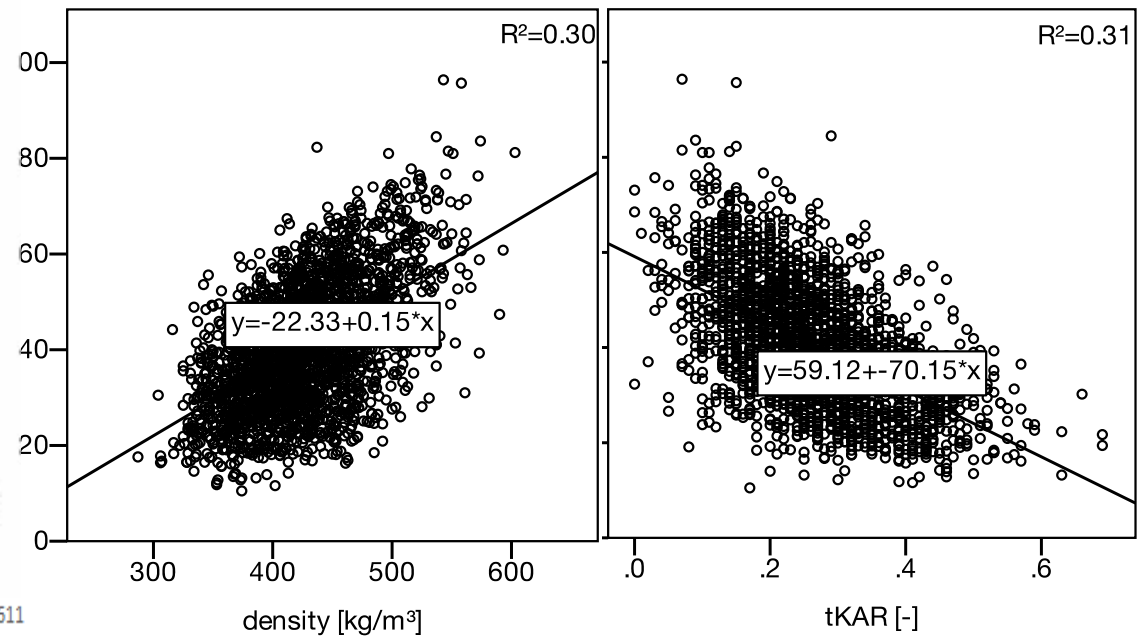
Step: stress\_w Process: 0  
Total Time: 0.000000





● All tested parameters (MOE\_dyn, TKAR, DEB, DAB, density) for spruce  $R^2 = 0.6036$ 
● Par1 and Par3 for spruce  $R^2 = 0.7492$   
● All tested parameters (MOE\_dyn, TKAR, DEB, DAB, density) for douglas fir  $R^2 = 0.6445$ 
● Par1, Par2 and Par3 for douglas fir  $R^2 = 0.6611$

**Visual grading**





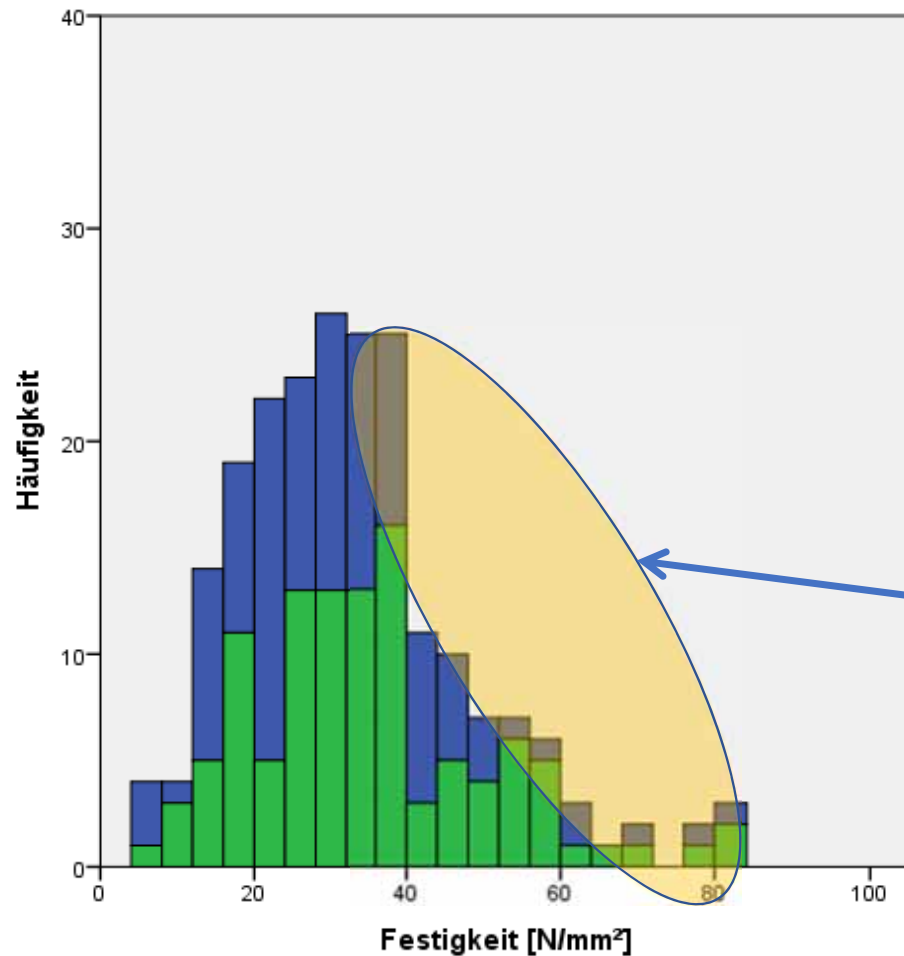
Property	T11	T14	T18	T21	T24	T28	T30
Strength properties [N/mm <sup>2</sup> ] $f_{t,0,k}$	11.0	14.0	18.0	21.0	24.0	28.0	30.0
Stiffness properties [kN/mm <sup>2</sup> ] $E_{t,0,mean}$	9.0	11.0	12.0	13.0	13.5	15.0	15.5
Density [kg/m <sup>3</sup> ] $\rho_k$	320	350	380	390	400	420	430

**Table 4.** Proposed tensile strength classes for medium-dense European hardwoods (DT-Classes).

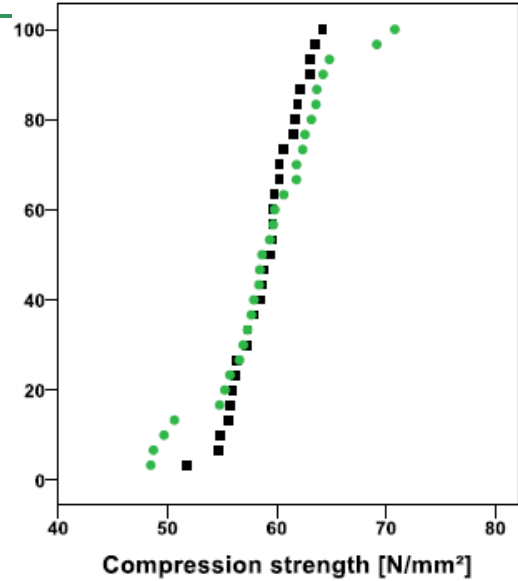
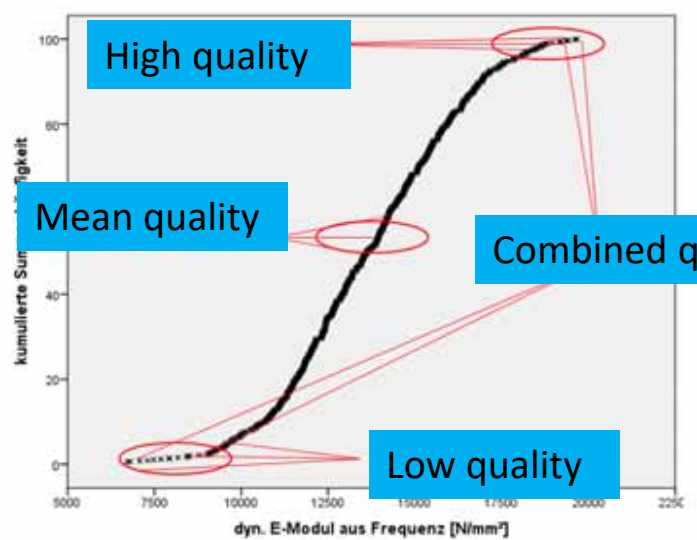
Property	DT22	DT24	DT28	DT30	DT34	DT38	DT42	DT46	DT50	
Strength properties [N/mm <sup>2</sup> ]	$f_{m,k}^a$	37	40	46	49	55	61	67	73	79
	$f_{t,0,k}$	22	24	28	30	34	38	42	46	50
	$f_{t,90,k}^b$	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	$f_{c,0,k}^c$	32	33	35	36	37	39	41	42	43
	$f_{c,90,k}^d$	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
	$f_{v,k}^e$	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Stiffness properties [N/mm <sup>2</sup> ]	$E_{t,0,mean}$	13000	13500	14000	14500	15000	15500	16000	16500	17000
	$E_{90,mean}$	810	830	880	930	1000	1030	1070	1100	1130
Density [kg/m <sup>3</sup> ]	$\rho_k$	550	550	550	550	610	610	620	630	640
	$\rho_{mean}^g$	660	660	660	660	730	730	740	750	760

Faggio con bassa resistenza → ideale per legno lamellare

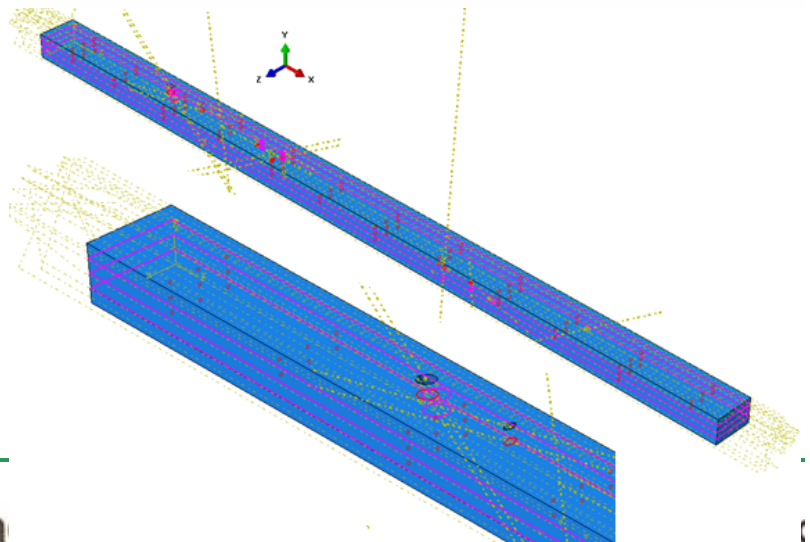
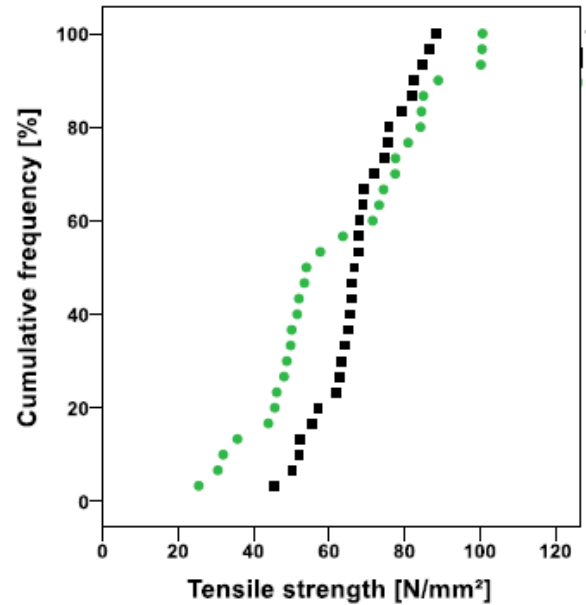
(DIN 4074-5 braucht Überarbeitung)



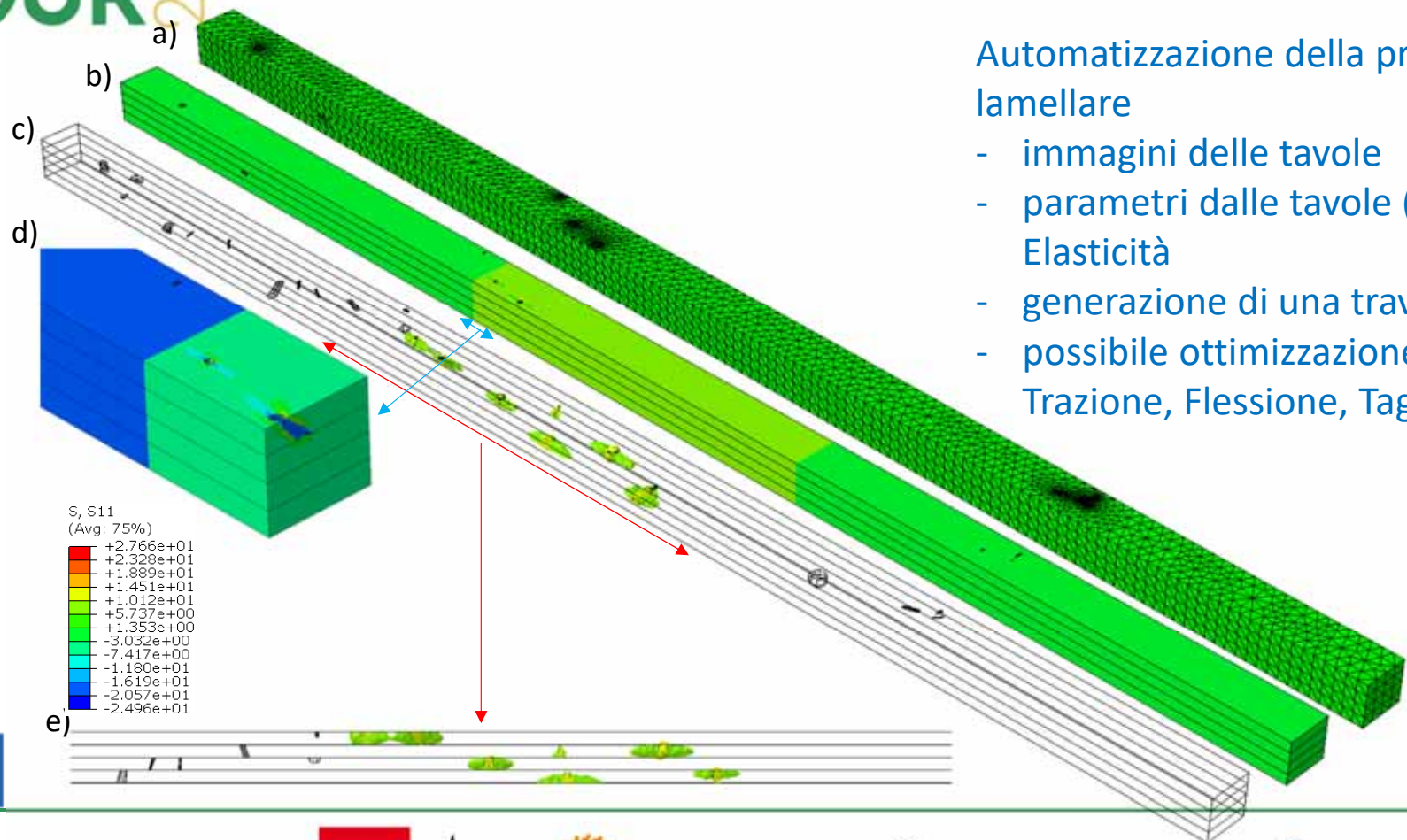
Clienti che pagano!  
 (Normalmente non è l'industria edile... 😊)



Glulam config.  
 ■ combined  
 ● homogeneous

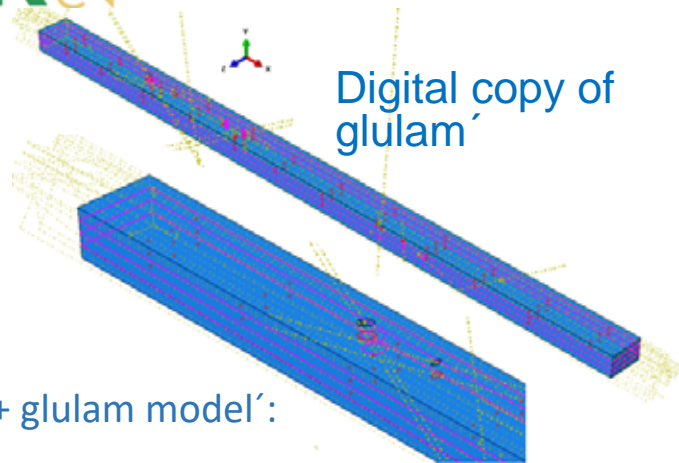






### Automatizzazione della produzione di legno lamellare

- immagini delle tavole
- parametri dalle tavole (Qualità, Modulo di Elasticità)
- generazione di una trave di legno lamellare
- possibile ottimizzazione (Resistenza / Rigidezza, Trazione, Flessione, Taglio,.... )



Virtual wood + glulam model':

- Knots
- Fibre flow / deviations
- Adhesive performance
- Automated lay-up (resource efficiency)
- Optimized for stiffness or strength



- Glulam of low grade beech
- Optimized cross sections with mixture of low and high grade lamellas



Production of beams and connections

Fully automated and connected to the design software (BIM / REVIT / FEM)



## Glulam – lamella strength classes

- Glued Laminated Timber - EN 14080:2013
- T-Classes for lamellas introduced
- Standards for grading of medium dense hardwoods need to be improved
- Standards for visual grading of tropical hardwoods can be used
- As we have the data of the boards, we also have data of the glulam



Beech

Spruce



• Glued Laminated Timber - EN 14080:2013

- T-Classes for lamellas introduced
- Standards for grading of medium dense hardwoods need to be improved
- Standards for visual grading of tropical hardwoods can be used
- As we have the data of the boards, we also have data of the glulam



Beech

Spruce

**Tension classes**

**Table 4.** Proposed tensile strength classes for medium-dense European hardwoods (DT-Classes).

	Property	DT22	DT24	DT28	DT30	DT34	DT38	DT42	DT46	DT50
Strength properties [N/mm <sup>2</sup> ]	$f_{m,k}^a$	37	40	46	49	55	61	67	73	79
	$f_{t,0,k}$	22	24	28	30	34	38	42	46	50
	$f_{t,90,k}^b$	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	$f_{c,0,k}^c$	32	33	35	36	37	39	41	42	43
	$f_{c,90,k}^d$	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
	$f_{v,k}^e$	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Stiffness properties [N/mm <sup>2</sup> ]	$E_{t,0,mean}$	13000	13500	14000	14500	15000	15500	16000	16500	17000
	$E_{90,mean}$	810	830	880	930	1000	1030	1070	1100	1130
Density [kg/m <sup>3</sup> ]	$\rho_k$	550	550	550	550	610	610	620	630	640
	$\rho_{mean}^g$	660	660	660	660	730	730	740	750	760





Lamellare di Faggio

Resistenza:

- Glulam: 24 – 48 MPa (60 MPa?)
- Microlamellare: 40 – 70 MPa
- Crosslam: 24 MPa

Abete / Pino / Larice

Faggio / Frassino / Acero / Rovere





Thanks to my colleagues:  
Andreas Rais - TUM  
Ani Khaloian - TUM  
Andriy Kovryga - TUM  
and  
M. Bacher - Microtec

Organizzato da:



In collaborazione con:



Promosso da:



Partner tecnico:



Con il patrocinio di:



Con il supporto di:



Media partner:



Partner tecnico finanziario:



Premium partner:

