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Slutrapport

Energimyndighetens titel på projektet – svenska

Energieffektivare Virkestorkning vid Sågverken

Energimyndighetens titel på projektet – engelska

More Energy-Efficient Sawn-Timber Drying at Sawmills

Organisation (namn, ev. avdelning eller institution, adress)

Luleå tekniska universitet
Avdelningen för träteknik
Forskargatan 1, 931 87 Skellefteå

Nyckelord: 5–7 stycken

Virkeskvalitet, fuktvandringsmodeller, dimensionsförändringar, röntgentomografi, högtemperaturtorkning

Förord

Detta arbete har stöttats av skogsindustriföretag och företag/grupperingar inom området virkestorkning. Utan deras intresse för torkningsfrågor och hur virkestorkning skulle kunna bedrivas på ett energieffektivare sätt hade den forskningen i realiteten avstannat på träteknikavdelningen i Skellefteå och därmed utgjort ett allvarligt tapp för den akademiska och tillämpade trätorkningsforskningen i Sverige. Förutom SCA Timber, Setra och Svenskt trä (Arbio) har samarbetet med Norra timber varit oerhört betydelsefullt för framåtdriften i projektet. Virkestorkningsföretaget Valutec AB har tidigare bidragit med utrustning för real-tidsstudier av torkningsförkopp i avdelningens torktub och röntgenbaserade tomograf. Detta har lett fram till publicering av högklassiga resultat i vetenskapliga artiklar, konferenser och andra fora. Under projektet utvecklades även laboratorieutrustning för virkestorkning i samarbete bla med Holmen trävaror för att studera torkningsfrågeställningar i lite större skala (och som mer efterliknar den industriella). Samarbetet med Valutec på slutet av projektet har varit av stor betydelse för utformning av torkningsbetingelser och styrning av torkförloppen för dessa studier och som vi tänker även framöver.

Innehåll

Sammanfattning

Projektet har fokuserat på att utveckla ny kunskap och nya metoder för mer energieffektiv virkestorkning genom avancerad röntgenbaserad mätteknik, experimentella torkförsök och modellering av fukttransport i trä. Arbetet har genomförts inom forskningsmiljön CT WOOD vid LTU i Skellefteå, där unik experimentell utrustning möjliggör tidsupplösta studier av fukttransport och materialförändringar i trä under pågående torkning. Kombinationen av industriellt relevanta torkförsök, CT-baserad analys, modellering och datadriven analys har skapat nya möjligheter att förstå och optimera virkestorkningsprocessen. Projektet har bland annat visat att: torktider kan reduceras utan betydande kvalitetsförsämringar, energieffektivisering är möjlig genom optimerade torkscheman och högtemperaturtorkning, reducerad värmeanvändning och kortare processtider är möjliga, CT-baserade analyser ger ny förståelse för fukttransport, interna gradienter och materialrespons i trä under torkning. Projektet har även bidragit till utveckling av: experimentella metoder för tidsupplöst CT-analys, analys- och bildbehandlingsverktyg för stora datamängder, arbetsflöden för registrering och analys av 4D CT-data, samt metodik för datadriven och materialanpassad virkestorkning. Forskningsarbetet har resulterat i: fem vetenskapliga tidskriftsartiklar, två konferensbidrag, en licentiatavhandling, fortsatt doktorandutbildning samt student- och masterprojekt kopplade till CT-baserad analys och experimentell virkestorkning. Under rapportens färdigställande pågår dessutom arbete med ytterligare vetenskapliga artiklar kopplade till högtemperaturtorkning, CT-baserad analys och modellering av fukttransport i trä. Projektet har samtidigt bidragit till kompetensuppbyggnad inom: träteknik och virkestorkning, CT-baserad träanalys, bildbehandling och modellering samt digitaliserad och datadriven träindustri. Den utvecklade metodiken bedöms även ha potential för framtida studier av andra träslag och internationella tillämpningar där kunskapen om torkprocesser och interna materialförändringar fortfarande är begränsad. Under projektperioden påverkades verksamheten av organisatoriska och ekonomiska utmaningar inom forskningsmiljön. Detta medförde förseningar inom vissa delar av projektet, särskilt kopplade till experimentell utrustning och modellutveckling. Trots detta kunde centrala delar av projektet genomföras, och forskningsgruppen etablerade viktiga resultat, metoder och analysverktyg som skapar en stabil grund för fortsatt forskning och industriell utveckling.

Summary

The project has focused on developing new knowledge and methods for more energy-efficient timber drying through advanced X-ray–based

measurement techniques, experimental drying trials, and modeling of moisture transport in wood. The work has been carried out within the research environment CT WOOD at LTU in Skellefteå, where unique experimental equipment enables time-resolved studies of moisture transport and material changes in wood during ongoing drying. The combination of industrially relevant drying experiments, CT-based analysis, modeling, and data-driven analysis has created new opportunities to understand and optimize the timber drying process. The project has demonstrated, among other things, that: drying times can be reduced without significant quality deterioration; energy efficiency can be achieved through optimized drying schedules and high-temperature drying; reduced heat use and shorter process times are possible; and CT-based analyses provide new insights into moisture transport, internal gradients, and material response in wood during drying. The project has also contributed to the development of: experimental methods for time-resolved CT analysis, analysis and image-processing tools for large data sets, workflows for registration and analysis of 4D CT data, as well as methodologies for data-driven and material-adapted timber drying. The research work has resulted in: five scientific journal articles, two conference contributions, one licentiate thesis, continued doctoral studies, and student and master's projects related to CT-based analysis and experimental timber drying. During the completion of this report, work is also ongoing on additional scientific articles related to high-temperature drying, CT-based analysis, and modeling of moisture transport in wood. At the same time, the project has contributed to capacity-building in: wood technology and timber drying, CT-based wood analysis, image processing and modeling, as well as a digitalized and data-driven wood industry. The developed methodology is also considered to have potential for future studies of other wood species and international applications where knowledge of drying processes and internal material changes is still limited. During the project period, the activities were affected by organizational and financial challenges within the research environment. This led to delays in certain parts of the project, particularly related to experimental equipment and model development. Despite this, core parts of the project were successfully completed, and the research group established important results, methods, and analysis tools that provide a solid foundation for continued research and industrial development.

1 Inledning/bakgrund

Virkestorkning är den mest energikrävande processen inom sågverksindustrin och står för en betydande del av sågverkens totala energianvändning. Samtidigt påverkar torkningsprocessen både virkeskvalitet, produktionskapacitet och materialutbyte. Effektivare virkestorkning är därför av stor betydelse för svensk träindustri, både ur energi-, klimat- och konkurrenskraftsperspektiv. Historiskt har utvecklingen av industriella virkestorkar främst fokuserat på produktionskapacitet, driftsäkerhet och virkeskvalitet, medan energieffektivisering haft mindre fokus. Dagens industriella torkprocesser bygger dessutom till stor del på modeller och empiriska torkscheman utvecklade under tidigare decennier. Dessa modeller beskriver inte alltid moderna industriella processer tillräckligt väl, särskilt inte vid högre temperaturer där andra mekanismer än diffusion får ökad betydelse. Projektets utgångspunkt har därför varit att skapa ny kunskap om fukttransport, torkningsmekanismer, energiflöden och materialrespons under torkning. Ett särskilt fokus har legat på att förbättra förståelsen för hur olika torkförhållanden påverkar fuktgradienter, deformationer och interna transportmekanismer i trä, samt hur denna kunskap kan användas för mer energieffektiva torkprocesser. För detta har avancerad röntgenbaserad datortomografi (CT) kombinerats med experimentella torkförsök, bildanalys och modellering. Forskningsmiljön CT WOOD vid LTU i Skellefteå erbjuder experimentell infrastruktur där trä kan studeras icke-destruktivt under pågående torkning. Detta möjliggör tidsupplösta analyser av bland annat fuktfördelning, deformationer, sprickutveckling och interna transportmekanismer i trä. Kombinationen av CT-baserad analys, experimentell torkning och träteknisk kompetens ger goda möjligheter att studera torkprocesser i trä på detaljnivå och att utveckla underlag för framtida modellering och processtyrning. Projektet har genomförts vid avdelningen för träteknik, Luleå tekniska universitet i nära samverkan med industriella aktörer inom svensk träindustri och har pågått under 2022-2026. Energimyndigheten såväl som skogsföretagen Norra timber, SCA timber, Setra och Svenskt trä har hjälpt till med finansieringen av projektet som för trätekniks erhållna del omfattade nära 11.5 MSEK.

Projektets övergripande mål har varit att bidra till en minskad energianvändning vid virkestorkning, förbättrad virkeskvalitet, ökad resurseffektivitet, samt bättre förståelse för de grundläggande mekanismerna bakom fukttransport i trä.

Projektets delmål har omfattat:

- utveckling av CT-baserade experimentella metoder,
- studier av snabbare och mer energieffektiva torkscheman,

- analys av högtemperaturtorkning,
- modellering av fukttransport och spänningsuppbyggnad,
- samt utveckling av kunskap som kan användas för framtida industriella torkmodeller och processtyrning.

Projektet har även haft som mål att bidra till stärkt kompetens inom: digitaliserad träindustri, avancerad träkarakterisering, datadriven processutveckling samt CT-baserad analys och modellering av virkestorkning. Arbetet inom projektet har genomförts inom ramen för arbetspaketen WP1–WP6 i den ursprungliga projektansökan.

2 Genomförande

Projektet har genomförts genom flera delprojekt med fokus på experimentella torkförsök, CT-baserad analys, energisystemanalys, modellering, bildbehandling samt metodutveckling. Experiment har utförts både i laboratoriemiljö och i samverkan med industriella aktörer. Särskilt fokus har lagts på gran och furu, eftersom dessa träslag dominerar svensk sågverksindustri. Som en del av projektet installerades även en pilot-/laboratorietork baserad på utrustning från sågverksindustrin. Torken kompletterades med styrsystem och reglerteknik motsvarande sådana som används i industriella virkestorkar. Detta möjliggjorde experimentella studier av olika torkscheman och materialrespons under kontrollerade förhållanden (se APPENDIX 1 och 2).

En central del av arbetet har varit användningen av tidsupplöst röntgentomografi (CT), där förändringar i fuktfördelning och materialstruktur kunnat följas under pågående torkning. Under projektets senare del utvecklades även analysmetoder för: tidsserier av CT-data, bildregistrering, deformationsanalys, voxelbaserad analys, automatiserade arbetsflöden samt kvantitativ analys av fuktgradienter och materialförändringar. Dessa arbetsflöden möjliggjorde mer reproducerbar och detaljerad analys av stora datamängder från experimentella torkförsök. Projektet inkluderade även metodutveckling kopplad till användning av CT-data och materialkarakterisering från sågverksprocessen. Målet var att undersöka hur information om exempelvis densitet, årsringar, kärnvedsandel och materialvariationer kan användas för förbättrad styrning och optimering av torkprocesser.

Inom ramen för student- och masterprojekt genomfördes även studier kopplade till CT-baserad materialkarakterisering, fuktfördelning och deformationer i trä under torkning. Arbetet omfattade även planering och genomförande av experimentella laboratorietorkningar där materialet delades in i olika grupper för att möjliggöra jämförelser mellan olika torkscheman och materialrespons under torkning. Urvalet av material utvecklades i dialog med industriella aktörer och baserades på framtagna torkscheman för både slumpmässigt utvalda grupper och grupper med olika materialegenskaper. Syftet var att skapa försöksserier som både representerade sågverkens normala virkesfångst och samtidigt möjliggjorde jämförelser mellan material med olika egenskaper. Arbetet bidrog till ökad förståelse för hur CT-baserad materialkarakterisering kan användas som stöd för framtida materialanpassad virkestorkning och förbättrad processtyrning inom träindustrin.

3 Resultat

3.1 Effektivare torkscheman

Studierna indikerade att vissa konventionella torkscheman är mer konservativa än nödvändigt. Genom högre temperaturer och torrare luft kunde torktider reduceras utan att tydliga kvalitetsförsämringar observerades. Resultaten visade att:

- sprickbildning kunde begränsas,
- målfuktkvoter uppnåddes samt att fuktgradienter kunde hållas inom acceptabla nivåer.

Projektet genererade samtidigt experimentella data som kan användas för fortsatt utveckling av modeller för fukttransport och materialrespons i trä under torkning.

3.2 Energieffektivisering

Projektet indikerade att energibesparingar är möjliga genom optimerade torkprocesser och högtemperaturtorkning. Studierna pekade på potential för:

- reducerad värmeanvändning,
- minskat ventilationsbehov,
- kortare processtider,
- effektivare användning av bioenergi
- samt minskad energianvändning kopplad till luftcirkulation och fläktdrift.

Samtidigt identifierades viktiga forskningsfrågor kopplade till: emissioner, permeabilitet samt materialpåverkan vid högre temperaturer.

3.3 CT-baserad metodutveckling och digital analys

Projektet vidareutvecklade CT-baserade metoder för att studera: fukttransport, kapillärflöde, interna gradienter, deformationer samt förändringar i träets struktur under torkning. Under projektets senare del utvecklades även analysverktyg för:

- 4D CT-data,
- tidsupplösta analyser,
- bildregistrering,
- deformationsfält,
- voxelbaserad analys
- samt automatiserad kvalitetssäkring av data.

Dessa metoder möjliggjorde en mer robust analys, förbättrad reproducerbarhet, samt effektiv hantering av stora experimentella datamängder. Projektet bidrog därmed till vidareutveckling av metoder för datadriven analys och modellutveckling inom träteknik och virkestorkning.

3.4 Modellering

En tredimensionell FEM-baserad modell utvecklades i projektets tidiga faser och visade lovande möjligheter för simulering av fuktflöden, spänningsuppbyggnad samt risk för sprickbildning. Trots att delar av modellutvecklingen bromsades av organisatoriska och ekonomiska utmaningar skapades resultat och erfarenheter som kan användas i fortsatt forskning. Arbetet bidrog samtidigt till utveckling av underlag för framtida fysikbaserade modeller för virkestorkning.

4 Diskussion

4.1 Utmaningar och avvikelser

Projektet påverkades under genomförandet av organisatoriska förändringar och begränsade resurser inom forskningsmiljön. Detta medförde förseningar inom vissa experimentella och modelleringsrelaterade aktiviteter, särskilt kopplade till installation och drift av experimentell utrustning. Personalomsättning och förändringar i organisationen påverkade också möjligheten att genomföra vissa planerade aktiviteter enligt ursprunglig tidsplan. Under projektperioden förlorade forskningsmiljön även delar av den kompetens och kontinuitet som tidigare byggts upp inom området, vilket påverkade möjligheterna till långsiktig metod- och modellutveckling. Trots dessa utmaningar kunde centrala delar av projektet genomföras, och projektgruppen fortsatte arbetet med experimentella metoder, analysverktyg och vetenskaplig produktion. Projektet har också tydliggjort betydelsen av långsiktig forskningsinfrastruktur, stabil kompetensförsörjning och kontinuitet inom avancerad experimentell träforskning.

Under projektets senare del genomfördes organisatoriska förändringar inom forskningsmiljön vid Luleå tekniska universitet, inklusive beslut under 2024 om avveckling av ämnesområdet träteknik till och med halvårsskiftet 2027. Detta skapade osäkerhet kring forskningsmiljöns långsiktiga utveckling och påverkade möjligheterna till långsiktig planering och kompetensuppbyggnad inom delar av verksamheten. Trots detta har projektgruppen fortsatt arbetet med metodutveckling, forskarutbildning och vetenskaplig produktion, och flera aktiviteter och forskningsspår fortsätter även efter projektperiodens slut.

Samtidigt har projektet tydliggjort det fortsatta behovet av forskning och kompetens inom området. Industriella aktörer inom träindustrin och företag kopplade till virkestorkning har uttryckt ett fortsatt intresse för den forskning och metodutveckling som bedrivits inom forskningsmiljön. För nordiska träslag såsom gran och furu finns redan relativt stor industriell erfarenhet och etablerad kunskap kring virkestorkning. Däremot bedöms den utvecklade CT-baserade metodiken ha särskilt stor potential för studier av andra träslag och material där kunskapen om torkprocesser och interna fuktförändringar är mer begränsad. Detta gäller exempelvis lövträ och internationella tillämpningar där andra materialegenskaper och torkförhållanden förekommer. Den utvecklade metodiken möjliggör detaljerade och tidsupplösta studier av fukttransport, deformationer och materialrespons under pågående torkning, vilket skapar nya möjligheter för framtida forskning och industriell processutveckling. Det pågår samtidigt dialog kring möjligheterna att föra vidare hela eller delar av verksamheten och den kompetens som byggts upp inom forskningsmiljön till ett annat universitet.

4.2 Industrinytta och energirelevans

Projektet adresserar direkt sågverksindustrins behov av: minskad energianvändning, förbättrad virkeskvalitet, ökad produktionskapacitet samt effektivare resursutnyttjande. Kunskapen från projektet kan på sikt bidra till:

- kortare torktider,
- reducerad värmeanvändning och minskat ventilationsbehov, ‘
- effektivare användning av bioenergi,
- minskade produktionskostnader samt förbättrat materialutnyttjande inom träindustrin.

Projektet har även bidragit till utveckling av metodik för mer materialanpassad och datadriven virkestorkning, där CT-baserad materialkarakterisering och analys kan användas som stöd för förbättrad processtyrning och optimering av torkprocesser. Den utvecklade metodiken bedöms samtidigt ha potential även utanför traditionell nordisk virkestorkning. För träslag såsom gran och furu finns redan omfattande industriell erfarenhet, medan behovet av ökad kunskap kring torkprocesser och materialrespons är större för många andra träslag och internationella tillämpningar. Särskilt bedöms metodiken ha potential för framtida studier av lövträ och andra material där interna fuktförändringar och deformationer under torkning idag är mindre väl förstådda. Projektet stärker även svensk kompetens inom:

- digitaliserad träindustri,
- avancerad träkarakterisering,
- CT-baserad analys och bildbehandling
- samt datadriven processutveckling och modellering.

Genom kombinationen av experimentell torkning, tidsupplöst CT och avancerad analys har projektet bidragit till utvecklingen av metoder och kunskap som kan användas för framtida energieffektivisering och digitalisering inom träindustrin.

4.3 Slutsatser och framtida arbete

Projektet har visat att CT-baserade experimentella metoder i kombination med modellering och industriell samverkan kan bidra till utvecklingen av framtidens virkestorkning. Resultaten indikerar att energieffektivisering är möjlig, mer materialanpassade torkscheman kan utvecklas, kortare torktider kan uppnås utan tydliga kvalitetsförsämringar, samt att bildanalys och tidsupplöst CT kan ge ökad förståelse för fukttransport och materialrespons under torkning. Projektet har samtidigt bidragit till utveckling av: experimentell metodik för tidsupplöst CT, analys- och bildbehandlingsverktyg, arbetsflöden för 4D CT-data och registrering av tidsserier samt underlag för framtida modellering och processtyrning inom virkestorkning.

Fortsatt arbete behövs särskilt inom:

- uppskalning till industriella processer,
- vidareutveckling av modeller,
- integration av CT-data i styrsystem och processtyrning
- samt verifiering av energieffektiva torkstrategier i fullskalig drift.

Den utvecklade metodiken bedöms även ha potential för studier av andra träslag och internationella tillämpningar där kunskapen kring torkprocesser och interna materialförändringar fortfarande är begränsad. Den apparatur, metodik och de analysverktyg som utvecklats inom projektet utgör samtidigt ett viktigt underlag för fortsatt forskning kring hållbar och energieffektiv träindustri. Under projektets gång har även kompetens och arbetsflöden byggts upp inom CT-baserad träanalys, bildbehandling och datadriven analys, vilket skapar förutsättningar för fortsatt forskning och industriell utveckling även efter projektperiodens slut.

5 Publikationslista

Projektet har bidragit till kompetensuppbyggnad inom: virkestorkning, CT-baserad träanalys, bildbehandling och modellering samt digitaliserad och datadriven träindustri.

Forskningsarbetet har resulterat i:

- fem vetenskapliga artiklar,
- två konferensbidrag,
- en licentiatavhandling,
- utveckling av analysmetoder och experimentella arbetsflöden
- samt fortsatt forskarutbildning inom området.

Under rapportens färdigställande pågår dessutom arbete med ytterligare vetenskapliga artiklar kopplade till högtemperaturtorkning, CT-baserad analys, samt modellering och analys av fukttransport i trä. Projektet har även bidragit till utveckling av kompetens inom tidsupplöst CT, 4D-bildanalys, registrering av CT-tidsserier, deformationsanalys samt kvantitativ analys av fukttransport i trä.

5.1 Forskarutbildning och kompetensuppbyggnad

Projektet har haft en viktig roll i uppbyggnaden av kompetens inom virkestorkning, CT-baserad träanalys, bildbehandling och modellering av fukttransport i trä. Arbetet har genomförts i nära koppling till forskarutbildning och metodutveckling inom forskningsmiljön CT WOOD vid Luleå tekniska universitet. En central del av projektet har varit utvecklingen av experimentella och analytiska metoder för tidsupplöst röntgentomografi (4D CT) och kvantitativ analys av fuktfördelning i trä under torkning. Detta arbete har bidragit till utveckling av kompetens inom tidsupplöst CT-analys, bildbehandling, registrering av CT-tidsserier, deformationsanalys samt datadriven analys av materialförändringar i trä. Projektet har också bidragit till utbildning av doktorander inom området.

Licentiatavhandling med titeln Four-dimensional computed tomography and image processing to investigate moisture in wood presenterades av 2023 av Boris Poupet vid Luleå tekniska universitet. Avhandlingen fokuserade på utveckling av tidsupplösta CT-metoder och bildanalys för att studera fuktfördelning och fukttransport i trä under torkning. Arbetet omfattade både experimentell metodutveckling och analys av fuktgradienter i virke under aggressiva torkningsförhållanden.

Som en del av forskarutbildningen genomfördes under 2024 även en halvtidsuppföljning av doktorandprojektet kopplat till högtemperaturtorkning och CT-baserad analys. Vid seminariet diskuterades projektets resultat och metodik tillsammans med externa experter från både forsknings- och industrisidan. Seminariet bidrog med värdefull återkoppling kring: energieffektivisering, torkprocesser, modellering samt fortsatt utveckling av experimentella och analytiska metoder. Projektet har även bidragit till fortsatt doktorandutbildning inom området. Ebrahim Hajiyans doktorandarbete fokuserar på högtemperaturtorkning, modellering och CT-baserad analys av fukttransport i trä. Disputation planeras till våren 2027.

Projektet har dessutom bidragit till utbildning genom student- och masterprojekt kopplade till CT-baserad träanalys och laboratorietorkning. Arbetena omfattade bland annat studier av sambandet mellan CT-baserade materialegenskaper, fuktfördelning och deformationer i virke under torkning (se Appendix 1 och 2). Sammantaget har projektet bidragit till fortsatt forskning och kompetensutveckling inom energieffektiv virkestorkning och CT-baserad träanalys.

5.2 Vetenskapliga artiklar

Poupet, B., Florisson, S., Couceiro, J., and Sandberg, D. (2023). Moisture gradients in sawn timber during aggressive kiln drying investigated with X-ray computed tomography. Wood Material Science & Engineering, 18(6), 2140–2149. DOI: 10.1080/17480272.2023.2269390

Hajiyan, E., Huber, J., Hansson, L., and Sandberg, D. (2024). High temperature drying of sawn timber — A review. Drying Technology, 42(9), 1397–1414, DOI:10.1080/07373937.2024.2365858.

Vikberg, T., and Hansson, L. (2024). Exploring the Potential of CT Image Processing Analysis for Assessing Capillary Flow in Pine Wood Logs. Pro Ligno, 1, 3–8.

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5.4 Resultatspridning och industrikontakter

Projektets resultat har presenterats både för forskarsamhället och för representanter från träindustrin genom konferenser, vetenskapliga publikationer och industrirelaterade aktiviteter. Forskningsgruppen deltog under 2024 på Trä & Teknik 2024, Nordens största mötesplats för träindustrin, där pågående forskning inom CT WOOD och energieffektiv virkestorkning presenterades för industri, forskare och andra aktörer inom träsektorn. Fokus låg bland annat på CT-baserad analys av trä, digitalisering av träindustrin, energieffektivisering samt bildanalys och modellering. Projektet har därigenom bidragit till kunskapsspridning kring hur avancerad mätteknik och datadriven analys kan användas för att utveckla framtidens träindustri. Forskningsresultaten och den utvecklade CT-metodiken presenterades även för representanter från sågverksindustrin vid STTF:s exkursion hos Fiskarhedens Trävaru AB under 2023. Presentationen fokuserade på hur CT-baserad analys kan användas för att studera: fuktfördelning, materialstruktur, torkrelaterade förändringar samt potentialen för digitaliserad analys och processtyrning inom träindustrin. Aktiviteten genomfördes inom ramen för STTF:s tema kring digitalisering och framtida kompetensförsörjning inom sågverksindustrin och bidrog till kunskapsspridning mellan forskning och industri.

Resultat från doktorandprojektet och halvtidsseminariet har även kommunicerats genom populärvetenskapliga inlägg på LinkedIn.

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7 Bilagor

APPENDIX 1.

Influence on Heartwood-Based Presorting and Zone-Specific Drying Schedules on Moisture Distribution in Scots Pine Board: Laboration Kiln Drying

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Master Thesis in Wood Science and Engineering Part I

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Abstract

This case study tested whether sorting Scots pine boards by heartwood content can reduce moisture variation when different kiln zones are simulated. Four batches were dried in a laboratory kiln using soft and harsh schedules representing middle and edge industrial kiln zones. Moisture content was measured at three positions along each board.

Deviations in two runs were corrected using Valmatics 4.0 simulations. Heartwood content was linked to initial moisture content, while basic density was similar across all batches. Combining experimental and simulated data showed that heartwood sorting reduced moisture variation by about 0.1 percentage points.

The effect is small but indicates potential for improving drying consistency. Larger-scale studies are recommended to confirm the effect under stable industrial conditions.

1. Introduction

Drying of sawn timber is a critical step in softwood processing, strongly influencing product quality, energy consumption, and overall process efficiency. Variation in final moisture content remains a challenge in industrial batch kilns, where differences in raw material properties and spatial climate gradients contribute to uneven drying. Heartwood content, in particular, is known to affect drying behavior due to its lower permeability and distinct anatomical structure compared with sapwood (Perre, 2007). Sorting boards according to heartwood proportion may therefore offer a practical strategy for reducing moisture variation, especially if boards are placed in kiln zones with climate conditions matched to their expected drying behavior (Pang, 2000).

This study investigates whether sorting Scots pine boards by heartwood content and placing them in kiln zones with different climate severity can reduce moisture variation after drying. A laboratory-scale kiln was used to emulate industrial middle- and edge-zone conditions, and both experimental and simulated data were analyzed to quantify the effect of heartwood-based sorting on final moisture distribution.

2. Methods and Materials

2.1 Kiln facilities and experimental period

The experiment was carried out in February 2026 at the Wood Technology laboratory of Luleå University of Technology, Campus Skellefteå. A research-scale batch kiln designed to replicate industrial drying conditions was used (Fig. 1). The kiln accommodates one small package of sawn timber (3 m length) and is equipped to reproduce typical climate conditions found in commercial sawmills (Tabel 1).

Drying schedules were selected to represent local industrial practice for Scots pine of the investigated dimension.

Table 1. Laboratory kiln specifications

Parameter	Value
Year	2001
Manufacturer	ABB
Model	Kammartork 2000
Inner dimensions (mm)	640 × 500 × 3000
Fan reversal	No
Fan configuration	Back wall, 2 fans, 2.2 kW each
Steam generator	50 kg/h
Control system	Valutec PLC

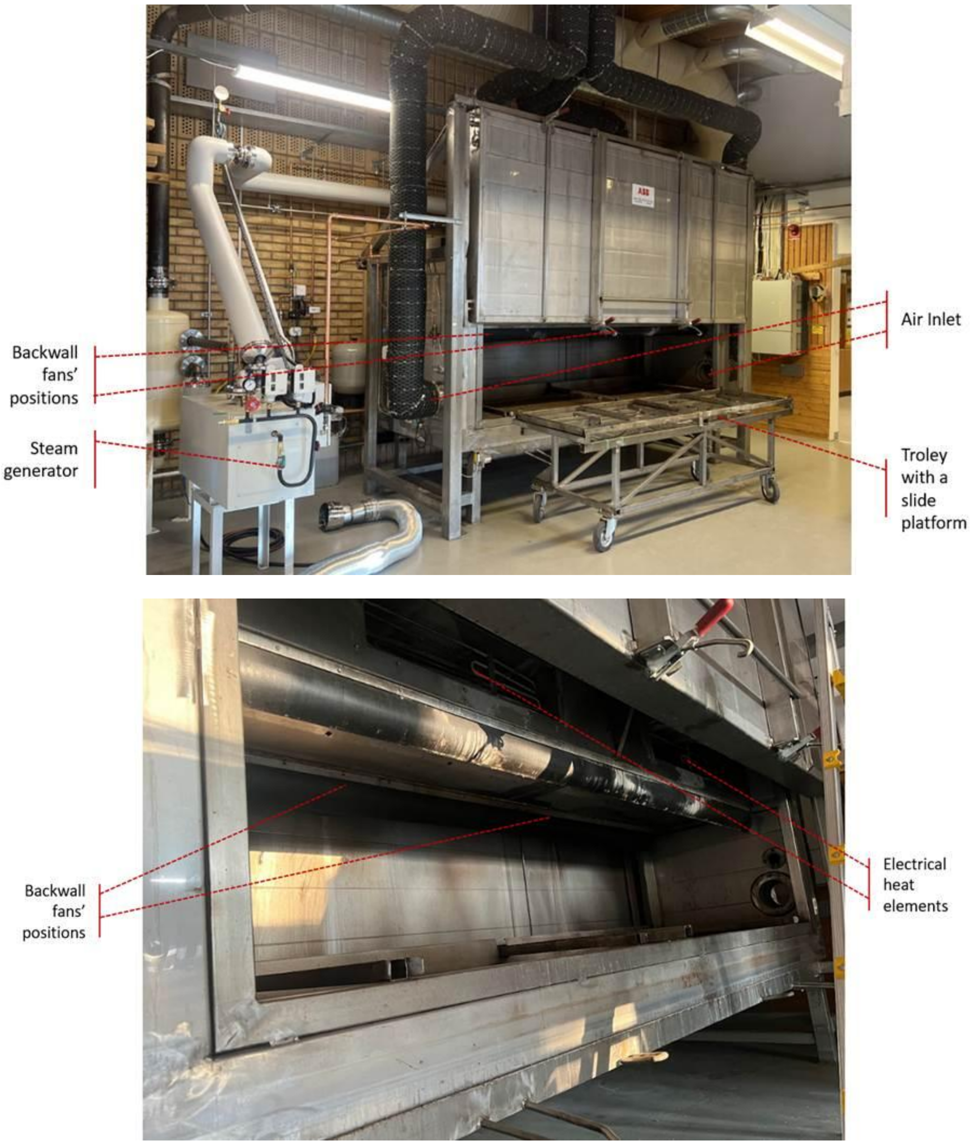


Figure 1. Laboratory kiln

2.2 Material selection and kiln loading strategy

Scots pine (*Pinus sylvestris*) boards with nominal dimensions 38 × 125 × 3000 mm were used. All material originated from the main yield (2X, centerboards). At the sawmill a package of 140 boards (length 3200–3600 mm) was manually sorted immediately after the sawing.

Boards were divided into four batches (32 boards each) based on heartwood content:

1. A Mix – unsorted, taken consecutively from the package
2. B Mix – unsorted, taken consecutively from the package

The rest of the boards was divided in two groups, sorted according to heartwood content, from which the two batches below was taken out for the study.

3 Heartwood – 32 boards with the highest heartwood proportion

4 Sapwood – 32 boards with the lowest heartwood proportion

Heartwood content was estimated visually by applying a reagent, composed of a water solution of sulphanilic acid and sodium nitrite, to the cross-sections of all boards, enhancing the contrast between heartwood and sapwood (Fig. 2). Heartwood percentage was determined from photographs using a classification template (Fig. 3).

Fig. 2. B Mix(left) and Heartwood (right) batches pre-sorted at the sawmill, with heartwood reagent.

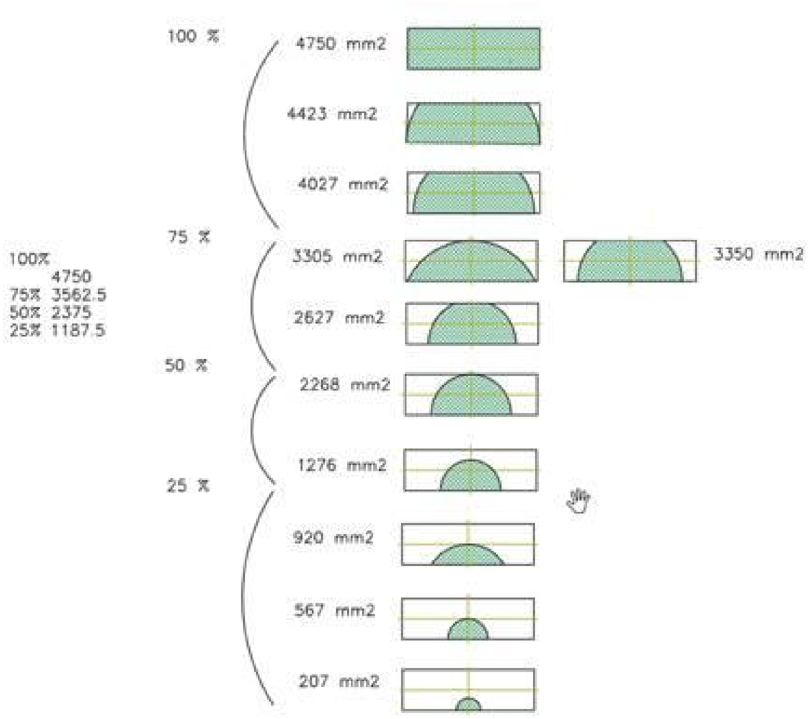


Fig. 3. Heartwood content classification template

All boards were trimmed to a uniform length of 3000 mm. Specimens not shorter than 50 mm were taken from offcuts and used to determine initial moisture content and basic density. Moisture content in green condition was calculated from green and oven-dry mass (103°C, 72 h). Basic density was determined from green volume and dry mass.

2.3 Drying schedules and kiln loading

To emulate different kiln zones, two drying schedules were developed based on an industrial schedule used in northern Sweden for 38-mm pine (Tab. 2). The “soft” schedule represented the milder climate in the kiln center, while the “harsh” schedule simulated the more severe conditions near the kiln edges where final moisture content usually will be lower in the boards.

Table 2. Drying schedules

Schedule	Soft	Harsh
Wet-bulb temperature (°C)	60	60
Dry-bulb temperature (°C)	73	75
Conditioning phase	No	No
Industrial zone emulated	Middle	Edge

Batch allocation:

- Soft schedule: A Mix, Heartwood
- Harsh schedule: B Mix, Sapwood

All drying runs were performed over two weeks in February. Before drying, all green boards were stored outdoors at –15 to –25°C, covered with nylon fabric and snow.

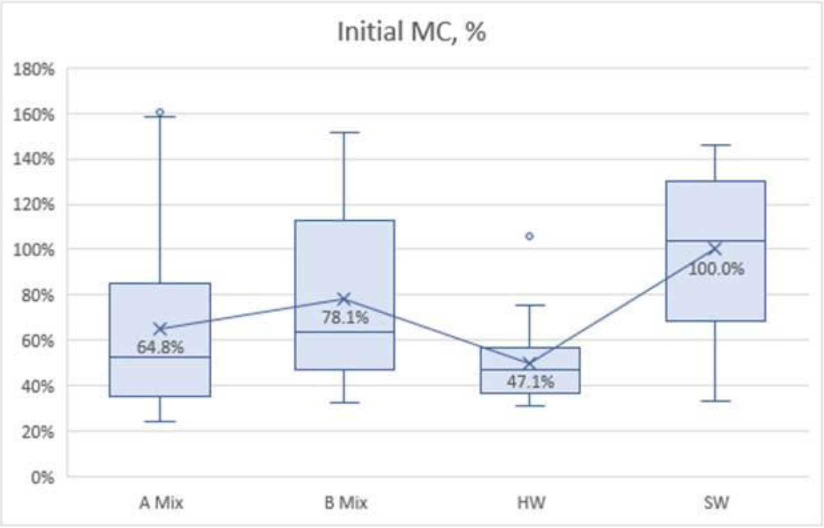
2.4 Moisture content measurements

Immediately after each drying run, three samples were cut from each board: one from the middle and two from the ends (at least 30 cm from the edges). Samples were 50 mm long and free from major defects. Moisture content was determined using the oven-dry method (Standards Sweden, 2004). For each board, the mean moisture content and within-board standard deviation were calculated.

3. Results and Discussion

3.1 Raw material properties.

Initial material properties were consistent with typical Scots pine timber. Initial moisture content varied in the boards with heartwood proportion, while basic density remained similar across batches (Fig. 4).



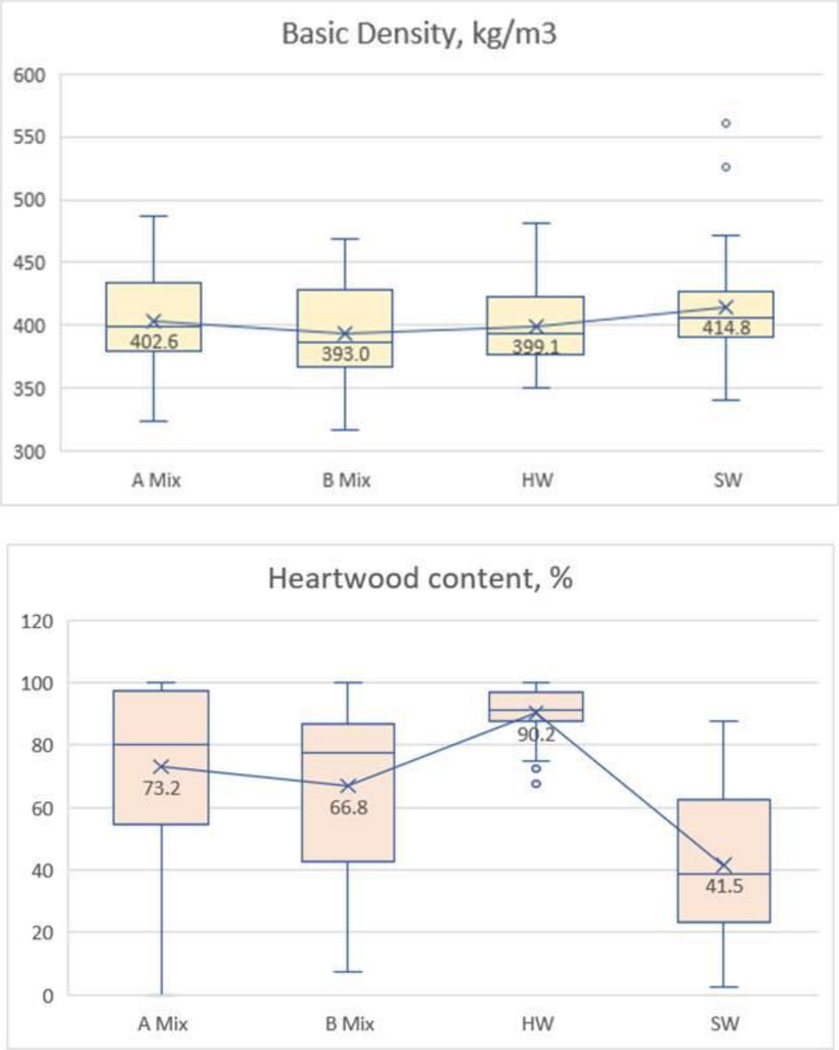


Fig. 4. Spread of initial moisture content, basic density and heartwood content among the batches.

3.2 Kiln performance and deviations

Two runs ("B Mix" and "Heartwood") experienced some deviations from the planned schedules, primarily increases in dry-bulb temperature (Fig. 5) in the start and in the end of processes. Key characteristics of the four runs are summarised in Table 3.

Table 3. Characteristics of the four kiln- runs

Run	A Mix	Heartwood	B Mix	Sapwood
Schedule	Soft	Soft	Harsh	Harsh
Duration (h)	49.3	47	50.6	51
Wet-bulb depression start (°C)	5	5	8	8
Wet-bulb depression end (°C)	13	13–14.8	15–26	15
Wet-bulb temperature (°C)	60	60	60	60
Notes	Manual fan adjustments	PLC–software connection lost	Dry-bulb increased to 96°C in end of process	Held as planned

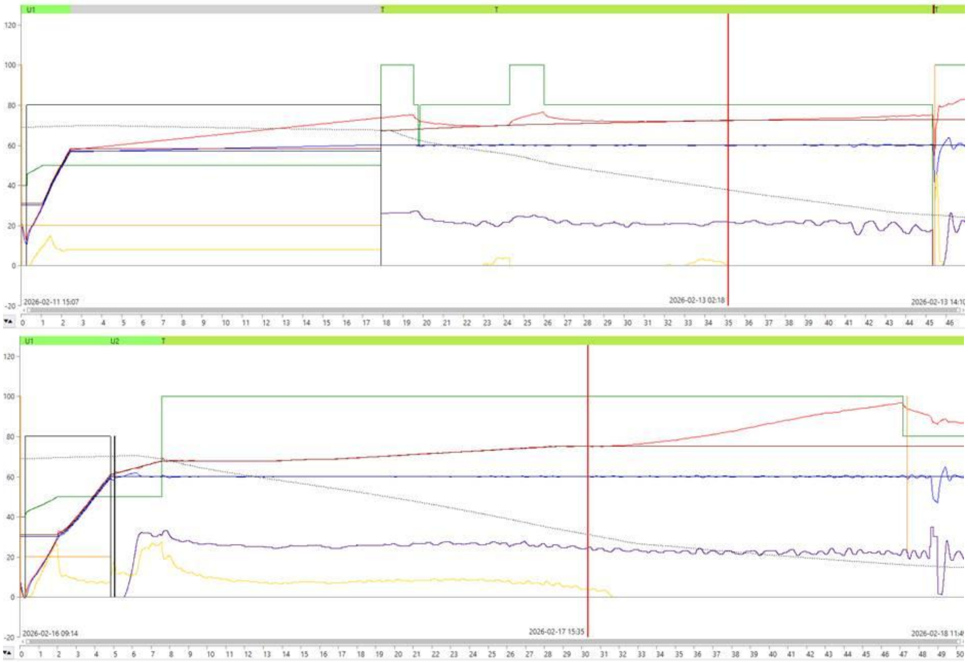


Fig 5. Deviations from schedules. Above: For batch "Heartwood", soft schedule, connection between PLC and desktop application was lost for 15 hours. Below: For batch "B Mix", harsh schedule, dry bulb temperature (red line) increased from planed 76 to 96 °C.

3.3 Final moisture content

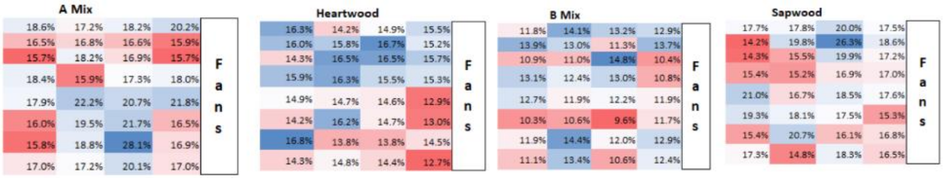
Final moisture content values of the boards in the batches are presented in Table 4.

Table 4. Final moisture content after drying

Batch	A Mix	Heartwood	B Mix	Sapwood

Schedule	Soft	Soft	Harsh	Harsh
Mean MC (%)	18.2	15.0	12.2	17.6
Standard deviation (%)	2.6	1.1	1.3	2.4

Moisture maps showed no clear relationship between fan position and final moisture content. (Fig. 6). In most batches, except the harsh B mix, closer to top-end samples used for MC oven-dry method were the driest and exhibited the lowest between-board variation. (Fig. 7).



A Mix

18.6%	17.2%	18.2%	20.2%
16.5%	16.8%	16.6%	15.9%
15.7%	18.2%	16.9%	15.7%
18.4%	15.9%	17.3%	18.0%
17.9%	22.2%	20.7%	21.8%
16.0%	19.5%	21.7%	16.5%
15.8%	18.8%	28.1%	16.9%
17.0%	17.2%	20.1%	17.0%

Heartwood

16.3%	14.2%	14.9%	15.5%
16.0%	15.8%	16.7%	15.2%
14.3%	16.5%	16.5%	15.7%
15.9%	16.3%	15.5%	15.3%
14.9%	14.7%	14.6%	12.9%
14.2%	16.2%	14.7%	13.0%
16.8%	13.8%	13.8%	14.5%
14.3%	14.8%	14.4%	12.7%

B Mix

11.8%	14.1%	13.2%	12.9%
13.9%	13.0%	11.3%	13.7%
10.9%	11.0%	14.8%	10.4%
13.1%	12.4%	13.0%	10.8%
12.7%	11.9%	12.2%	11.9%
10.3%	10.6%	9.6%	11.7%
11.9%	14.4%	12.0%	12.9%
11.1%	13.4%	10.6%	12.4%

Sapwood

17.7%	17.8%	20.0%	17.5%
14.2%	19.8%	26.3%	18.6%
14.3%	15.5%	19.9%	17.2%
15.4%	15.2%	16.9%	17.0%
21.0%	16.7%	18.5%	17.6%
19.3%	18.1%	17.5%	15.3%
15.4%	20.7%	16.1%	16.8%
17.3%	14.8%	18.3%	16.5%

Fig. 6. Moisture content maps of 4 batches, kiln cross-section.

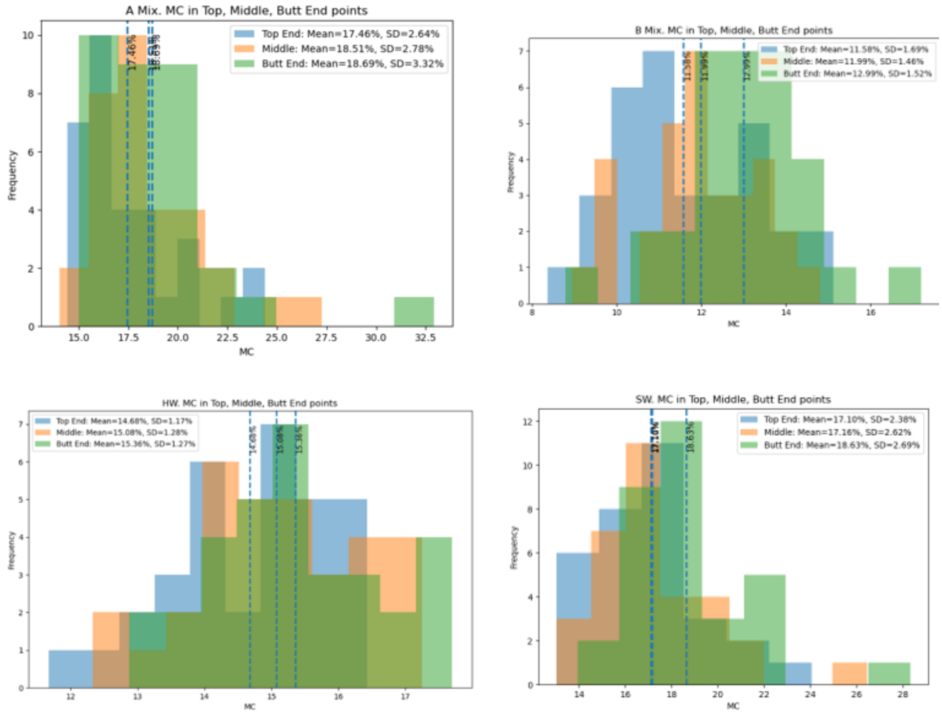


Fig. 7. MC spread along length of boards.

3.4 Simulation results

Two drying runs (B Mix and heartwood) experienced deviations from the planned schedules. To reduce and compensate for the influence of these deviations on the final analysis, the affected runs were re-simulated using the Valmatics 4.0 kiln simulator. The simulator incorporates kiln configuration, initial moisture content, basic density, fan speed, and psychrometric changes.

Table 5. Simulation results

Batch	Experiment	Simulation (with deviations)	Simulation (ideal schedule)
B Mix (Mean MC %)	12.2	11.9	16.2
Heartwood (Mean MC %)	15.1	15.2	16.0

Simulations were performed both with the actual deviations and with ideal schedule conditions. Simulated data were combined with experimental data to compare:

- an unsorted load (A Mix + B Mix)
- a heartwood-sorted load (Heartwood + Sapwood)

Three statistical approaches were used to analyse the new corrected data (Table 5) showing MC and standard deviation of two datasets with the two batches with no errors:

1. Combined variance
2. Linear scaling
3. Scaling and centering

Simulated and experimental data were combined to compare the unsorted and heartwood-sorted loads. All statistical approaches produced similar results. Sorting by heartwood content reduced moisture variation by approximately 0.1 percentage points. (Fig. 8)

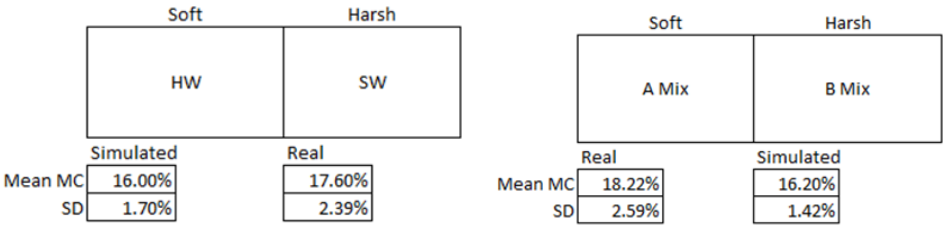


Fig. 8. Mean moisture content values and standard deviation of combined batches.

5. Discussion and Conclusion

This study examined whether sorting Scots pine boards by heartwood content and allocating them to kiln zones with different climate severity can reduce moisture variation after drying. Heartwood content was found to correlate with initial moisture content, while basic density remained uniform across batches.

Although two drying runs experienced schedule deviations, simulation using Valmatics 4.0 enabled reliable reconstruction of expected outcomes. When combining experimental and simulated data, heartwood-based sorting resulted in a small but measurable reduction in moisture variation—approximately 0.1 percentage points.

Further research using full-scale kilns and larger sample sizes is recommended to validate the effect under more stable kiln conditions.

6. Acknowledgements

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Johan Oja, Norra Timber, supported the project with raw material, access to the production site, ideas, important technical and research help.

Valutec, especially Thomas Wamming and Robin Holmbom, provided the experiments with theoretical background, created drying schedules, and offered technical support whenever it was needed.

Wood Technology Department, Luleå University of Technology. I am grateful to Olof Broman, Mikael Byström, Olov Karlsson, Lars Hansson, and Micael Öhman for their help with experiments routines, lab equipment, and data analysis.

Thank you all for your support and contributions.

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APPENDIX 2.

CT-based Spiral Grain and Compression Wood as to Warp in Killed-Dried Norway Spruce Timber

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Master thesis in Wood Science and Engineering Part II

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Abstract

Warp in sawn timber, particularly twist, bow, and spring is a major source of value loss in softwood production. Spiral grain and compression wood are among the primary anatomical reasons of these distortions. Specifically, compression wood early detection in industrial log-scanning workflows remains challenging. This study investigated the relationships between CT-scanner-derived log properties and warp development in kiln-dried Norway spruce (Picea abies) boards. Twenty five logs sourced from a sawmill in northern Sweden were scanned with an industrial CT scanner prior to sawing. The resulting 50×100 mm boards were dried in a laboratory kiln to a target moisture content of 12% and subsequently measured for twist, bow, and spring. CT-derived spiral grain angle showed the strongest correlation with board twist (R^2 = 0.52–0.59), consistent with findings reported in previous literature. Compression wood patterns visible in CT cross-sections of green logs were found to correspond with elevated bow and spring values in dried boards. A visual evaluation experiment demonstrated that human raters could identify logs likely to produce severely warped boards based on compression wood distribution patterns in logs CT images. These results support the feasibility of integrating compression-wood image analysis into industrial pre-sorting workflows as a complement to existing algorithms for sorting green logs with CT.

1. Introduction

Dimensional stability is a critical quality parameter for structural and appearance-grade sawn timber. Warp, as twist, bow, and spring, occurs during and after kiln drying as a result of differential shrinkage driven by wood's anisotropic structure. In Norway spruce (Picea abies) warp is particularly influenced by spiral grain (twist) and the presence of compression wood. Spiral grain refers to the helical deviation of wood fibres from the longitudinal axis of the stem. Even moderate grain angles can produce significant twist in dried boards because the tangential and longitudinal shrinkage coefficients differ substantially (Perstorper et al., 1995). Compression wood is a reaction tissue formed on the underside of leaning stems and branches. Its abnormally high lignin content and altered microfibril angle cause considerably greater longitudinal shrinkage than normal wood, making it a primary driver of bow and spring (Timell, 1986).

Computed tomography (CT) scanning of logs has become increasingly common in modern sawmills, primarily for optimising sawing patterns and detecting internal defects. CT scanners provide three-dimensional density maps that allow the visualisation of internal log features including heartwood boundaries, knot geometry, pith position, fiber orientation, and so on. Several studies have demonstrated that CT-derived spiral grain measurements correlate well with board twist after drying (Grönlund et al., 1995; Tarvainen, 2005). However, the application of CT data for predicting bow and spring in an industrial context, and specifically the potential to use compression wood patterns visible in green-log scans as a pre-sorting tool, remains an active area of research.

The present study aims to:

1) quantify the relationships between CT-scanner-derived log parameters, in particular spiral grain angle, and twist development in kiln-dried Norway spruce boards;

2) characterise the compression wood patterns observable in CT cross-sections of boards exhibiting extreme and marginal warp;

3) assess whether the same patterns can be identified in CT images of green logs under industrial conditions, with a view to supporting pre-sorting decisions before to sawing.

2. Material and Methods

The experiment was conducted in April 2026 at a sawmill in northern Sweden. Twenty-five spruce logs ranging from 3.4 to 5.5 meters in length were selected to represent as wide a range of characteristics as possible, including growth rate, presence of large knots, damage, curvature, core eccentricity, and other relevant factors. The logs were numbered and marked with a unique binary code on both ends against a contrasting background (Fig. 1) to ensure easy visual traceability through the log CT scanner and the sawline.

Figure. 1. Marked logs at the log yard.

The logs were passed one by one through a Microtec CT scanner and sorted into a separate bin. The following scanner data were saved for analysis: three-dimensional density contrast images of the logs, spiral grain, heartwood volume, density and taper, average ring width, maximum pith deviation (curvature), and other parameters.

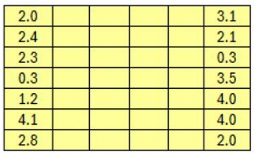
This batch of logs was sawn into 50×100 mm 2X center yield boards and passed through a Microtec Goldeneye scanner. After the boards left the green sorter, they were ID-marked according to their log of origin and cut to 3 m lengths from the butt end on the same day. The butt end was trimmed by 30 cm to eliminate the already dried edge of the log (Fig. 2).

Figure. 2. Green boards cutting to 3 m and marking.

Five-centimeter-long samples were taken from the top-end offcuts for initial moisture content and basic density evaluation. The samples were double-sealed in plastic bags and weighed within two hours of cutting. The air temperature at the time of sampling was +3 °C. The boards were then transported to LTU Skellefteå and stored under a nylon tarpaulin outdoors.

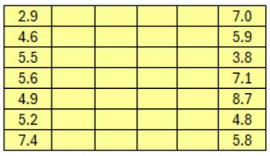
A laboratory kiln was used to dry the batch of boards. The kiln capacity is approximately 0.5 m^3 per charge. Standard 25×47 mm spacer sticks were used, five per row. The drying schedule was based on a production drying programme for the given board dimensions, wood species, and a target final moisture content of 12%. The conditioning stage was deliberately excluded from the schedule in order to preserve the full magnitude of board distortion and thereby obtain more pronounced warp values.

After drying, the boards were left at room temperature and ambient relative humidity for three days to allow the moisture gradient to equalise. The gradient was checked immediately after drying and again after three days using a pin-type resistance meter, with measurements taken both at the surface and at full needle depth in the center of each board (Fig. 3).



2.0					3.1
2.4					2.1
2.3					0.3
0.3					3.5
1.2					4.0
4.1					4.0
2.8					2.0

A. Average MC gradient = 2.4



2.9					7.0
4.6					5.9
5.5					3.8
5.6					7.1
4.9					8.7
5.2					4.8
7.4					5.8

B. Average MC gradient = 5.7

Figure. 3. Moisture gradient measurements using resistant meter (a difference between surface moisture content and full needles deep moisture content in a middle of a board). A. - 3 days after drying, B. - right after kiln drying.

The boards were then placed on a custom-built flatness reference table to quantify spring, bow, and twist (Fig. 4). Twist was measured in accordance with Standard SS-EN 1309-3 (Standards Sweden, 2018) as the board distortion over a 2 m gauge length, recorded from both the butt-end and top-end edges of each board. The direction of twist (positive or negative) was also noted. Spring and bow gap was measured in the highest point along board length. The longitudinal position of maximum spring and bow, whether closest to the top end, the butt end, or the mid-length, was recorded where identifiable.

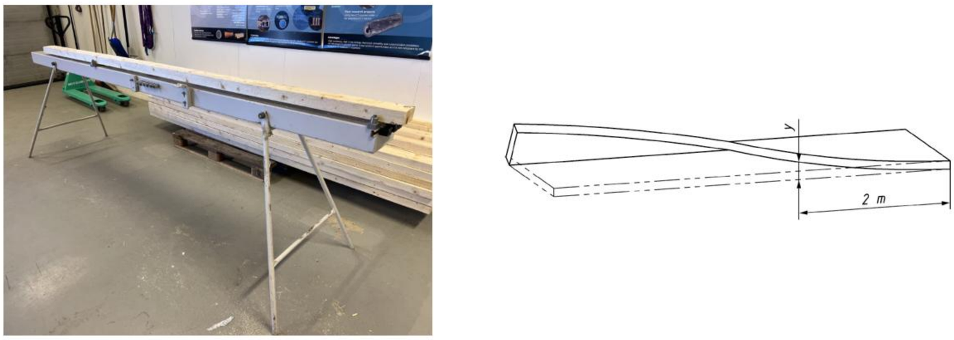


Figure. 4. Left: custom-built flatness reference table to quantify warp. Right: board distortion value “y” at 2 m length.

The dried boards were subsequently scanned in the laboratory CT scanner Microtec Mito to identify compression wood patterns characteristics in longitudinal cross-sections. The aim was to relate these patterns to measured spring and bow values, and to compare the compression wood distributions in dry boards with those observed in green log cross-sections.

For this analysis, five boards with extreme warp values (spring and bow) and five reference boards (nearly straight) were selected. Cross-sections were captured at 25 cm intervals along each selected board, and features common to similarly distorted boards were recorded and analysed.

To investigate the relationship between green log CT scans and the final bow and spring of dried boards, the cross-sections of green logs were evaluated visually by two independent assessors working in random order. The evaluation was based on density pattern characteristics identified as relevant to board warp in the dry board analysis. Each cross-section was graded on a four-point scale according to the brightness and extent of high-density sectors consistent with compression wood. The logs receiving the highest grades were then compared with the corresponding board bow and spring values measured after drying.

Following CT scanning, 5 cm-long specimens were cut from each board for oven-dry moisture content determination in accordance with SS-EN 13183-1 (Standards Sweden, 2004). Three specimens were taken from each board: one from within 40 cm of each end and one from the mid-length. Moisture content was also measured at the same locations using a resistance-type pin meter. All specimens were dried in an oven at 103 ± 2 °C for a minimum of 72 hours.

3. Results

3.1. Raw Material: Initial Moisture Content and Basic Density

Initial moisture content (MC) and basic density (BD) were determined for both boards from each of the 25 logs in the experimental batch, yielding 50 specimens in total. The measured MC values ranged from 31.4% to 148.3%, with a mean of 55.4% and a standard deviation of 25.3%. Basic density ranged from 300 to 451 kg/m^3, with a mean of 370.0 kg/m^3 and a standard deviation of 37.4 kg/m^3. These ranges are consistent with values reported for softwood timber in the green or freshly sawn condition (Knigge and Schulz, 1966; Swedish Wood, n.d.).

A pronounced negative relationship was observed between initial MC and BD across the batch (R^2 = 0.48), as shown in Fig. 5. This inverse correlation is well established in wood science: lower-density wood typically contains a greater volume fraction of void space within its cellular structure, which accommodates more free water in the green state, resulting in proportionally higher moisture content (Skaar, 1988).

The MC distribution was right-skewed, with the majority of boards having MC below 65%. Comparison of boards from the same log (e.g., boards 06.1 and 06.2, with MC of 98.5% and 98.8%, respectively) indicates that within-log variability was generally low, whereas between-log variability was the dominant source of dispersion in the dataset.

The heterogeneity in both MC and BD within the batch reflects the log selection strategy, which aimed to capture a wide range of internal wood features. This variability is expected to influence the development of drying stresses and, consequently, the degree of warp.

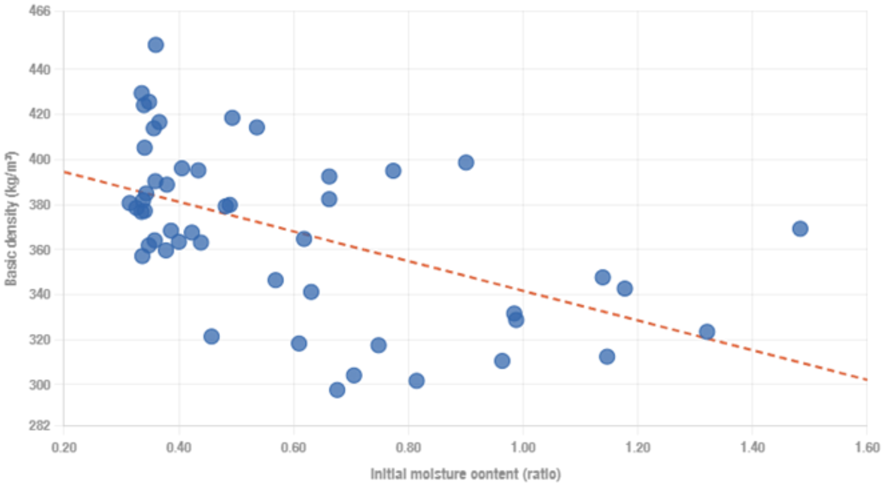


Figure 5. Initial moisture content and basic density of boards.

3.2. Rejected boards.

Because of limited oven capacity, eight boards from four logs (02, 03, 16, and 17) were rejected from drying due to severe damage and warp already present in the green condition. Boards from log 17 exhibited such pronounced bow that they would have compromised package stability in the kiln (Fig. 6). According to the Goldeneye scanner data from the green sorter, boards from log 17 had the highest bow and spring values immediately after sawing.

Figure 6. Boards from log 17. High bow rate in a green condition.

3.3. Kiln drying results.

During drying, wet- and dry-bulb temperatures followed the scheduled values, as shown in the drying scheme in Figure 7. Drying lasted 65 hours.

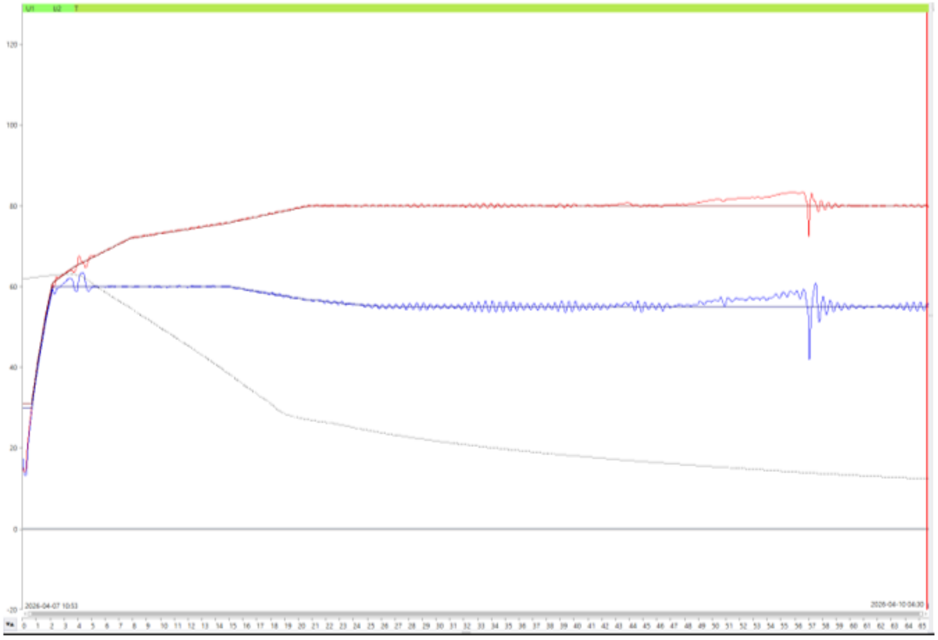
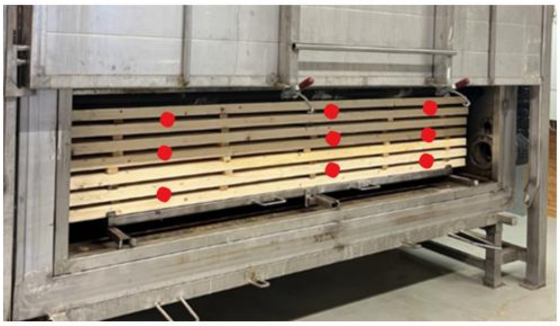


Figure 7. Drying scheme.

Air velocity inside the laboratory kiln was measured using an anemometer with a resolution of 0.1 m/s. Measurements were taken at full fan speed with the door closed, with the anemometer positioned at nine locations across the front plane of the board stack. The ambient temperature during measurement was approximately 20 °C.

Airflow was not uniform across the kiln volume. The left side of the chamber exhibited approximately three times lower air velocity than the center and right sides, as shown in Fig. 8.



Airflow, m/s

2.0		0.6		2.0
0.6		2.2		1.3
0.5		2.6		1.8

Figure 8. Table on the right shows airflow velocity values, measured in the points on the picture on the left. Left side and the upper middle have the slowest flow.

This airflow asymmetry is consistent with the observed moisture content variation across the boards. According to oven-dry MC measurements, the left side of the boards (by kiln position) was wetter than the right side in 88% of cases (37 out of 42 boards), with an average difference of 0.6 percentage points between sides. By contrast, the butt end was wetter than the top end in only 19 out of 42 boards (45%). Given that boards were stacked with alternating top-end and butt-end orientations, this result indicates that lateral position within the kiln was the dominant factor driving MC variation, rather than the longitudinal orientation of the board within the stem. Tables 1 and 2 show MC variation by kiln position and stem longitudinal orientation, respectively.

Table 1. Average oven dry moisture content values across 42 boards along ***stem*** *position*

Top end	Middle	Butt end
10.1 %	10.1 %	10.5 %

Table 2. Average oven dry moisture content values across 42 boards along ***kiln*** *position*

Left side	Center	Right side
10.6 %	10.1 %	10.0 %

The mean and median oven-dry MC across the 42 boards was 10.2%, with a standard deviation of 1.3% (Table 3). Values ranged from 7.9% (board 14.1) to 13.6% (board 01.2), and the distribution was approximately symmetric about the mean (Fig. 9). These results indicate that the kiln schedule brought the large majority of the batch to a final MC slightly below the 12% (target MC).

Table 3. Mean moisture content and standard deviation of 42 boards after kiln drying.

	OD method	Pin meter

Mean MC	10.2 %	11.3 %
Standard deviation	1.3 %	1.9 %

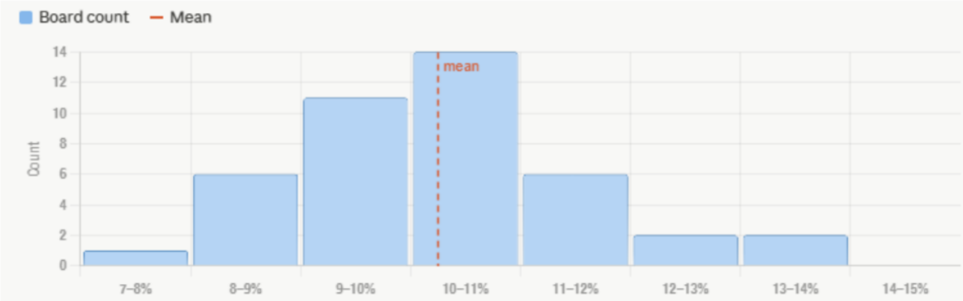


Figure 9. Distribution of board-average oven dry moisture content in boards.

3.4. Twist results

Twist values ranged from 0 mm (board 25.2) to 28.3 mm (board 28.1), with a mean of 8.5 mm and a standard deviation of 6.5 mm across the 42 boards. The wide range confirms that variation in inner log properties is a significant driver of twist. Five of the 25 logs produced boards with a negative twist direction.

The six logs showed most twisted boards with maximum distortions exceeding 18 mm over a 2 m gauge length, while the five logs produced straightest boards with maximum distortions of no more than 5 mm. These are presented in Tables 4 and 5, respectively.

Table 4. The most twisted boards and their distortion values on 2 m length, measured from both sides of a board.

Log #	Board #	Twist from Top pressed, mm	Twist from Butt pressed, mm
04	04.1	16.7	10.9
	04.2	13.3	20.0
08	08.1	14.0	10.9
	08.2	17.3	18.9
14	14.1	18.7	16.7
	14.2	11.8	7.6
18	18.1	18.6	6.1
	18.2	17.6	14.0
19	19.1	22.7	22.0

	19.2	6.6	8.7
28	28.1	28.3	19.7
	28.2	22.6	16.6

Table 5. The least twisted boards and their distortion values on 2 m length, measured from both sides of a board.

Log #	Board #	Twist from Top pressed, mm	Twist from Butt pressed, mm
01	01.1	1.5	4.7
	01.2	3.8	1.3
11	11.1	2.4	2.8
	11.2	1.9	3.0
13	13.1	1.2	1.0
	13.2	3.6	4.1
25	25.1	1.3	2.6
	25.2	0.0	0.1
27	27.1	3.6	2.3
	27.2	3.5	3.3

Of all CT-derived parameters, spiral grain angle showed the strongest relationship with measured board twist, consistent with findings reported in previous studies (Perstorper et al., 1995; Straže et al., 2011). The relationship was most pronounced between the CT spiral grain value of a log and the minimum twist value of the boards from that log — defined as the lowest of the four twist measurements per log (two boards, each measured from the top and butt ends over a 2 m length). This minimum twist value may be interpreted as the baseline twist potential of a log attributable to spiral grain alone, while higher twist values in individual boards are likely governed by the combined effect of spiral grain and other anatomical features or defects. Identifying logs with high minimum twist potential therefore offers a practical basis for pre-sorting logs with CT to reduce warp.

Spiral grain was estimated by the CT scanner manufacturer using two algorithms.

The first algorithm, applied at 50 mm from the pith, is based on spiral grain coefficients M and Q derived from a linear fit of grain angle as a function of radial distance ($SG50 = M \times 50 + Q$), determined empirically

(Fig. 10). Other models were also calculated for radial distances of 100 mm and 150 mm, but these yielded substantially lower R^2 values.

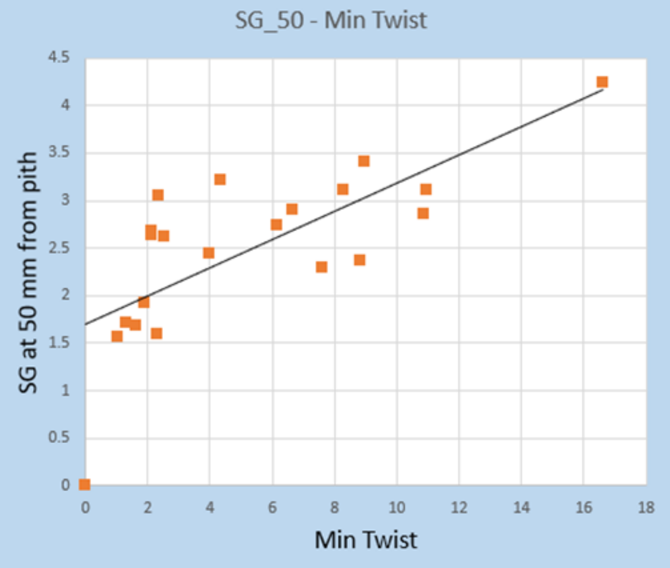


Figure 10. CT spiral grain – the lowest board twist relation on 50 mm from pith, based on empirically determined spiral grain coefficients M and Q, SG50 = M × 50 + Q.

The second algorithm: measured fiber angle from polar images of the log cross-section at 75 mm from the pith (Fig. 11).

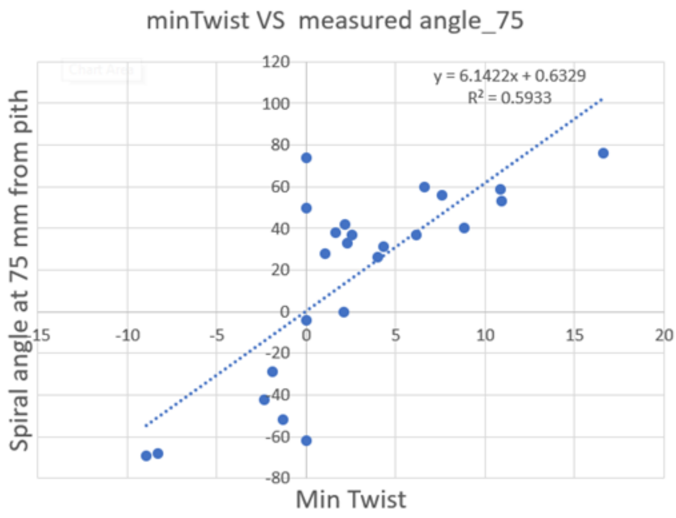


Figure 11. CT spiral grain, measured manually from images – *the lowest board twist relation on 75 mm from pith.*

An example of the resulting angle measurements is shown in Fig. 12, where the x-axis represents quarter degrees of the full rotation angle and the y-axis corresponds to position along the log length. The angle estimate was corrected by offsetting it from 90° to account for its orientation (right- or left-handed spiral).

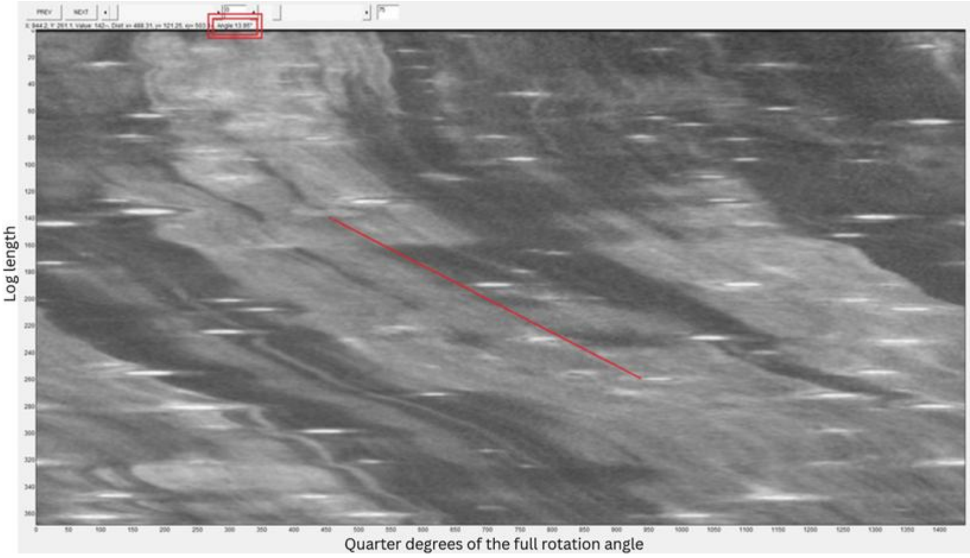


Figure 12 Measuring the fiber angle on polar images of a log at 75 mm from the pith where X-axis represents quarter degrees of the full rotation angle and Y-axis corresponds to the log length.

The both ways of estimating spiral grain value in CT scans showed good enough description, R^2=0.52 and R^2=0.59, which corresponds with previous experiments (Tarvainen, 2005; Grönlund, Oja, Grundberg, Nyström, & Ekevad, 1995). It shows robustness of using CT data spiral grain for prediction of twist dealing with timber warp reduction such as pre-sorting, pre-twisting and top-loading.

3.5. Bow and Spring results

After kiln drying, all available boards were measured for two primary warp types: bow (curvature in the flat plane along the board length) and spring (curvature in the edgewise plane). The longitudinal position of maximum warp (top, mid, or butt) was also recorded when identifiable. In our experiment, bow magnitudes ranged from 0.2 mm (board 05.2) to 15.0 mm (board 27.2), with a mean of 4.1 mm and a standard deviation of 3.3 mm (Fig. 12). Eleven boards (26%) exceeded a bow of 5 mm. The most severely bowed boards were 27.2 (15.0 mm), 28.1 (12.5 mm), and 24.2 (10.7 mm).

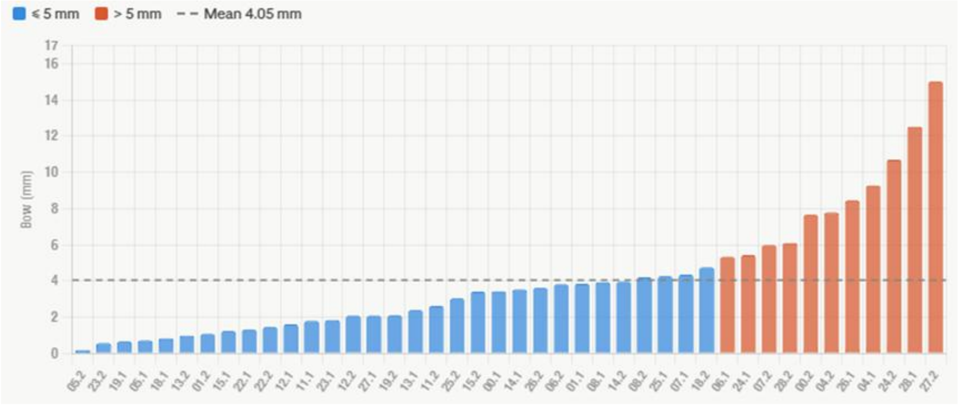


Fig. 12. Boards sorted by bow magnitude. Orange bars exceed 5 mm.

Spring ranged from 0 to 15.0 mm, with a mean of 3.1 mm and a standard deviation of 3.5 mm (Fig. 13). The distribution was markedly uneven: 10 boards (24%) showed zero or negligible spring, while the remaining 32 boards were broadly distributed between 0.6 and 15.0 mm, with 21% (n = 9) exceeding 5 mm.

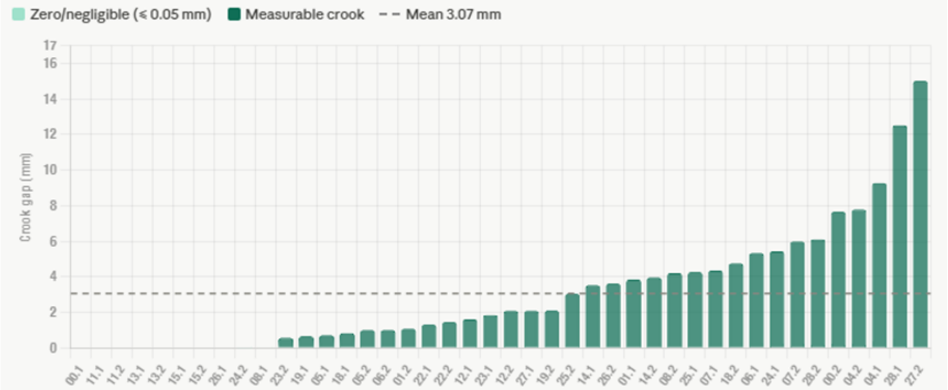


Fig. 13. Boards sorted by spring. Light tale = zero or negligible spring.

The longitudinal position of maximum bow and spring was recorded for 22 boards. Majority of boards exhibited maximum spring at mid-length (Fig. 14)

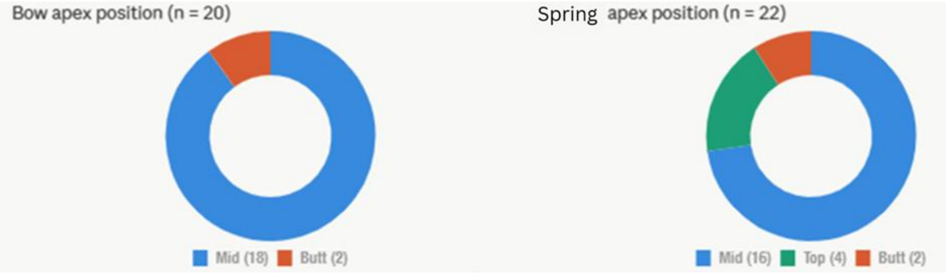


Figure 14. Position of maximum warp along board length, recorded where identifiable.

Across all boards, bow and spring were positively correlated, confirming that in boards where both warp types were expressed, their magnitudes were proportional.

Boards sawn from the same log showed considerable variation in bow in several cases (Fig. 15). The largest within-log difference was observed for log 27, where bow differed by 12.9 mm between the two boards. Logs 28 and 26 also showed high within-log differences (6.4 and 4.8 mm). This variability confirms that warp is not a uniform property of a log, but is governed by localised radial position which can differ substantially between boards cut from adjacent positions in the same cross-section (Ormarsson et al., 1998; Kliger et al., 2003).

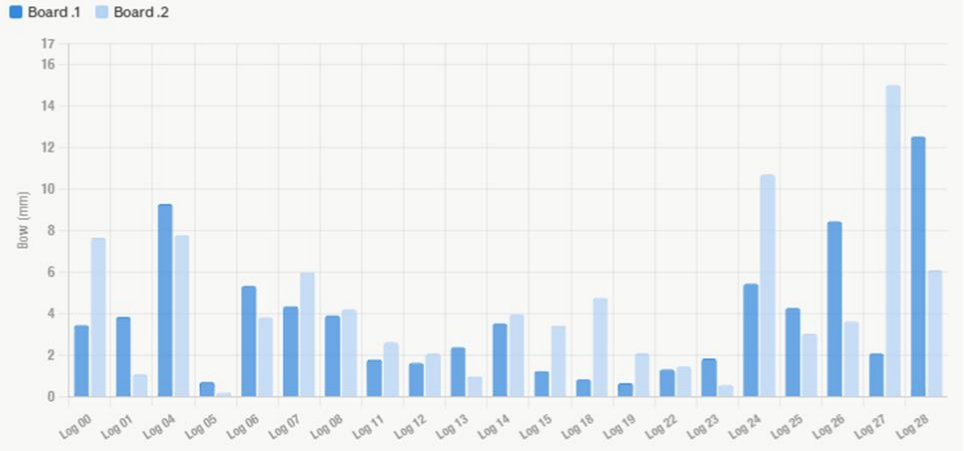


Figure 15. Bow measures of boards from the same log shown side by side. Large within-log differences indicate position-dependent growth characteristics.

3.6. Dry boards CT-scanning results.

Following CT scanning of the dried boards, cross-sectional images of the boards with the highest bow and spring (log 17 not dried, and logs 27, 28, 24, and 22) and the straightest boards (logs 05, 11, 12, and 13) were analysed for pattern tendencies in high-density sectors of the early rings, indicative of compression wood (Figs. 16 and 17). CT-cross-sections were captured at 25 cm intervals along the length of each selected board.

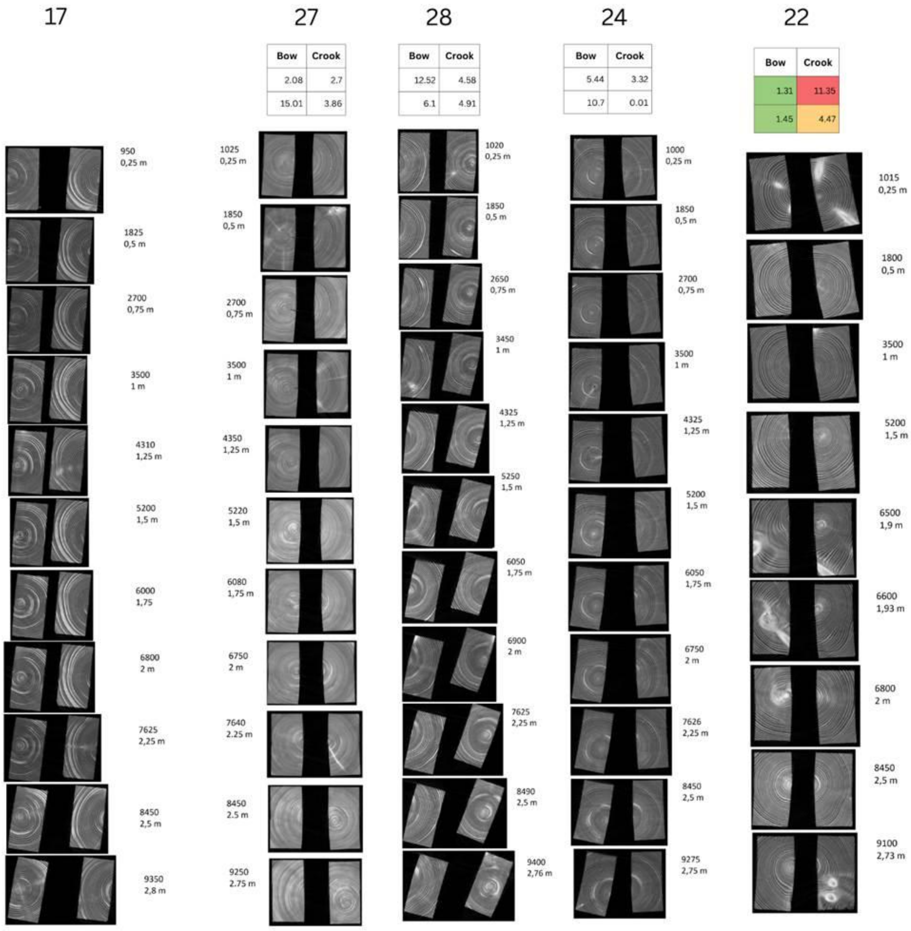


Figure 16. CT scan crossections at every 25 cm of length of the boards with highest bow and spring. Top end of the board is in top of the figure. Appearance of compression wood could be seen as white thin half rings or sectors.

Figure 16.1. The boards with highest bow and spring. The same boards as CT-scanned at Figure 16

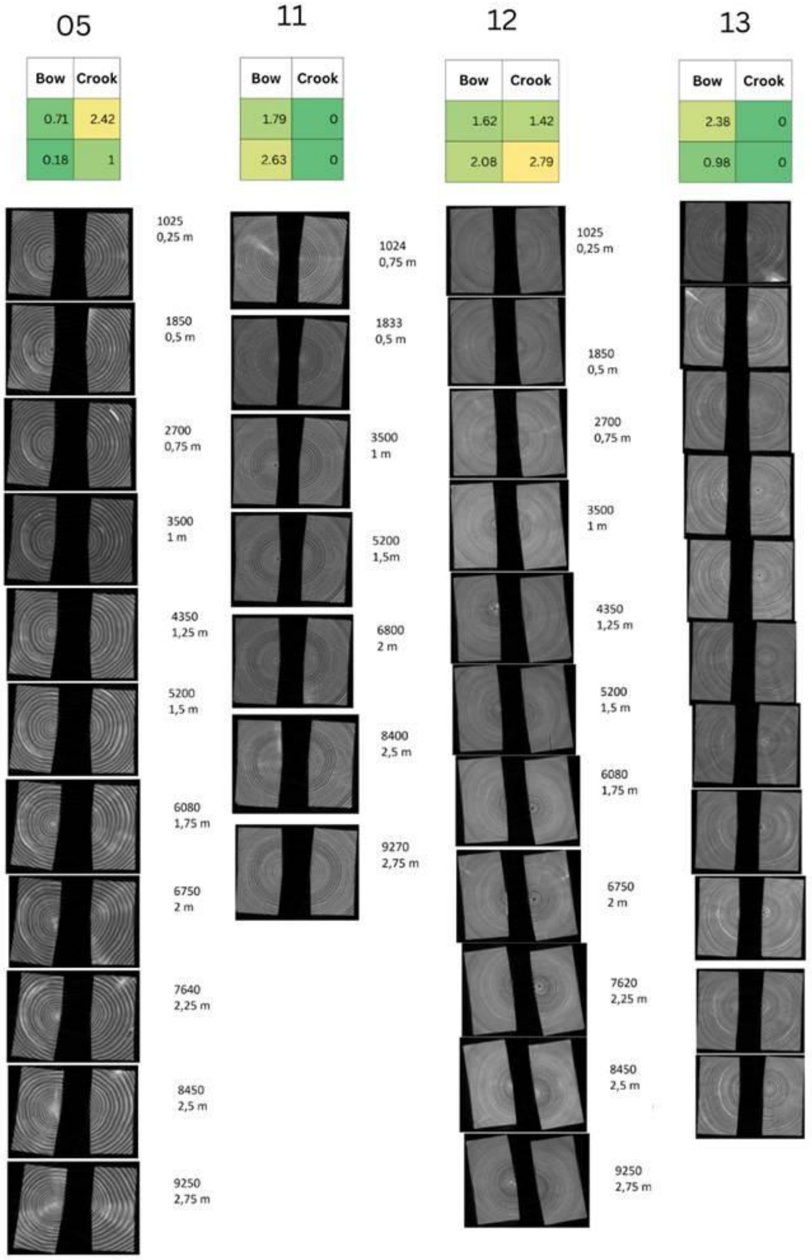


Fig. 17. CT scan crossections at every 25 cm of length of the boards with low bow and spring.

Figure 17.1. The boards with low bow and spring. The same boards as CT-scanned at Figure 17

The difference in compression wood patterns between warped and straight boards is clearly visible. The high density and brightness of the cross-sectional sectors in warped boards contrasts markedly with the more uniform and less bright annual rings of boards with low warp. It is important to distinguish between latewood and compression wood: latewood can exhibit high density, but it is distributed uniformly around the circumference and shows consistent brightness across rings, as seen in log 05 (a fast growing tree). Compression wood, by contrast, typically occupies all or a substantial part of the width of one or more annual rings, asymmetrically distributed around the pith. Boards from log 27 showed bow and spring concentrated towards the butt end.

The following characteristics were identified as distinguishing features of the cross-sectional pattern in boards with a high degree of warp:

1. A large number of rings containing sectors of abnormally high density, equal to or exceeding the density of the latewood, distributed over more than half the ring width but not around the full circumference.
2. The presence of several rings with the characteristics described in point 1 in close proximity to the pith. This proximity appears to be governed either by the ring number from the pith (reflecting elevated stresses in juvenile wood) or by the dimensions of the board cross-section relative to the log.
3. The longitudinal extent of the pattern described in points 1 and 2 is approximately 1 m or more, which also helps to distinguish compression wood from localised resin pockets.

Representative examples of these patterns from logs 17, 27, and 28 are shown in Fig. 18.

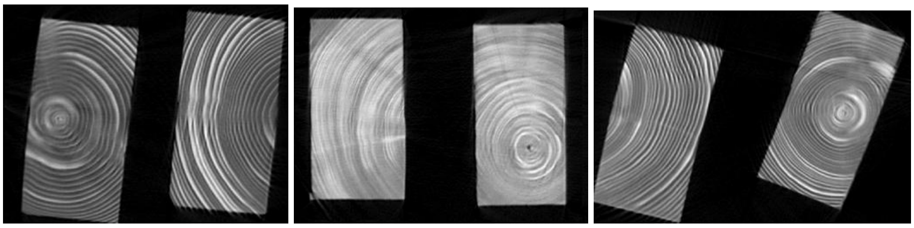


Figure 18. Crossections of boards from logs 17, 27, 28 with the highest bow rate, illustrating typical compression wood spread pattern.

3.7. Random evaluation experiment.

The next step was to determine whether the compression wood patterns identified in dry boards could also be recognised in CT images of green logs acquired from the industrial sawmill scanner. Fig. 19 shows cross-sections of logs 17, 27, and 28, corresponding to the boards shown in Fig. 18. The characteristic pattern is clearly identifiable in the heartwood region of the green log images.

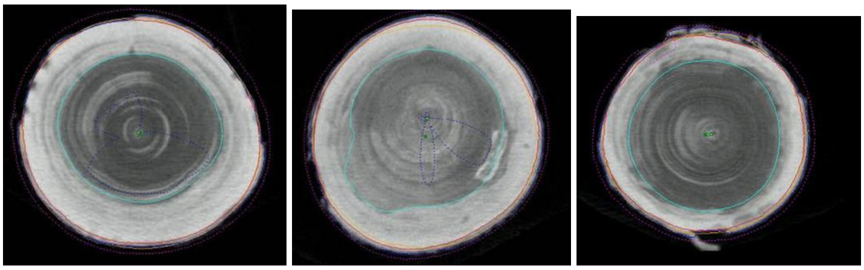


Figure 19. Crossections of green logs 17, 27, 28 with the highest bow rate in dry boards, illustrating compression wood pattern visibility in heartwood region.

To confirm the feasibility of detecting potentially high-warp logs during the green log scanning phase, the following experiment was conducted. Two assessors independently reviewed the CT cross-sections of all green logs in random order. Each log was rated for the intensity and longitudinal extent of high-density ring sectors consistent with compression wood, and for the proximity of such sectors to the pith, following the criteria established in Section 4.6. The logs receiving the highest grades were those that subsequently produced boards with the highest bow and spring values after drying, including logs 17, 27, and 28.

These results demonstrate that it is possible to identify logs at risk of producing severely warped boards prior to sawing, based on the compression wood pattern visible in green log CT scans. In the current production workflow, the presence of compression wood is typically inferred from an eccentricity-based filter, the offset between the pith and the log centroid. The results of this study suggest that an additional image-analysis filter, trained on compression wood density patterns, could substantially reduce the number of false negatives in this screening step. Notably, log 17 did not exhibit a large pith deviation and would therefore not have been flagged by the eccentricity filter alone, yet it displayed the most contrast compression wood pattern in the dataset and produced the boards with the largest bow.

4. Conclusion and Discussion

This study examined the relationships between CT-derived log properties and warp in kiln-dried Norway spruce boards, with a particular focus on spiral grain and compression wood as predictors of twist, bow, and spring. The key findings can be summarised as follows.

Spiral grain angle was the single strongest predictor of board twist in this experiment, explaining 52–59% of the variance depending on the estimation algorithm and distance from pith. This result is consistent with previous work (Perstorper et al., 1995; Grönlund et al., 1995; Straže et al., 2011) and confirms the robustness of CT-derived spiral grain measurements as a practical predictor of twist in industrial settings. The correlation was strongest when the minimum observed twist value per log was used as the response variable, suggesting that the spiral grain means the baseline twist potential of a log, while additional anatomical features such as knots and local grain distortions can amplify the final twist in individual boards. This distinction has practical implications: logs with high minimum twist potential can be flagged for targeted downstream interventions such as pre-twisting or top-loading during kiln drying, whereas single high-twist boards from otherwise straight logs may reflect local defects rather than a log-level property.

Bow and spring showed a strong positive correlation, confirming that both distortions tend to co-occur in boards with high compression wood content. The most severely warped boards exhibited characteristic CT cross-sectional patterns: multiple rings with sectors of abnormally high density, consistent with compression wood, distributed over more than half the ring width and concentrated in the zone near the pith. These patterns were clearly distinguishable from the more uniform high-density latewood seen in straight boards. The identification of such patterns in dry board CT scans provided the basis for the subsequent evaluation of green log scans.

The random evaluation experiment demonstrated that the compression wood patterns identified in dry boards could also be recognised in CT cross-sections of green logs obtained from an industrial Microtec scanner. Two independent raters, working from predefined assessment criteria, assigned the highest grades to logs 17, 27, and 28 - the same logs that produced the most severely bowed boards after drying. Notably, log 17 did not exhibit a large pith deviation and would therefore not have been flagged by the existing eccentricity-based filter in the production line according to current algorithms used at sawmills. This highlights a limitation of eccentricity as a sole indicator: logs can contain severe compression wood even when the pith is relatively centred, a scenario that is not uncommon in trees that have experienced repeated or asymmetric gravitropic loading. As a future work, an image-analysis model trained to detect the relevant density patterns could therefore substantially reduce the rate of false negatives in current pre-sorting systems.

Several limitations of the present study should be mentioned. The sample comprised only 25 logs sawn into boards of a single target size (50×100 mm), which constrains the generalisability of quantitative relationships to other dimensions and log populations. The laboratory kiln used in the experiment showed a airflow asymmetry: the left side of the chamber delivered approximately three times lower air velocity than the right side. This resulted in a systematic moisture content gradient across the width of the kiln stack, with 88% of boards showing higher residual moisture on their left side. Although both the twist and bow analyses are based on final measured values that integrate all drying effects, the uneven airflow may have introduced additional stress gradients. Finally, the visual evaluation of compression wood patterns in green logs was performed by only two raters. A larger study would be needed to validate the consistency of such assessments and to define precise grading criteria for an automated classifier.

In conclusion, this study confirms the value of CT-derived spiral grain angle as a predictor of board twist and provides experimental evidence that compression wood distribution patterns in CT cross-sections of green logs can serve as indicators of bow and spring risk in sawn timber. The results support the development of an automated compression wood filter based on image analysis, as a complement to existing pre-sorting criteria in industrial CT-scanning workflows.

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