



UNIVERSITY OF
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Correlating Non-Destructive and Semi-Destructive Test Results with Mechanical Properties of Reclaimed Timber

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Kira Circularis

- National project implemented by six universities
- Two-year – implementation period 4/2024-03/2026
- Total budget 1.5 M€
- Supporting the development of new circular economy products, services and innovations in the construction sector
- Promoting the formation of circular economy ecosystems in the construction sector
- Themes: circulation of materials, building components and buildings





Kira Circularis

- Work packages
 - WP1: Governance and interaction
 - WP2: Innovation learning process
 - WP3: Material circulation (material cycle)
 - WP4: Reusable or re-manufacturable building components
 - WP5: Buildings designed for disassembly or to be designed for disassembly
 - WP6: Impact assessment



TURKU AMK



**Euroopan unionin
osarahoittama**

UEI



inland



Kaakkois-Suomen
ammattikorkeakoulu





Why this matters?

- Re-use needs fast, non-destructive screening with traceable accuracy
- Engineers want density (ρ), MOE (E), sometimes MOR (without lab time) for design
- **Three main points:**
 - (i) density drives predictability
 - (ii) calibrated constants in context
 - (iii) a short protocol beats a long method list



Objective of the research

- Evaluate the suitability of NDT and SDT methods for assessing the condition of wood products.
 - Initial testing using virgin wood material and application to recycled wood
- To explore how combinations of non-destructive (NDT) and semi-destructive (SDT) testing methods relate to key mechanical properties
 - Tests will be carried out in controlled lab conditions
 - (SFS-EN 408:2010+A1. $T=+20^{\circ}\text{C}\pm 2$ RH=65±5%)
 - Average wood moisture content MC=14,45 %



Scope of the Study

- Method selection to match the property of interest
 1. Density and specific density (G)
 2. Ultrasonic velocity (m/s)
 1. Fundamental frequency (Hz)
 3. Modulus of elasticity MOE
 - (global and dynamic as output/estimated)
- Note: Visual grading complements any method used.



Testing devices

NDT (non-destructive testing)

- Fakopp Portable Lumber Grader (*dynamic MOE*)
- Pundit PL-200 (*ultrasonic velocity*)
- Hitman HM200 (*acoustic stiffness tester*)
 - *Max Velocity = 5,5 km/s*

SDT (semi-destructive testing)

- Fakopp Screw Withdrawal Meter (*density, shear strength and modulus*)
- IML-RESI PD400 (*drilling resistance/amplitude*)
 - *Feed speed:= 200 cm/min and Needle speed= 3000 rpm*

DT (destructive testing)

- AMT Systems KA500 (*MOE global*)



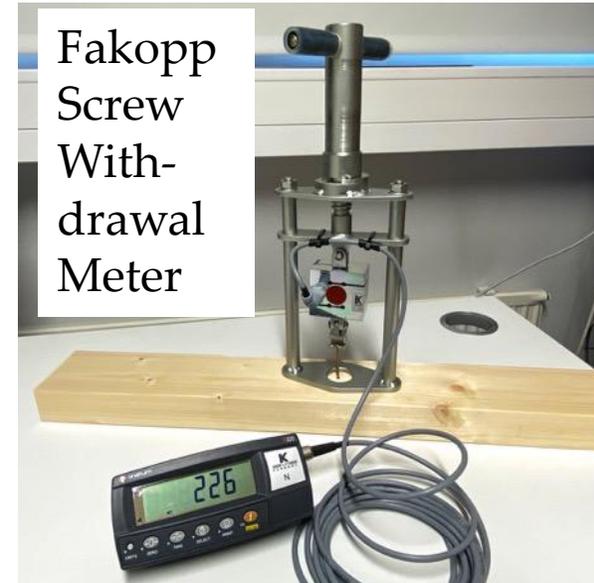
Pundit PL-200



IML-RESI PD400



Fakopp
Portable
Lumber
Grader



Fakopp
Screw
With-
drawal
Meter



Test Specimens

- **Used material was virgin material not recycled**
 - Why? To see the differences between methods and not to be affected so largely with differences of test specimens.
- **Test specimens:**
 - Sawn timber strength class C24 48x98x2000 (bxhxL) (planed size 45x95x2000).
 - N=10 (small sample size and needs more data)
 - Specimens cut to avoid finger joints, large checks/knots, warp, twist, growth defects



Density estimation

- Weighing and size measurements acted as reference for NDT and SDT density assessment as G (specific density)
- Devices/ methods
 - Fakopp Screw Withdrawal Meter
 - G , Handbook(1) and G_{est}
 - p = maximum withdrawal load, $K= 108,25$ (metric), D =nominal screw diameter (mm), L = embedded length
 - IML-RESI PD400 (p =kg/m³)

$$G(K) = \sqrt{\frac{p}{K D L}}$$

$$\rho = 227,114 + 7,633 \cdot \text{Amp}_{per} + 3,432 \cdot \text{Amp}_{diag}$$

(1) Wood Handbook — Wood as an Engineering Material (FPL–GTR–282), Chapter 8: Fastenings

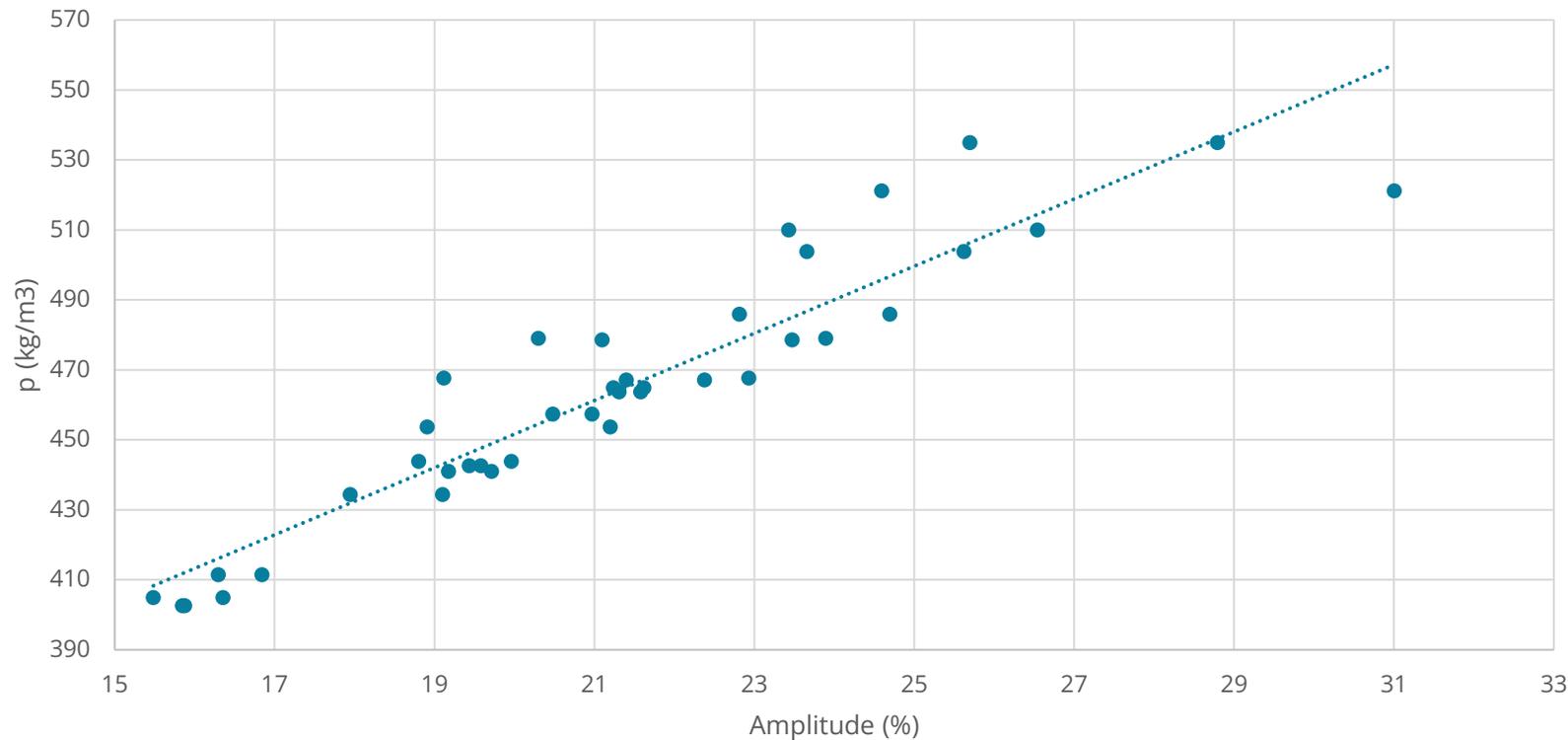


IML-RESI PD400

$\rho, \text{est1}$ (kg/m³)

$\rho, \text{est1} = 227,114 + 7,633 \cdot \text{amp}_{\text{per}} + 3,432 \cdot \text{amp}_{\text{diag}}$

$R^2 = 0,924$

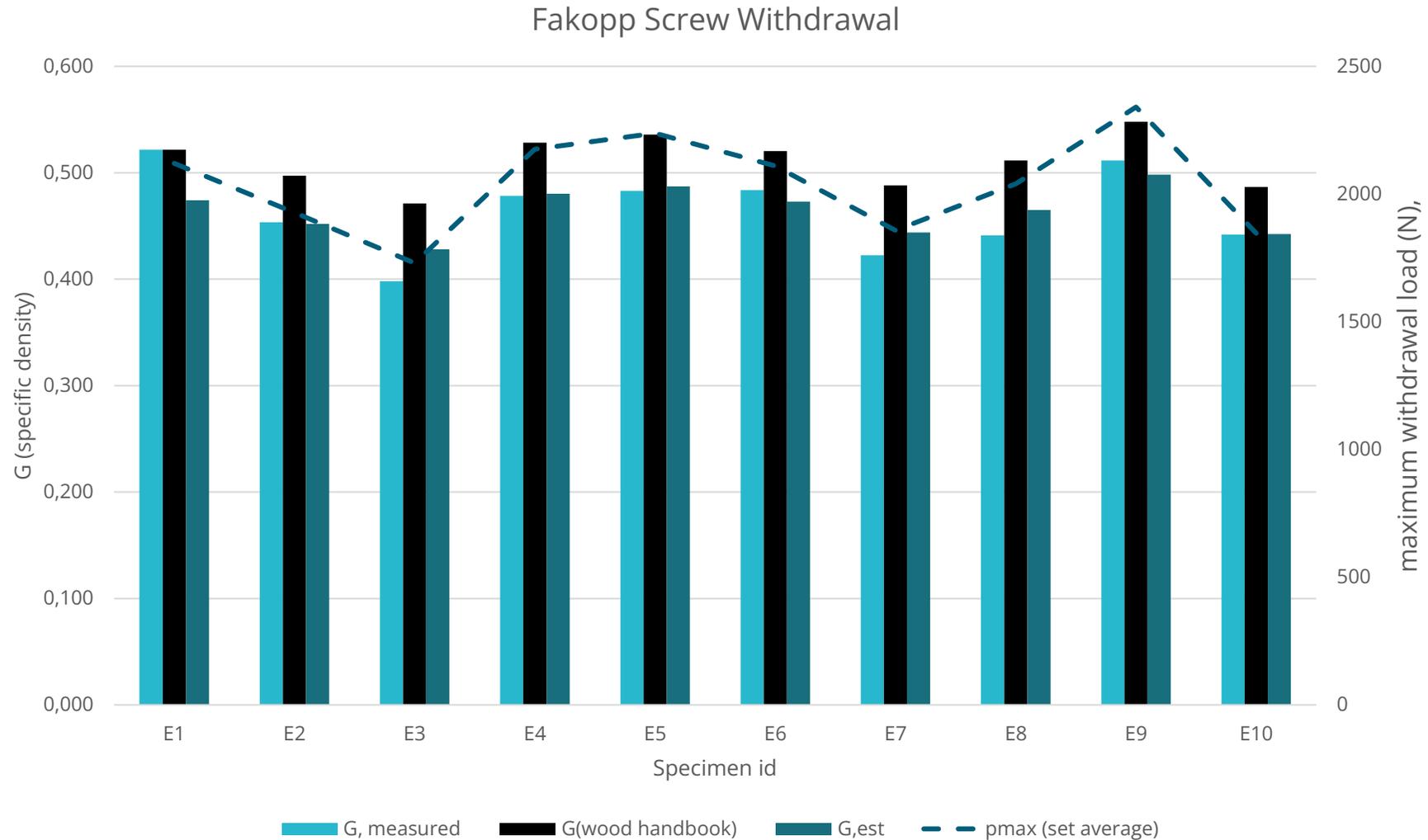


IML-RESI PD400

- Amplitude showed correlation with density.
- Amplitude should be approximately 30 %
- If not adjustment of feed or needle speed or both

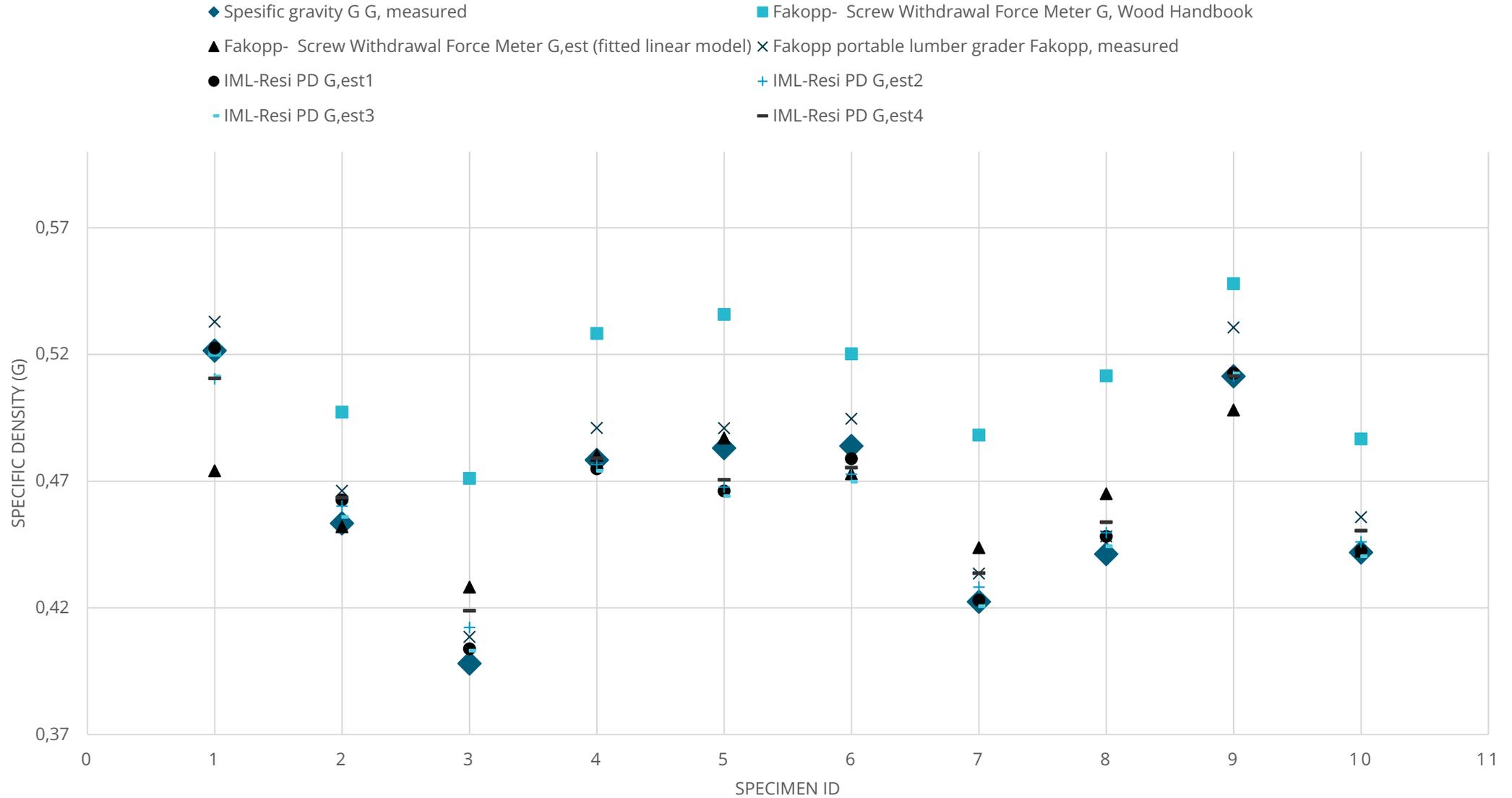
$$\rho = 227,114 + 7,633 \cdot \text{Amp}_{\text{per}} + 3,432 \cdot \text{Amp}_{\text{diag}}$$

Fakopp Screw Withdrawal Meter





SPESIFIC GRAVITY G



Specific gravity G		Fakopp-Screw Withdrawal Force Meter	Fakopp-Screw Withdrawal Force Meter	Fakopp portable lumber grader	IML-Resi PD			
id	G, measured	G, Wood Handbook	G,est (fitted linear model)	Fakopp, measured	G,est1	G,est2	G,est3	G,est4
E1	0,52	0,52	0,47	0,53	0,52	0,51	0,51	0,51
E2	0,45	0,50	0,45	0,47	0,46	0,46	0,46	0,46
E3	0,40	0,47	0,43	0,41	0,40	0,41	0,40	0,42
E4	0,48	0,53	0,48	0,49	0,47	0,48	0,47	0,48
E5	0,48	0,54	0,49	0,49	0,47	0,47	0,46	0,47
E6	0,48	0,52	0,47	0,49	0,48	0,47	0,47	0,48
E7	0,42	0,49	0,44	0,43	0,42	0,43	0,42	0,43
E8	0,44	0,51	0,47	0,45	0,45	0,45	0,44	0,45
E9	0,51	0,55	0,50	0,53	0,51	0,51	0,51	0,51
E10	0,44	0,49	0,44	0,46	0,44	0,45	0,44	0,45

- Difference to measured values 0-16 %
- Most accurate with fitted linear model for Fakopp and IML-Resi (G,est and G,est1...G,est4)
- With IML-Resi accuracy can be improved with perpendicular and diagonal drilling (G,est1)

G,measured	Weighted and calculated		
G,handbook	G=F,max/(15700*D*L), Wood Handbook — Wood as an Engineering Material (FPL-GTR-282), Chapter 8: Fastenings		
G,est	G=Square root (F,max/(130,995*D*L)) fitted linear model (R^2=0,993)		
	Density estimation (linear)	Units	Linear model
G,est1		kg/m3	p=227,114+7,633*amp, per+3,432*amp,diag
G,est2 (based on amp, per+diag)		kg/m3	p=259,7830+9,5987*amp(diag or per)
G,est3 (based on amp, perpendicular)		kg/m3	p=235,05+10,581*amp(diag or per)
G,est4 (based on amp, diagonal)		kg/m3	p=276,42+8,9698*amp(diag or per)
Multiple R-squared (R^2)			
			0,924
			0,802
			0,883
			0,751
Linear models based on measured weight and density with a explaining factor of amplitude %.			



MOE estimation

- Destructive 4 point bending tests (SFS-EN 408) as reference for MOE. As a shear corrected $E_{m,g}$ (AMT Systems KA500)
- Devices/ methods
 - Fakopp Portable Lumber Grader (static)
 - Hitman HM200
 - Pundit PL200
 - Derived values from measured density (for IML-Resi and Fakopp based on velocity)

$$MOE_{mea} = \frac{m}{l * w * h} (2lf)^2 0.92(1 + u/50)$$

where ρ : specific gravity
l: length
w: width
h: height
u: moisture difference in %
f: frequency of the longitudinal vibration
u: moisture difference in %. If $u > 18$ than $u=18$.
 $MOE = MOE_{mea} - 6.2CKDR$
PORTABLE LUMBER GRADER,
Software and hardware guide,
Version 2.0

$$E_d = \rho V^2$$

E_d : dynamic modulus of elasticity (along the grain)
 ρ : **gross density** of the log (green, at time of acoustic testing)
 V : measured acoustic (longitudinal) velocity of the log

$$MOE(IML-RESI PD) = 25,321 * (G * 1000)$$

Pulse velocity and fundamental frequency (per device)

Pulse velocity V (m/s)												
id	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	Average	Mean
Fakopp PLL	5694	5522	4919	5332	4979	5434	5114	5418	5318	5325	5306	5325
HITMAN HM200	5667	5470	4890	5297	4950	5407	5073	5380	5310	5283	5273	5297
PUNDIT PL200	5901	5429	4786	5247	5021	5787	5450	5744	5329	5785	5448	5448
Fundamental frequency f0, Hz (1/s)												
id	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	Average	Mean
Fakopp PLL	1423	1380	1230	1333	1244	1358	1278	1354	1329	1331	1326	1331
HITMAN HM200	1417	1368	1223	1324	1238	1352	1268	1345	1328	1321	1318	1324
PUNDIT PL200	1473	1356	1194	1310	1267	1446	1357	1433	1332	1447	1361	1357

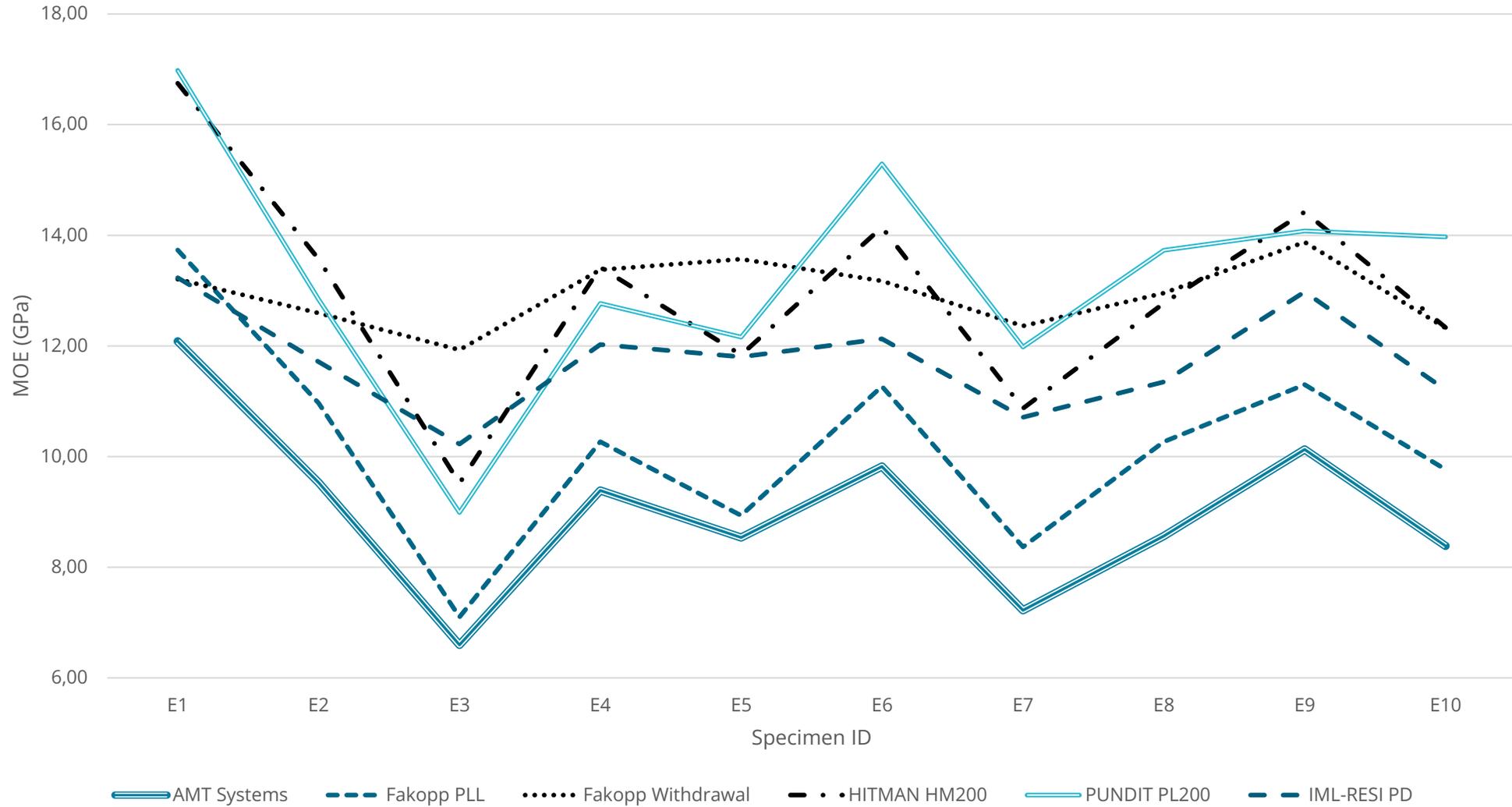


MOE estimation

MOE dynamic (Gpa)	AMT Systems KA 500	Fakopp portable lumber grader	Fakopp portable lumber grader	Fakopp- Screw Withdrawal Force Meter	HITMAN HM200	Pundit PL-200	IML-RESI PD
id	MOE1 (MOE, global)	MOE2.1 (MOE, mean dyn)	MOE2.2 (MOEcalc as static with CKDR)	MOE3	MOE4	MOE5	MOE6
E1	12,08	16,84	13,73	13,21	16,75	16,98	13,23
E2	9,53	13,97	10,97	12,59	13,57	12,84	11,71
E3	6,60	9,91	7,10	11,93	9,52	8,99	10,23
E4	9,39	13,70	10,27	13,38	13,42	12,77	12,02
E5	8,54	12,07	8,93	13,57	11,84	12,16	11,80
E6	9,82	14,35	11,27	13,17	14,14	15,29	12,13
E7	7,22	11,29	8,37	12,36	10,87	11,98	10,71
E8	8,56	13,01	10,27	12,95	12,77	13,73	11,35
E9	10,13	14,71	11,30	13,88	14,42	14,08	12,98
E10	8,38	12,80	9,77	12,32	12,33	13,97	11,21



MOE ESTIMATION $P \cdot V^2$ VS. $E(m, g)$





Summary: density

- Drilling resistance/amplitude and screw withdrawal force show correlation with density (specific gravity)
 - Perpendicular drilling and diagonal drilling together show higher correlation than just perpendicular/ diagonal drilling
 - Effect of needle and drill speed needs more research
 - Screw withdrawal primarily reflects near-surface density; for larger members multi-depth tests.
 - A simple linear (or log-linear) model works, but coefficients are site/species/setup-specific and should be calibrated and rechecked



Summary: MOE

- MOE from acoustics ($E_d = \rho V^2$)
 - Accuracy depends on density input and signal quality
 - Not a significant difference between devices in signal speed or fundamental frequency
 - E_d is typically 10–50 % higher than E_m , g. A conversion model is needed to remove bias.
- Density sensitive and with reclaimed timber defects and heterogeneity might increase scatter
 - Depends also on species, MC and device setup
- **Best correlation given with Fakopp PLG in relation to bending test (MOEcalc as static with CKDR)**



Field protocol?

- Protocol (in given order)
- Visual grading + MC : MC (pin-type, pre-test) and visual grading INSTA or similar practice
- Density proxy: Drilling resistance or screw withdrawal
- Stiffness (ultrasound/ TOF)
- Estimate of density and MOE
- Decision rule
 - Grading (applying EN 388)
 - -Reuse OK (Properties within target threshold range?)
 - -Fail/repair/modify/OK



Further research needs

- Validation and standardization of methods:
 - Comparative studies are needed in which NDT/SDT methods are systematically compared with destructive tests on different wood species, moisture levels and age groups.
- Integration of digital tools:
 - A uniform data structure and standardized data interface from measurement devices to design software.
- Suitability studies for recycled materials:
 - Experimental information is needed on how different mechanical and chemical modification methods affect the properties
 - How these products can be certified for construction use?



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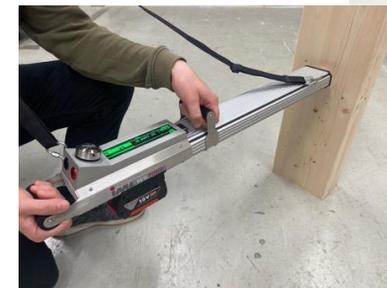
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