VTT PUBLICATIONS 533

Raw material characteristics of maritime pine (*Pinus pinaster* Ait.) and their influence on simulated sawing yield

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VTT Building and Transport

Dissertation for the degree of Doctor of Science in Technology
to be presented with due permission of the Department of Forest Products
Technology for public examination and debate in Auditorium P1
at Helsinki University of Technology (Espoo, Finland)
on the 3rd of November, 2004, at 13 o'clock.

ISBN 951–38–6373–5 (soft back ed.)
ISSN 1235–0621 (soft back ed.)

ISBN 951–38–6374–3 (URL: http://www.vtt.fi/inf/pdf/)
ISSN 1455–0849 (URL: http://www.vtt.fi/inf/pdf/)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 5, PL 2000, 02044 VTT
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Technical editing Leena Ukskoski

Otamedia Oy, Espoo 2004

Pinto, Isabel. Raw material characteristics of maritime pine (*Pinus pinaster* Ait.) and their influence on simulated sawing yield. Espoo 2004. VTT Publications 533. 51 p. + app. 69 p.

Keywords maritime pine, *Pinus Pinaster* Ait., 3D stem models, stem shape, knots, heartwood, sapwood, sawing simulation, production yields

Abstract

The objective of this work was to study maritime pine (*Pinus pinaster* Ait.) wood characteristics and their impact on the sawing yield using virtual stem models and sawing simulation procedures. In the first part of the work, a characterisation of maritime pine as raw material for the wood industry was performed. The stem shape, distribution of knots, and heartwood/sapwood contents were studied. In the second part of this work, the virtual stems provided the raw material for sawing-simulation studies.

The stem reconstruction, bucking, and sawing simulation modules of WoodCIM® were used. WoodCIM® is an integrated optimising software system, developed at the Technical Research Centre of Finland (VTT), for the optimisation of the wood conversion chain. The software was adapted for maritime pine and validated. Thirty five maritime pine stems were randomly sampled from 4 sites in Portugal. These were mathematically reconstructed into virtual stems, based on image analysis of flitch surfaces. The 3D virtual stems included the description of external shape, internal knot architecture, and heartwood core. The reconstruction of the heartwood shape was a new feature added to the reconstruction module during this study. Input data concerning final products and process variables for sawing simulation were obtained directly from the wood-based industry.

The average volume percentage of knots in 83 year-old maritime pine trees, varied from 0.07% for butt logs to 1.95% for top logs. Heartwood diameter either followed the stem profile or showed a maximum value at the height 3.8 m, on average, while sapwood width was higher at the stem base and after 3 m remained almost constant along the stem height. Production yields were higher for logs with origin of the first half of the stem as diameters were large and taper reduced when compared with top logs. Butt logs showed the highest value yields because of the knot core profile. When the target was to maximise the production of heartwood containing components, best yields were obtained with logs bucked between 3 and 9 m height.

The results in this study increased the basic scientific knowledge about maritime pine concerning the variations of wood characteristics and their influence on sawing yield outputs. Also, these can contribute to further development of industrial applications of defect detection and sawing simulation tools.

Pinto, Isabel. Raw material characteristics of maritime pine (*Pinus pinaster* Ait.) and their influence on simulated sawing yield. [Características da madeira de pinheiro bravo (*Pinus pinaster* Ait.) como matéria-prima e influência nos rendimentos em serração obtidos por simulação da conversão]. Espoo 2004. VTT Publications 533. 51 p. + app. 69 p.

Palavras chave Pinheiro bravo, *Pinus pinaster* Ait, geometria do tronco, nós, borne, cerne, simulação da serração, rendimentos de produção

Resumo

O conhecimento das propriedades da madeira, enquanto matéria-prima industrial, e de como a transformar de forma a responder com eficiência às necessidades do mercado, é essencial para a optimização da cadeia de conversão da madeira. O aumento de competitividade do sector madeireiro em Portugal passa por uma modernização tecnológica e uma especialização da mão-de-obra, pela aposta na reflorestação e condução silvícola dos povoamentos com vista a obter produções sustentadas e madeira de boa qualidade e, principalmente, pela aposta na produção de produtos de qualidade com um elevado valor acrescentado. Para tal é necessária uma análise global da cadeia de conversão da madeira, desde a floresta ao produto final (Figura 1). Num extremo da cadeia encontra-se uma matéria-prima de elevada variabilidade e no outro os consumidores com especificações crescentes em termos de qualidade dos produtos finais. Neste sentido, os recentes desenvolvimentos de técnicas de modelação e programas de simulação surgem como uma ferramenta útil em vários níveis da cadeia de conversão. Estes programas permitem não só um aumento rápido de conhecimentos sobre a matéria prima e uma modelação da sua formação como também uma previsão das propriedades dos produtos serrados antes da operação de serração.

O presente trabalho visa aumentar o conhecimento sobre as características da madeira de pinheiro bravo (*Pinus pinaster* Ait.) e a influência destas nas suas utilizações finais. O trabalho é desenvolvido através de modelação da qualidade e geometria do tronco e de simulação da sua conversão. O pinheiro bravo é a principal espécie em Portugal, correspondendo a cerca de 30% do território florestal nacional, e a maior fornecedora de matéria-prima para a indústria de serração. Os resultados apresentados foram obtidos através da adaptação a esta espécie dos módulos de reconstrução virtual do tronco, toragem e simulação da serração do programa WoodCIM®, desenvolvido no VTT – Technical Research Centre of Finland. O programa WoodCIM® integra a simulação de vários estágios da transformação da madeira com vista à optimização da sua cadeia de conversão. Os resultados obtidos foram compilados em cinco publicações científicas listadas na secção "list of publications".

Na primeira parte construíu-se um banco de troncos virtuais gerados através da análise de imagem de varrimentos de tábuas e utilizaram-se algoritmos para a reconstrução de toros e troncos. Com base na informação gerada por estes modelos virtuais dos troncos foi feita uma caracterização da madeira de pinheiro bravo enquanto matéria-prima para a indústria de serração. Foram estudados a forma do tronco, a distribuição e dimensões dos nós internos e os conteúdos de

borne e cerne (Estudos I e II). A selecção das características a estudar foi feita com base no seu impacto na qualidade dos productos finais. Foram também analisadas as diferenças entre o modelo e a realidade.

Na segunda parte do trabalho, estes troncos virtuais foram utilizados como matéria-prima de entrada para os programas de simulacão da toragem e da serração. O Estudo III explorou as potencialidades do programa de simulação WoodCIM® para investigar o impacto das características da matéria-prima na conversão do pinheiro bravo. No Estudo IV, os resultados gerados pelo programa foram validados em relação a dados obtidos em ambiente industrial. Por fim, o Estudo V usou os modelos desenvolvidos e o programa de simulação para estudar os potenciais de produção de produtos de cerne a partir da madeira desta espécie.

Em Portugal foram amostradas 35 árvores em quatro locais dentro da área de distribuição do pinheiro bravo: Leiria (S1), Mação (S2), Alpiarça (S3) e Marco de Canavezes (S4). As árvores foram cortadas em toros de 2,5 e 5 m e estes serrados em pranchas, enviadas para a Finlândia. Através da utilização do sistema de inspecção e aquisição de imagens WoodCIM® – foi feito o varrimento de todas as pranchas. As imagens obtidas, em formato bitmap (RGB), foram transferidas para o programa Puupilot onde foram registadas as coordenadas geométricas de cada prancha e de todos os defeitos. O programa mostra a imagem da prancha no monitor e é assistido por um operador. Deste modo constitui-se uma base de dados com todas as coordenadas geométricas de cada prancha e de todos os defeitos que, posteriormente, servirá de base à reconstrução tridimensional dos toros e troncos (por junção dos toros reconstruídos). O modelo virtual do tronco inclui uma representação tridimensional da sua geometria, da arquitectura dos nós internos e da geometria do cerne (Figura 3). A reconstrução do volume de cerne constitui uma nova função adicionada ao programa de reconstrução que foi desenvolvida no âmbito do presente trabalho (Estudo II). Para a simulação da serração destes troncos virtuais, os dados relativos ao processo de conversão e à qualidade, dimensões e preços dos productos serrados foram obtidos por informação da Indústria Portuguesa de serração.

Os resultados mostram que, em árvores de 83 anos, o volume médio de nós relativamente ao volume total do toro varia de 0,07% nos toros de base ate 1,95% nos toros do topo. O núcleo nodado varia de 28% do raio do tronco na sua base até 83% a 70% da altura total da árvore. Nestas árvores mais velhas, o cerne representa 17% do volume até 50% da altura da árvore, enquanto que em árvores mais jovens (42–55 anos) esta proporção é de cerca de 12–13%. A idade de formação do cerne foi estimada em 13 anos, com uma taxa de transformação do borne em cerne de 0,5 e 0,7 anéis por ano para árvores com, respectivamente, idades inferiores ou superiores a 55 anos. A evolução do diâmetro de cerne com a altura da árvore apresenta dois padrões distintos: ou seguindo o perfil do tronco, ou apresentando um máximo a cerca de 3,8 m de altura, em média (Figura 8). Por outro lado, a largura de borne é maior na base do tronco diminuindo até cerca de 3 m de altura, após o que permanece quase constante ao longo do tronco. Devido ao seu diâmetro superior e à reduzida conicidade, os toros obtidos na primeira metade do tronco apresentaram os rendimentos de conversão mais elevados em todos as simulações, especialmente quando o alargamento do tronco na base foi evitado. Os toros de base apresentaram também os rendimentos em valor mais elevados devido ao seu reduzido núcleo enodado. No entanto, para a maioria das árvores, quando o objectivo é maximizar a produção de componentes serrados contendo cerne, foram os toros com origem entre 3 e 9 m da altura do tronco que apresentaram os melhores rendimentos. Demonstrou-se que existe potencial para a produção de produtos de cerne de pinheiro bravo desde que se desenvolvam esforços adicionais na selecção da qualidade da matéria prima e também na seleção dos produtos serrados. Esta produção de produtos de cerne terá sempre de ser integrada com os restantes produtos serrados do borne.

Os módulos do programa WoodCIM® que foram adaptados ao pinheiro bravo neste trabalho (reconstrução virtual dos troncos, toragem e simulação de serração) mostraram poder ser ferramentas utéis para a investigação das características da madeira desta espécie e para a optimização dos seus usos finais em serração. Os resultados contribuem para o aumento do conhecimento sobre a variabilidade das características da madeira de pinheiro bravo e a sua influência na qualidade dos produtos finais. Para além do conhecimento científico, os resultados poderão contribuir para o futuro desenvolvimento de aplicações industriais dos sistemas de modelação e simulação aqui testados.

Preface

This thesis was carried out in the Technical Research Centre of Finland, VTT – Building and Transport in collaboration with the Centre for Forest Studies, Technical University of Lisbon. The thesis was developed for the degree of Doctor of Science in Technology from the Forest Products Technology Department, Helsinki University of Technology. Financial support was given by a Doctoral scholarship from Portuguese Foundation for Science and Technology (FCT) and grants from the Research Foundation of Helsinki University of Technology and the Foundation of Technology (TES). Part of the work was carried out under the research programme PAMAF 8185, financed by INIA (Instituto Nacional de Investigação Agrária, Portugal) and support by a Marie Curie Research Training Grant.

I want to express my sincere gratitude to Professor Helena Pereira and Dr Arto Usenius, my instructors, who directed my research wisely in all steps of this work and also for their support and encouragement through all the time. Having the possibility of sharing their different expertise areas and background experience was, without doubt, a very important contribution to my professional development.

I also thank my supervisor on behalf of the Department of Forest Products Technology, Professor Tero Paajanen for all the guidance during my studies and most useful comments and suggestions on my work. His practical mind and support were most valuable at critical phases of this thesis.

It has been a pleasure to work with my co-authors Eng. Sofia Knapic and Lic.Tech. Tiecheng Song. I wish to thank Lic.Tech. Song for all the alterations to the sawing simulation program and for his infinite patience while teaching me all the steps of it. I thank Eng. Knapic for helping me with her practical mind and most valuable friendship. It was a pleasure to share the long working days and nights, full of good humour and lots of tea and biscuits.

I owe my sincere thanks to everyone in VTT Building and Transport (former VTT Building Technology) for hosting me, sharing their expertise during these years, and making this thesis possible. Especially I would like to thank those with whom I had the pleasure of working more closely with: Antti Heikkilä, Jorma Fröblom, Timo Usenius, Olof Sommardahl, Eero Halonen, Pirjo Kari, Kari Niittylä, Heikki Murto, Tapio Kanko, and Pasi Hemmilä. And also those who had to work close with me sharing the same office space: Unto Vassara, Marta Margarido, Sofia Knapic, Leena Suomi-Lindberg, Sini Metsä-Kortelainen, and especially Juha Mikkola, my Suomi teacher. Kiitos kaikille!

I would like to thank everyone in the Centre of Forest Studies, ISA – Technical University of Lisbon where I gave my first steps in research. Thanks to the friends and colleagues that never stop helping me in different phases of this work even when I have been so long and so far away. Special thanks to Dr. Jorge Gominho and Dr. Paula Soares.

Also, I owe my thanks to all the Professors and Researchers at the Wood Laboratory of the Forest Products Technology Department, Helsinki University of Technology for all the support and feedback during my studies and the execution of this thesis. I am especially grateful to Lic.Tech. Jussi Virtanen with whom I had fruitful discussions and Ms. Eeva Alho for all the practical help.

I am grateful to Professor Fátima Tavares and Professor Anders Grönlund for all the constructive comments given during the pre-examination of my thesis.

Thanks are due to the Portuguese National Forest Service (Direcção Regional Agrária da Beira Litoral) and to Sonae Indústria and AJI Serração, who supplied the trees and, in the last case, supported the industrial study. Thanks also to the Industries and Institutions that supplied me with data and technical help in various stages of this work: ASilva&Silva, Cerne, Alberto Gaspar, AIMMP, Metla, and Häme Polytechnic, Evo – Degree Programme in Forestry.

I would like to thank Dr Erika Holt for the valuable linguistic corrections to this thesis and for her cheerful friendship since my first times at VTT.

Also, I which to thank my colleagues who supported me in the sampling field work and data collection: Vanda Oliveira, José Pedro Frenandes, Sofia Knapic, Diogo Baptista, Marta Margarido, José Manuel Pires, and António Glória.

To all my friends in Portugal, Finland, and a bit all over the world my thanks for the support and for making my life so colourful. And to the LTL "aivo-social group", thank you for adopting me so many times. Especially, I am greatly indebted to Cristina Simões, my dearest friend with whom I shared so many unforgettable moments during these years in Helsinki.

I owe my warmest thanks to my beloved family for believing in me and for giving me the courage to stay so far from home. Thank you for your endless love that helped me so much in reaching my goals. Muito obrigada por todo o vosso apoio!

Finally, I would like to thank Mika Seppä for all the love that he brought into my life and for all the support and encouragement during the finalization of this thesis.

I want to dedicate this thesis to the memory of my father, António Raul Teixeira Pinto, who taught me that nothing in life is granted without risks and loads of work!

Helsinki, September 2004

List of publications

This thesis is based on the following publications which are referred to in the text by Roman numerals I–V:

I **Pinto I.**, Pereira H. and Usenius A. (2003) Analysis of log shape and internal knots in twenty maritime pine (*Pinus pinaster* Ait.) stems based on visual scanning and computer aided reconstruction. *Ann. For. Sci*. 60: 137–144.

II **Pinto I.**, Pereira H. and Usenius A. (2004) Heartwood and sapwood development within maritime pine (*Pinus pinaster* Ait.) stems. *Trees* 18(3): 284–294.

III **Pinto I.**, Pereira H. and Usenius A. (2002). Sawing simulation of *Pinus pinaster* Ait. IUFRO WP S5.01.04 "Connection between forest resources and wood quality: modelling approaches and simulation software". British Columbia, Ed. G. Nepveu, INRA, Nancy: 429–438.

IV **Pinto I.**, Knapic S., Pereira H. and Usenius A. Simulated and realised industrial yields in the sawing of maritime pine (*Pinus pinaster* Ait.). *Reviewed and accepted for publication in Holz. als Roh- und Werkstoff.*

V **Pinto I.**, Usenius A., Song T. and Pereira H. Sawing simulation of maritime pine (*Pinus pinaster* Ait.) stems for production of heartwood containing components. Reviewed and accepted for publication in *Forest Product Journal.*

Contributions of the author, Isabel Pinto, in the preparation of the above listed studies:

Studies I–III and V: the author carried out the sampling, measurements, data analysis, writing, and publishing work with input from the co-authors.

Study IV: The author carried out sampling, measurements, sawing simulation, and writing and publishing work with input from co-authors. The second author has done sampling and measurements in the industrial environment.

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1. Introduction

Wood is a natural renewable resource traditionally found to be a good structural material. Wood processing is ecologically friendly and its products create warm feelings and have high aesthetic values. However, as an engineering material, wood has the disadvantage of non-homogenous properties with a large variability in the tree (both radial and vertical), between trees, and between stands. Also, whereas demand in wood products is forecasted to increase, production forests world-wide are under different pressures and trends are to decrease raw material availability to the wood-processing industry. On the other hand, new solutions should be found to create new products with high added value and satisfying customer needs in relation with other competing materials. The wood industry needs to optimise conversion processes in order to create higher value from fewer raw materials and to promote the link between the customer-specific needs and the forest production. Deeper knowledge of wood properties and how to efficiently process it to respond to market needs are key issues for the optimisation of the whole wood conversion chain.

In this context, the development of machine vision systems and sawing simulation tools increases the knowledge on raw material properties and allows testing different conversion scenarios which support product development and production decisions. Progress in scanning and defect detection technologies and algorithms for virtual reconstruction of logs allow advances in optimisation and sawing simulation procedures. The application of these technologies to the whole wood conversion chain improves the efficiency of raw material utilization and the exchange of information between different levels. Integrated machine vision and sawing simulation systems can be applied in medium-to-long range strategic planning, as well as for operational production control.

Maritime pine (*Pinus pinaster* Ait.) is an important softwood for Southern Europe, covering over 3 million ha. In Portugal, it is the most important species and has a recognised economic importance. This species is the raw material for the sawmill, particleboard, plywood, pulp, and paper industries. The sawmill industry consumes about 70% of the annual wood yield (CESE, 1996). The Portuguese wood-based industry has been facing some problems for the last years, arising particularly from the primary sector, especially the ownership structure and severe forest fires. These imply a decrease in the quality and quantity of the raw material supply to the timber industry and difficulties to compete, in the global wood market, with other species for the mass production of sawn products. A better organisation of the primary sector, optimisation of the raw material conversion, and customised and innovative products are key factors for this species competitiveness in the solid wood products market.

2. Objectives and overview

The multidisciplinary research carried out in this work focuses on the interaction between forestry, harvesting, and industrial wood conversion. The objective was to increase the knowledge on maritime pine wood characteristics and to study the impact of these on the conversion process. The study was performed by applying a technique for the construction of virtual stem models and sawing simulation procedures to maritime pine. The results contribute to the improvement of this species' utilisation as a raw material for the solid wood industry.

In the first part of the work, a characterisation of maritime pine as a raw material for the wood industries was performed based on the 3D virtual reconstructed stems. The objectives in studies I and II were to characterise shape of the stem, internal distribution of knots, and heartwood/sapwood contents. The differences between the studied stem models and reality were also analysed.

The virtual stems were reconstructed based on image analysis of scanned flitches and provided the raw material for sawing simulation studies in the second part of this work (III to V). The reconstruction and sawing simulation were performed by different modules of WoodCIM®, an integrated optimising software system developed at the Technical Research Centre of Finland (VTT). These WoodCIM® modules were reconfigured to maritime pine and its industrial processing conditions. Input process data and products specifications were obtained from the sawing industry.

The potential of WoodCIM® to investigate the impact of the raw material characteristics in the conversion of maritime pine into solid wood products is explored in study III. The aim of study IV was to compare industrially measured sawing yields with the ones estimated by simulation. This supports the analysis of simulated outputs for validation purposes.

Study V explores the potential of maritime pine for the production of heartwood containing components. Specifically, it was aimed at studying how different raw material variables can influence on the sawing yields of heartwood products.

The wood conversion chain is complex involving many affecting parameters not possible to cover completely in one study. Therefore this work presents limitations especially concerning the wood characteristics studied, the sampling and validation procedures. The wood characteristics studied were limited to stem shape, internal knots, and heartwood/sapwood contents. Validation of yields by product quality grade was not possible to carry within this work. The study was based on a sample of 35 maritime pine stems randomly sampled from 4 stands in Portugal. Although the generated batch of logs (total 218 logs) covered a wide range of characteristics, the sample size is still low to cover all the variability of the studied variables.

3. Background

3.1 The wood conversion chain

The utilisation of wood resources starts in the forest, with the supply of raw material, including the bucking of stems into sawnlogs, and proceeds via the manufacturing of sawn timber and its further conversion into products and their end uses (Figure 1). The wood conversion chain consists of forest producers, sawmills, secondary wood processing industries, and finally the consumer of the final product. The different operations proceed sequentially with the final product of one stage being the raw material for the next one.

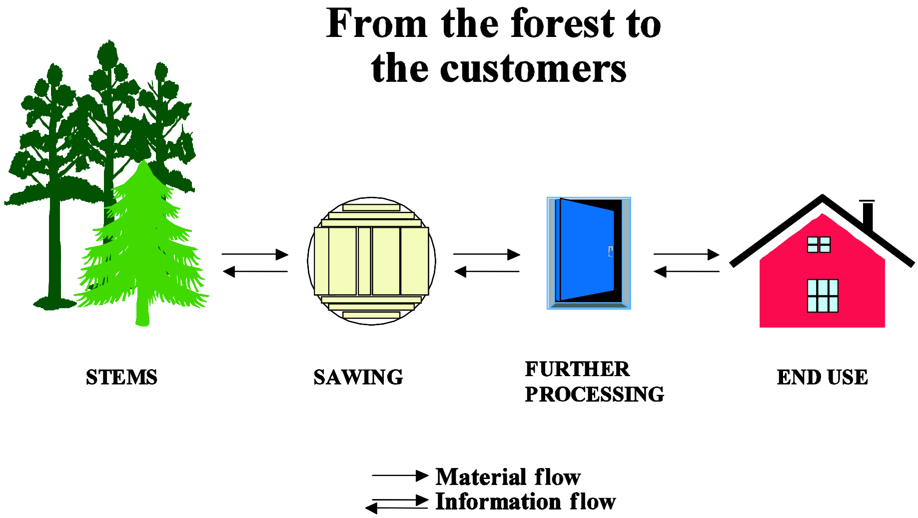


Figure 1. The wood conversion chain (Usenius 1999).

The business environment has changed over the last years from the "Industrial age" to the "Information age". In the "Information age" the market is global and competition is against the best companies in the world. Also the production is customer-oriented rather than volume-oriented and efficiency is achieved by integrating processes and linking business with customers and suppliers (Kaplan and Norton 1996). Traditionally, the wood conversion chain operates with an information gap between its different levels and also has volume-oriented manufacture processes. Moreover, the high variability of the wood properties may create incompatibilities between the initial raw material and the final product, leading to waste, and economical losses. To maintain competitiveness in the "Information age", the wood conversion chain needs to be optimized as a whole. Wood raw material must be chosen taking into account the requirements set for the final products. Therefore, the optimisation of the wood conversion chain requires a flow of information in the reverse course of the raw material flow. In this way, the end-users will press the industry to supply products with certain requirements and these, in turn, can press the raw material producers. The business in the wood industry is increasingly dynamic, flexible, and customer-oriented which requires effective planning of the production along with more flexible and faster decisions.

Modelling, image analysis, traceability, simulation, and machine vision systems are useful tools for the integration and optimisation of the wood conversion chain as a whole. These allow the production, identification, and selection of the correct raw material for a certain end product. Simulation tools can be used to test different scenarios in a virtual world thereby supporting production research and creating information for management, decision-making, and process control. This requires a constant collaboration between the industry and the research centres.

3.2 Maritime pine

3.2.1 The species

Maritime pine (*Pinus pinaster* Ait.) is an important softwood for Southern Europe. Its origin is still not very clear but it has naturally spread in the Mediterranean regions of France, Corsica, Spain, Italy, Sardinia, and Sicily (subspecies *pinaster*) and in the Atlantic regions of Portugal, Spain, and France (subspecies *atlantica*). In the last decades, this species was introduced with success into South Africa, New Zealand, and Australia. In Portugal, it is the most important with an occupation area above 1 million ha (30% of the total Portuguese forest area). (Figure 2)

Pinus pinaster Ait. is an evergreen species with an adult tree height of 25 m to 40 m. The crown is usually pyramidal at young ages and round in adult trees. Well adapted to very temperate maritime climates, this species has characteristics of a pioneer species. It registers higher growth rates in low/medium altitudes (between sea level and 1100 m) in sites with 11–15 ºC as an average annual temperature and with high humidity and precipitation. In Portugal, the average annual production of maritime pine is 5.6 m^3/ha/year. In relation to edaphic conditions, it is a very tolerant species with preferences for light and sandy soils, and growing very well on acidic and poor soils (Alves 1982). The main natural enemies of Maritime pine are fire, some fungi, wood beetles, and its high sensitivity to the attack of processionary caterpillars. Maritime pine is managed as high-forest silvicultural systems with clear cutting followed, commonly, by natural regeneration.

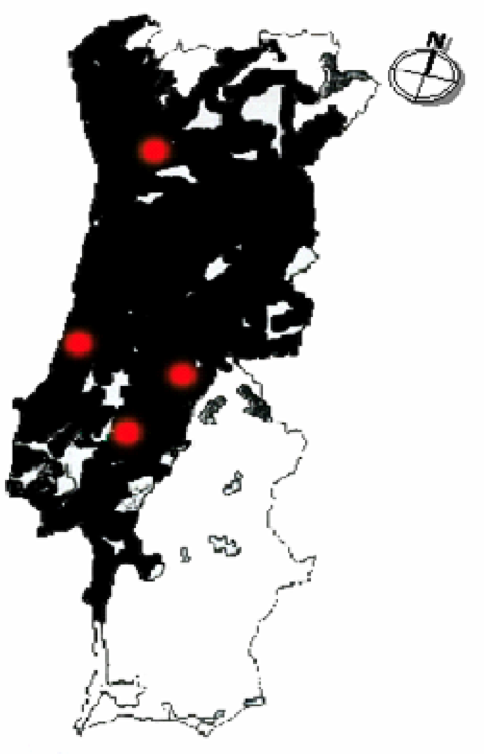


Figure 2. Distribution of maritime pine in Portugal (dotted marks shown the localisations of the stands sampled for this study).

3.2.2 The wood

Maritime pine wood is pale yellow in the sapwood and reddish-brown in the heartwood. The heartwood is distinct and in the transverse section the growth rings are distinct and clearly visible. Some trees have straight-grained wood while others present spiral grain. The wood is resinous with a rather coarse and uneven texture, and a stripe figure (tangential section) due to the growth rings. The annual rings may present a widely variable thickness but are usually wider in the centre near the pith and thinner at the periphery. The width of the latewood tends to be constant (Carvalho 1997, Cruz et al. 1998). Growth rings show a clear contrast between earlywood and latewood, mainly due to the dark thick-walled latewood cells. The pith is more or less circular with a considerable volume. Maritime pine wood is classified as light or moderately heavy and moderately strong in a mechanical point of view (LNEC 1997). The main physical and mechanical properties are summarised in Table 1.

Table 1. Average physical and mechanical properties of maritime pine wood.

Physical properties	
Density: (H=12%) (gr/cm^3)	0.53–0.60
Total volumetric shrinkage (%)	14
Total tangential shrinkage (%)	8.5
Total radial shrinkage (%)	5.0
Volumetric shrinkage coefficient (%)	0.6
Fiber saturation point (%)	30
Mechanical properties	
Compression parallel to grain: strength (N/mm^2)	53
Shearing strength (N/mm^2)	10
Static bending: bending strength (N/mm^2)	96
Cleavage: Rupture force (N/mm^2)	4
Tension parallel to grain: tensile strength (N/mm^2)	87
Tension perpendicular to grain: tensile strength (N/mm^2)	3

Source: LNEC 1997 (small clear specimens, 12% moisture content)

3.2.3 Potential and limitations for industrial uses in solid wood products

Maritime pine wood is used as raw material for the sawmill, plywood, particle board, fiber board, pulp, and paper industries. In Portugal, the wood based sector represents 8.6% of the total industrial Gross Value, 3.8% is coming from the pulp and paper industry and 4.8% from the other wood-based industries. Sawmills consume around 70% of the produced maritime pine timber. This species represent 88% of the volume of raw material consumed in these industries (CESE 1996).

Considering its strength, workability and easy treatment with preservatives, maritime pine wood has the potential to be used in several products, both indoors and outdoors. It is currently used in structural elements for roofs and floors, stair frames, prefabricated timber buildings or components, joinery and furniture. It has also been used in foundations, transmission poles, railway sleepers, scaffolding, fences, and other elements to be applied in open air or in ground contact. Although products for building construction have been the traditional end products of the sawmill industry, in the last 30 years pallets have become the main production item in volume.

The timber has good workability if it is well seasoned and without many defects. It is readily easy to work with machinery and hand tools, and allows a good finishing. It holds mechanical fasteners well, glues easily, and can be given a good finish. Drying can be carried out rather easily, either by air-drying or by kiln drying. This species is sensitive to sap staining and mould growth, thereby it must be dried rapidly, though avoiding seasoning checks and distortion (LNEC 1997, Cruz et al. 1998).

When compared with other pine timbers, like Scots pine, maritime pine wood is normally more resinous and when produced under conditions favourable to rapid growth is generally coarser, knottier and with a large proportion of sapwood (DSIR 1960). For structural uses, knots, pith, and associated juvenile wood are amongst the worst defects. Being a fast-growth species, maritime pine is very sensitive to climatic changes which are very common in the moderate seasons of Southern Europe. This increases wood heterogeneity especially concerning growth ring widths and anatomic element dimensions. Also, the stands of this species are frequently close to the sea, thereby exposed to frequent winds which increase the quantity of resin pockets, stem eccentricity, and reaction wood.

Therefore, it is very important to make a careful selection of this timber, in accordance with the intended uses. In Portugal, the structural timber of maritime pine is classified with visual grading rules into two main grades: grade E (structures) is suitable for general purposes, and grade EE (special structures) is the higher strength grade. This classification is based on the Portuguese standard NP 4305 (1994) and it is compatible with the Eurocode 5 (ENV1995-1-1).

Maritime pine is a very resinous conifer and has been commonly used for resin production. Resin tapping is done by wounding the lower part of the stem and stimulating the exudation of resin with acid. The butt log of resin-tapped pines shows therefore scars on the external part of the stem and considerable quantities of resin remain in the wood. This industry is now in a deep crisis due to the lack of competitiveness in international markets, mainly in relation to imports from China and to the high labour costs. Therefore, most stands have abandoned resin tapping. However, many of the pine trees available have been tapped and are a concern for the sawmill industry because the valuable butt logs are depreciated.

3.3 Measuring and modelling raw-material properties

The knowledge of the wood raw material properties in prior to conversion allows selecting it for certain uses and processing it according to customer's specifications. Looking upstream, the variability of these wood properties can be connected with tree and stand growing conditions such as genetics, silvicultural history and site environment. On the other hand, a good model for the wood raw material is required for a virtual sawing capable of predicting quality distribution of the sawn products. Therefore, the measurement and modelling of wood properties can support foresters and industry in producing and processing the right raw materials for a specific end use. Application of machine vision systems and modelling tools to the wood conversion chain, makes it possible to create virtual representations of stands, trees, and logs. These 3D models and representations of trees and logs give information about their geometry and internal properties which created the concept of "the glass log".

3.3.1 How to measure

The tree and logs model and representations can be divided into two main groups according to the techniques used and the origin of the raw material information:

- Growth models (models with a physiological base),
- Empirical models based on direct measures (on the board, log, or stem).

The growth models create tree and stand representations based on ecophysiological processes using inventory data and individual tree measurements. Traditionally, these models concentrate on forest production and management. In the second stage, these advance to link the management of forest resources and the simulation of tree growth with the wood properties (Kellomäki et al. 1999, Mäkelä and Mäkinen 2003) and further with the simulation of the raw material conversion and end products (Houllier et al. 1995, Blaise et al. 2002, Verkasalo et al. 2002, Ikonen et al. 2003).

The direct measurements of logs and stems can support research on the raw material properties and on the development of new systems for direct application to industrial environments concerning saw-milling optimisation and simulation procedures. The mathematical reconstruction of logs and trees based on scanning technology can now provide accurate 3D representations and detailed information regarding geometry of stems and internal properties. These measurements can be destructive, if the analysis is made on log parts, or non-destructive if it is made on whole log or stem. The destructive approach is, obviously, only applied in the research, development, and validation phases as industrial application requires non-destructive techniques. There are several techniques that can be applied to collect data on stems and logs. The most commonly used in scientific research and/or industrial applications are based on scanning the log surface and its internal properties by ultrasound, x-ray, gamma ray, infrared, nuclear magnetic resonance (NMR) or optical systems.

Virtual representations of logs and stems can be created based on the analysis of images resulting from the optical scan of boards (Song 1998, Funk et al. 2002). On these, the geometric and quality features are identified allowing virtual reconstruction of the original stem/log raw material. The analysis of high-resolution wood images (e.g. obtained with RGB colour-based scan systems) allows the accurate identification of different wood properties. Although destructive, these methodologies can generate a virtual raw material database with detailed information on wood properties. This allows the study on wood properties and the testing of different conversion scenarios. Also, it supports the development of industrial applications of sawing simulation programs.

In the past few years, x-ray based applications have been researched and developed for the wood industry in order to detect inner characteristics of the logs and stems (Grundberg 1999, Oja et al. 2001). This technique registers the quantity of x-ray radiation that goes through the material being measured which is a function of its thickness, density, and humidity. The study of a 3D object requires multiple measurements in different directions. In a log/stem case this means measurements at different angles around its longitudinal axis. The increase in measurement angles leads to higher accuracy for the detection of internal defects but also implies an increase in the signal processing and consequently in the scanning time. Therefore, industrial applications of x-ray based technologies try to find a balance between the defect detection accuracy, the needs for on-line speed, and the costs.

In order to increase the detection accuracy of the inner properties, an x-ray based biomedical technique, the computer tomography (CT), has been applied to wood science (Wagner et al. 1989, Hagman and Grundberg 1995, Schmoldt et al. 1996, Oja 1997, Bhandarkar et al. 1999). The CT scanning of logs and stems is based on measurements taken at a high number of angles. In this case, the x-ray source and detector (with a curved shape) rotates around the log or stem. As mentioned above, the limitation to the industrial application of this technique is the scanning time and the costs.

Another biomedical technique being investigated for wood applications is Nuclear Magnetic Resonance (NMR), as it allows detection of wood properties with high accuracy (Chang et al. 1989, Morales et al. 2002). This technique is based on the nuclear properties of the material and, as a generalisation, one can say that the output signal is proportional to the concentration of hydrogen atoms. Therefore, in NMR images the intensity value of a pixel will be a function of the moisture and chemical elements of wood (lignin and cellulose, for example). This technique is only used in research studies as the signal acquisition is too slow for industrial applications, and it requires very specific installation conditions and high costs.

3.3.2 What to measure

Wood formation is a process with many different variables including genetic inheritance, tree age, climatic variations, soil conditions, and silvicultural practices. All these factors interact with each other and act at different levels with various intensities implying large variation in growth conditions and, as a consequence, variation in wood properties. The variability is present within the tree, between different trees, and between different stands (Zobel and Buijtenen 1989).

The selection of which properties to detect or measure for the development of virtual representations of the wood raw material depends on their impact in the quality requirements of the end products. Thus the wood quality must be defined in terms of end uses and this definition should be harmonised throughout the different parts of the wood conversion chain. Quality should be defined based on all the wood characteristics and properties that affect the value yield in the chain and the serviceability of end products (Zhang 1997). The quality definition concerns wood properties, defects, and the presence of desirable and undesirable characteristics.

Each product has a particular set of quality requirements and these are connected to variables of wood resource. Quality of solid wood products normally involves evaluation of the characteristics at the stem and log level (form and volume, reaction wood and eccentricity, size and type of knot, growth ring width, heartwood and sapwood) and wood properties (grain, wood density, anatomical and chemical characteristics, mechanical properties, durability and permeability, aesthetic aspects). The choice of the variables described below was based on the perspective used in this thesis.

3.3.2.1 Stem shape

Tree form and stem volume are directly connected with log value, harvesting and processing costs, and sawing value yields. During conversion, log diameter, taper, and sweep significantly impact the lumber yield and grade. These are among the main characteristics for log grading before conversion. Large taper might reduce sawing yield in order to avoid wane in the final products. Furthermore, mechanical properties will be reduced due to the impact of the taper in the grain. Log diameter also affects the size of the lumber to be produced. The same volume of logs from different diameter classes could result in different product outputs. Smaller logs are generally associated with higher conversion costs, reduced yield, poor dimension stability, and increase number of defects (Zhang 1997).

3.3.2.2 Knots

Knots are portions of the branches enclosed within the wood of the stem. If the branches are alive at the time of the inclusion, knots are called green or sound as their tissues are continuous with the stem ones. When the branch dies the continuity of the tissues breaks and originates an attached dead or dry knot. These might be attacked by decay and be classified as rotten knots (Desch and Dinwoodie 1996). The quantity, size, and quality of the knots in a tree stem are a function of the species and genetics, growing environment, and forest management.

Characteristics of internal knots such as knot quality, length, and diameter distributions within the stem, strongly contribute to the value yield from log sawing. Knots are denser than the stem wood and imply grain deviation not only in the knot zone but also in adjacent wood. Dead knots affect more the mechanical properties and aesthetic aspects than sound knots. It is important to estimate the size, type, and also the position of the knot in the sawn wood. Normally an edge knot affects strength more significantly than a knot located at the centre of the flat face. Knots are the main cause for sawn timber downgrading particularly due to their effects on warping, mechanical properties and aesthetics. For maritime pine, Machado (2000) reports that knots count for 50% of the rejections in the grading for structural uses and for 44% of downgrading in visual strength grades.

Studies on knottiness have been carried out by several authors for Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.), and silver birch (*Betula pendula* Roth.) using different techniques: direct measurements of the knot parameters (Pietilä 1989, Vestøl et al. 1999, Heräjärvi 2002, Vestøl and Høibø 2000), peeling methods to produce veneer strips, further measured with an electronic device (Lemieux et al. 1997), CT-scanning technologies (Björklund 1997, Björklund and Petersson 1999, Moberg 1999, Oja 1997), and inventory data and predicting models (Colin and Houllier 1991, 1992; Houllier et al. 1995, Mäkinen and Colin 1998, 1999, Mäkinen et al. 2002). For maritime pine, knottiness has been studied through crown architecture and external branch measurements (INRA 1994, 2000, Paulo and Tavares 1996, Tavares and Campos 2000). This species' crown is well branched, especially at young ages and natural pruning is weak. However, several branches dry and allow the remaining ones to increase in diameter.

3.3.2.3 Sapwood and heartwood

In the xylem of most tree species, with natural ageing, the parenchyma cells die and lose their reserve material, wood is impregnated with complex organic compounds (normally referred to as extractives), and water conductance is hindered by the aspiration of pits. This process forms two histologically similar but physiologically different zones: the outer sapwood and the inner heartwood.

The sapwood contains living parenchyma cells and reserve materials and has conducting, storage, and supporting functions. The outer rings transport water and minerals from the roots to the cambium and leaves. The heartwood is physiologically inactive concerning water conduction. The organic compounds impregnated are responsible for the natural durability of this xylem zone and for its usually darker colour. The mechanisms underlying the formation of heartwood and its functions are not yet well known. It has been suggested that heartwood formation serves to regulate the amount of sapwood to a physiologically optimum level (Bamber 1976) following the “pipe-model” theory relating sapwood area to foliage mass (Shinozaki et al. 1964). The amounts of heartwood and sapwood should therefore be related to all factors and conditions that affect crown size and vitality (Mörling and Valinger 1999, Bergström 2000). Other studies support that, after a certain initiation phase, heartwood is formed at a constant annual ring rate. Consequently, heartwood would be related with cambial age and with the factors that impact growth rates, mainly in the early stages (Hazenberg and Yang 1991; Wilkes 1991; Climent et al. 1993, 2002; Sellin 1994; Björklund 1999; Gjerdrum 2002).

Heartwood and sapwood contents vary between and within species and have been related to growth rates, stand and individual tree biometric features, site conditions, and genetic control. Reviews on heartwood and sapwood formation and variation have been reported by Bamber and Fukazawa (1985), Hillis (1987), and Taylor et al. (2002).

During the heartwood formation the process of the pit aspiration decreases the moisture content and forms a natural physical barrier to the penetration of insects and fungi. At the same time, the death of the parenchyma cells implies the loss of sugars in this xylem zone. This decreases the conditions for organisms to develop. Also the accumulated extractives are toxic to these organisms. All these factors make the heartwood to be naturally more durable than the sapwood. On the other hand, the infiltration of the extractives in the cell wall reduces heartwood's shrinkage and swelling capacities, thus increasing its dimensional stability. Therefore, heartwood and sapwood have different moisture content, chemical composition, colour, density, mechanical, and technical properties such as suitability for chemical treatments.

In maritime pine, the heartwood is naturally resistant and the sapwood is very easily impregnated by preservation products. The sapwood is susceptible concerning wood-destroying fungi, termites, and wood-boring beetles like *Anobium* and *Hylotrupes*. The heartwood is slightly to moderately durable to the fungi, moderately durable to termites, and durable to wood-boring beetles (Cruz et al. 1998). In this species, the dry heartwood shows a strong reddish colour. Studies concerning heartwood and sapwood development in this species have shown that this xylem zone represents 20% of the cross-sectional area and 44% of the diameter at breast height and contains 3 times more extractives than sapwood (Esteves 2000). Stokes and Berthier (2000) and Berthier et al. (2001) studied the heartwood irregularity in relation with reaction wood in leaning trees and found more heartwood rings on the leaning side of the tree, while Ezquerra and Gil (2001) reported on heartwood anatomy and stress distribution in the stem.

The content of sapwood and heartwood within the tree, its proportion and variations, have therefore a significant impact on the utilisation of the wood. For pulping, heartwood may be a disadvantage as its extractives can affect the process and product properties. For solid wood applications, the different properties of these two stem zones influence issues such as drying, aesthetic values for the consumer (ex. panels and furniture), gluing ability, painting, durability and ecological concerns. For sawmill, joinery, and furniture industries heartwood-targeted products provide good opportunities to increase competitiveness of wood products in relation to other substitute materials. The increasing concern about the preservative treatments makes the natural-durable heartwood products an environmentally friendly alternative for the consumer. Moreover, heartwood products, when careful selected, have better dimensional stability and the application of reconstructive techniques, such as finger joint, helps to reduce the defects and material heterogeneity.

3.4 Sawing simulation

Within the context of the wood conversion chain optimisation, sawing simulation tools have been developed in order to link wood raw material, production processes, and products together for supporting production planning procedures in mills. Models and simulation tools allow studying how a set of logs and its properties, specific conversion variables, options, and scenarios are impacting on the sawing yields. Sawing simulation software always requires extensive input data concerning products, sawing processes, and wood raw materials.

The first studies used input raw material data derived from the measurements of actual logs (McAdoo 1969, Tsolakides 1969, Cummins and Culbertson 1972, Richards 1973, Usenius 1980, Grönlund 1989). Logs were described as straight truncated cones with circular cross sections. Others have displayed the raw material with computer graphics as in the studies of Pnevmaticos et al. (1974), Occena and Tanchoco (1988) and Todoroki (1990). Pnevmaticos used truncated cones and cylinders to approximate log shapes and rectangular boxes to approximate defects. Defect location and dimensions were randomly generated. In Todoroki's first studies, logs were represented as a series of polygon cross sections and defects as cross-sectional whorls. In 1988, Todoroki modified the log profile to allow the representation of eccentric logs by elliptical cross-sections and in 1990 it was further developed as the AUTOSAW simulation system (Todoroki, 1996).

In other cases, a growth modelling approach has been used and tree models representing external and internal stem features are the input data (Leban and Duchanois 1990, Lönner and Björlund 1999, Ikonen et al. 2003). Leban and others (1990, 1996) developed the programs Win-EPIFN for geometric reconstruction of stems and SIMQUA for prediction of the wood properties in the boards. The SIMQUA software is focused on modelling of wood quality and linking it with different growth models. The model can be used to evaluate the quality and values of the boards from one existing forest resource at one regional level. The tree wood properties and the sawing pattern are given as inputs and the sawing of boards with the respective properties is simulated.

With the development of scanning technologies, several research teams have created scanner-based simulation tools. These use data based on scanning of logs or boards and reconstruction algorithms producing a 3D description of a log or stem concerning its internal defects and shape. Raw material data were derived from computed tomography (Occena and Schmoldt 1996, Schmoldt et al. 1996, Chiorescu and Grönlund 2000, Thawornwong et al. 2003) or scanning of boards (Åstrand and Rönnqvist 1994, Usenius and Song 1996, Usenius 1999, 2000). Åstrand and Rönnqvist (1994) developed a simulation model for optimisation of crosscutting operations in the secondary wood industry. The model is based on information from scanned boards and matches the quality requirements of the end products to the quality of the raw material. Another system, the virtual

SawMill (vSM) sawing simulation software, uses as input raw material the digital logs from the Swedish Stem Bank, a database of 200 virtual Scots pine stems reconstructed based on CT scanning images (Grundberg 1999). This simulator allows testing different sawing alternatives and outputs physical data of the products, as well as economic results. The program also permits to use direct sawmill input from the 3D profile log scanners.

Over the years, wood sawing simulation systems have been designed and improved in order to reach an accurate virtual wood conversion chain linking raw material properties to industrial production. With the development of possibilities for defect detection and information systems, it is increasingly possible to add new raw material properties to the models and to integrate more operations within the wood conversion chain.

Since the early 1970s an integrated optimising software system, the WoodCIM® (Usenius 1980, 1999, 2000) has been under development, at VTT, the Technical Research Centre of Finland. This consists of several software modules that support research and can be linked to the product and material flow control system or other computer systems at the sawmill:

- software for optimising selection of stands and bucking of stems
- program for optimising the limits of sawlog classes
- simulation program for predicting the value yield in sawmilling
- software for optimising manufacturing of components
- sawing model based on linear programming.

The WoodCIM® software system has been developed for the wood conversion chain of Scots pine (*Pinus sylvestris* L.) and spruce (*Picea abies* (L.) Karst.). For the work described in this thesis, the stem reconstruction, bucking, and sawing simulation modules of WoodCIM® were adapted to the conversion of maritime pine.

4. Material and methods

For the studies presented in this thesis, mathematical reconstruction algorithms were used to produce 3D virtual models of logs and stems of maritime pine (*Pinus pinaster* Ait.) (Figure 3). These provided the data for studying raw material characteristics as log external shape, internal knots, and heartwood/sapwood contents (Studies I and II). A sawing simulation tool used this virtual raw material as input to provide data for studies III to V, concerning maritime pine production yields. These techniques are described briefly below and in more detailed in the respective papers.

4.1 Wood raw material – Sampling maritime pine trees

Thirty five maritime pine trees were sampled from 4 stands in Portugal, covering the species' area of distribution and different management types: 20 trees in Leiria (S1), 5 trees in Mação (S2), 5 trees in Alpiarça (S3), and 5 trees in Marco de Canavezes (S4). Due to low quantities of heartwood, trees from S2 were excluded from study IV. For that study, the sampled sites were referred to as LE, AL and MC, respectively for S1, S3 and S4. However, in this thesis the sample sites are always referred to as S1, S3 and S4.

The trees were randomly sampled within each site. Diameter at breast height (DBH), total height, crown height and height of the first visible dry branch were measured for each tree. Two cross diameters (N-S, W-E) were measured every 2.5 m along the tree and the bark thickness was determined with a bark gauge in the location of the greatest thickness. Table 2 gives the biometric data for the sampled trees. The trees were bucked into 5 and 2.5 m logs, where the North-South orientation was marked. Wood discs (5 cm thick) were taken for growth ring analysis at the bottom end of each log and at the top end of the top log.

Table 2. Biometric characteristics of the sampled maritime pine trees (mean with standard deviation in parentheses) and site index.

Stand	**S1**		**S2**		**S3**		**S4**	
Site Index (1)	DH (40)> 17 m		DH (40)> 14 m		DH (40)> 18 m		DH (40)> 21 m	
Age	83 years		43–55 years		42–55 years		48–55 years	
Number of sampled trees	20		5		5		5	
Total height (m)	28.8	(2.8)	15.7	(3.4)	21.3	(1.0)	24.1	(1.0)
Crown height (2) (m)	8.7	(2.6)	7.7	(3.5)	9.1	(1.9)	10.0	(2.0)
Dead Crown base (m) (3)	16.0	(2.1)	7.7	(1.2)	7.8	(1.3)	8.0	(1.6)
DBH (cm)	47.8	(7.3)	28.0	(2.3)	38.9	(9.2)	42.7	(5.3)
Volume over bark (m^3) (4)	2.7	(0.7)	0.5	(0.1)	1.3	(0.6)	1.6	(0.1)
Volume under bark (m^3)	2.3	(0.6)	0.4	(0.0)	0.9	(0.4)	1.2	(0.2)

(1) Dominant height (DH) at 40 years (Tomé et al. 1998) (2) Crown height = total height – live crown base height; crown base at the simultaneous occurrence of 2 green branches (3) Height from tree base to the first visible dry branch (4) Precise cubic method, Smalian formula.

4.2 Virtual reconstructed stems

The 35 sampled trees were transformed into a set of virtual stems by mathematical reconstruction based on the so-called flitch method. A total of 133 logs were live sawn into 25-mm thick flitches. The flitches were scanned using the WoodCIM® camera system providing RGB (colour component) information and the scanned images were processed using the PuuPilot image analysis software. On the image of the flitch and with assistance from the operator, the system registered the xy-coordinates of the geometrical outline of the sawing surface and heartwood, the log pith line and the location, and size, shape, and quality factor of each knot. The mathematical reconstruction of the log in the xyz-coordinate system is then based on the geometrical and quality features of the flitch, its thickness, and with the support of the North-South reference line to create the 3rd coordinate. Finally, the whole stem is reconstructed by addition of the different logs from one tree. Cross-sections of the log/stem were described with a set of 24 radial vectors between pith and outline points of the surface of the log along the length of the log in 50 mm intervals (Song 1987, 1998; Usenius 1999).

In the scanned images of all flitches, the heartwood part was identified out from the sapwood by colour difference. The data concerning the geometric features of the heartwood, were processed with the same algorithms and methodology described above for the log/stem geometry. Therefore, a 3D representation of the heartwood along the log was obtained and integrated with the reconstructed logs' data (shape and knot internal structure) based on the common pith xyz points. The heartwood in the stem was subsequently reconstructed by joining the different logs of the tree. Details of the log/stem reconstruction can be found in studies I and II. Figure 3 shows the output of a mathematical reconstruction of one maritime pine log.

4.3 Raw material characteristics

The parameters for the studies on the stem geometry and knots (studies I and II) and heartwood and sapwood (paper II) were calculated based on the virtual stems.

- Log shape and internal knots (I)

Log shape was described by diameters for each 50 mm of log length, and by taper and pith curviness. Pith curviness was defined as the maximum deviation (in any direction) of pith, found along the log, in relation to an imaginary axis defined by a straight line connecting the pith points at butt and top end of the log (mm/m). Each individual knot was described by its diameter, length, and volume (total and sound), the knot pith position in the tree height (Z-coordinate), and the compass angle in the stem/log cross-section (Figure 4). These outputs were used to study the variation of knot length, diameter, and volume with tree height level: for each dimension it was calculated the average of all knots within sections of 5% of tree height.

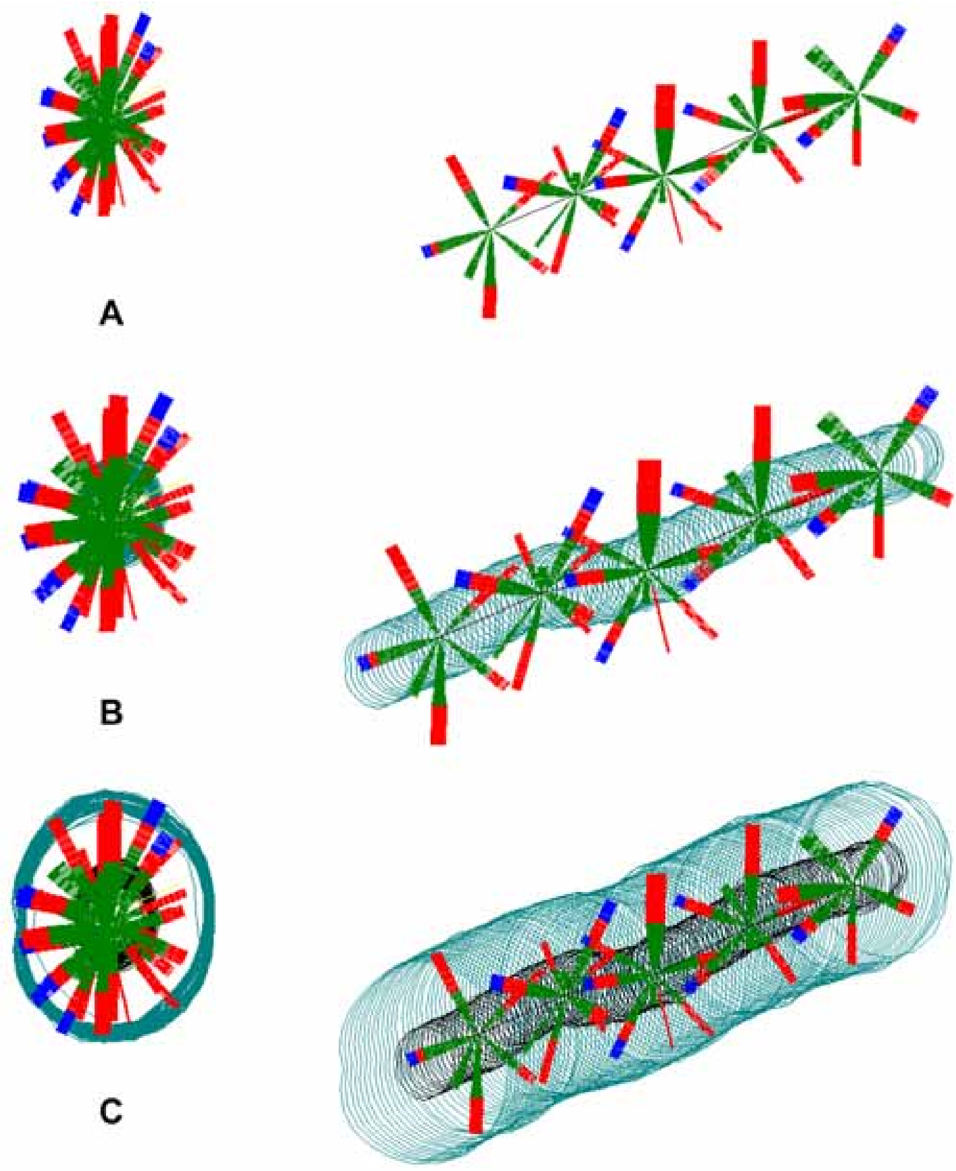


Figure 3. Mathematical reconstruction of one maritime pine log showing in two and three dimensions: the internal knot architecture (A), the heartwood and the internal knot architecture (B), and the full model with the geometry of the log (C). Knot colour code: green – sound, red – dry, blue – rotten.

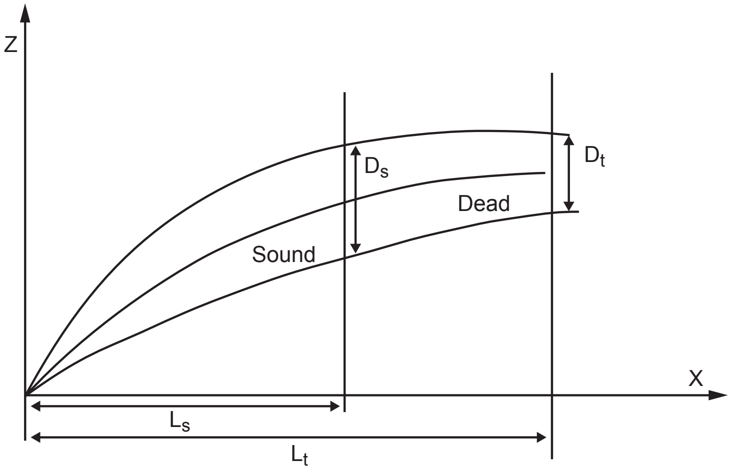


Figure 4. Projection of a knot to the xz plane, total (Dt) and sound (Ds) knot diameter, and total (Lt) and sound (Ls) knot length. Axes z and x correspond, respectively, to the axial and radial direction (Adapted from Song 1998).

- Heartwood and sapwood (II)

The amount of sapwood and heartwood was computed for each 50 mm section of stem height by using the following variables: average stem, heartwood and sapwood diameter, area and volume, and respective proportions in the stem. The sapwood area and volume were calculated as the difference between the corresponding values for stem and heartwood. Growth rings within heartwood and sapwood were counted and measured on wood discs. These were used to study the heartwood development with tree age and also to compare reconstructed heartwood and sapwood dimensions with real values.

4.4 Sawing simulation

The bucking and sawing simulation software modules of WoodCIM® were used in studies III to V. The software used is flexible allowing modifications for the adaptation to a new species and processing conditions. The free specification of product dimensions and qualities, concerning size and number of knots is also possible. The software was reconfigured for maritime pine.

The bucking module allows cutting the virtual stems into any desirable log length and with different lengths in the same stem. In the Portuguese wood industry, 90% of the sawn logs have 2.6 m length. Therefore, this was the log length used in studies III and IV. In study V stems were cut into different log lengths: 2, 3, 4, and 5 m.

The program calculated the sawing yield by using different sawing set-ups for each log and by choosing the best combination of sawing patterns, dimensions, and qualities of the sawn timber products. The nominal and green dimensions of sawn timber products, the quality requirements for each face, prices of sawn timber products and of by-products, and saw kerfs were also introduced as input variables. The output results were the best set-up and sawing pattern, the number of sawn timber products by dimension and grade, and the volume and value yield of sawn timber products. The results were obtained for the entire batch of logs, for the logs of one stem, for the individual logs, and for a specified log group (i.e. butt, middle, and top logs).

The potentialities of this software for the application to the industrial conversion of maritime pine were explored in study III. Using the reconstructed maritime pine stems as input, the influence of raw material and process variables on the simulated sawing yields was studied. The sawing module could be applied using as input both the original virtual stem as well as the heartwood part extracted from the stem because heartwood was reconstructed using the same algorithms as for the stem shape (II). Therefore, heartwood can be virtually sawn separately from the stem allowing the calculation of sawing yield for the heartwood products (V). By adapting different wane specifications, it was possible to saw components with at least one heartwood face, the remaining volume being within the sapwood (Figure 5). The heartwood containing products are referred to as heartwood products. Sawing set-ups and input process data were obtained from the Portuguese sawmill industry and were defined, for each case, in studies III to V.

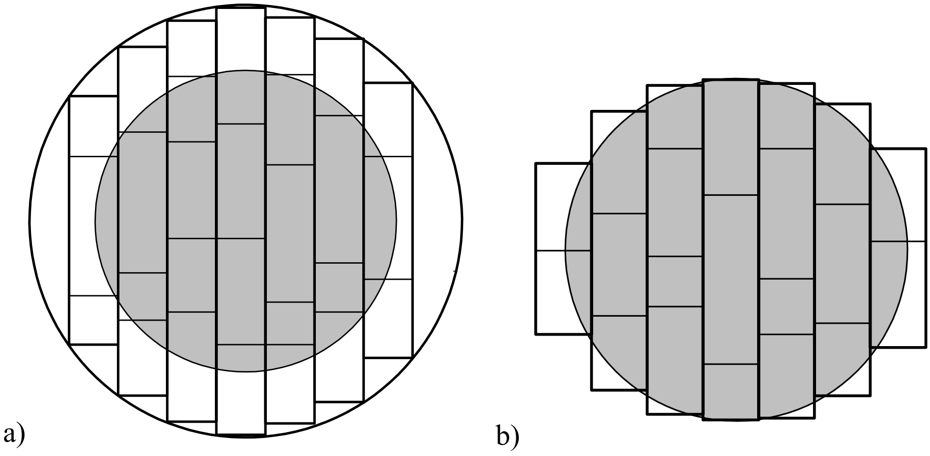


Figure 5. A schematic representation of the sawing simulation of whole log (a) and heartwood part (b).

4.5 Validation of stem model and sawing simulation results

The scanned images of all the flitches of the 4 logs from one tree containing a total of 245 knots were manually analysed to determine the number of knots and their original position in relation to tree height. These values were compared with the reconstruction output (I). Also in study I, the reconstructed stem diameters were analysed in relation to collected field data. Diameters measured in the harvested trees were compared with the reconstructed ones at the same height level. The heartwood and sapwood reconstruction was validate by comparing it with growth ring measurements obtained from the wood discs (II). The sawing simulation output concerning estimated volume yields was studied in relation to industrial measured yields (V).

5. Results and discussion

The virtual 3D maritime pine stems allowed a clear visualisation of important quality features and their subsequent study and quantification, e.g. log geometry, knot parameters and heartwood. These have been explored in studies I and II. The reconstruction of heartwood shape in study II was a new feature added to the reconstruction module.

Study III reports the potentialities of the WoodCIM® sawing simulation software for application to the industrial conversion of maritime pine. The main adaptations developed for this species were explained and the sawing simulation results analysed in relation to raw material properties and process variables. The sawing simulation module was further utilised to study the production of heartwood containing products from maritime pine in study V. In order to evaluate the errors resulting from generated results in a virtual environment, studies I–IV compared the reconstructed stem features and sawing simulation outputs with real values.

5.1 Wood raw material

The maritime pine trees studied were sampled from four sites (S1–S4) with variable natural conditions and also with different silvicultural history. These differences were reflected in the results, with the biggest gap being between S1 and the other remaining sites. The Leiria site (S1) is a state-owned forest where management is oriented to produce wood raw material for high added-value timber products. The silviculture consists of 5-year rotation thinnings between 20 and 40 years of tree age, pruning before the first thinning (up to 2 m height), and clear cutting at an approximate age of 80 years (Gomes, 1999). In the private-owned Portuguese pine stands (S2, S3, and S4) rotation is about 40–50 years. In most of the cases there are no cultural operations and no cleaning of undergrowth vegetation.

Trees harvested from S1 are probably a part of the best quality fraction available in Portugal for the saw-milling industry. Also, the number of sampled trees was higher in S1. Therefore, some data was analysed considering two groups: S1 trees and S2, S3, and S4 trees (II, III, and V). Results concerning trees from S2 to S4 were also analysed considering some other aspects as S2 was a mountain site and some of the S3 trees were severely resin tapped.

5.2 Data validation

5.2.1 Stem model

The stem and heartwood diameters obtained from the reconstructed model followed very closely the actual diameters (I and II). For the stem reconstruction, the difference between modelled and field measured diameters was below 1% of the measured values except for the 20 m level where the modelled diameter was 4% higher than the measured diameter. These higher differences found for top logs resulted from the more irregular shape of stem at this level, already located in the dead crown area and with larger knots. The accuracy of the model regarding heartwood diameter was in the same range, though the variability of the differences was higher. On average, the modelled diameters were 4% below the measured ones, ranging from –12.9% to +8.4% at the different height levels. The correlation between modelled and measured diameters was highly significant ($P<0.001$, $R^2 = 0.88$) and showed very few outliers.

Differences between the actual stem and heartwood diameters with the reconstructed ones may have arisen from the different number of diameter measurements taken for the average. The reconstruction model gives 12 heartwood and stem diameters for each cross-section. The actual values were the average of two diameters for the stem (measured in the field) and 4 for heartwood (on the wood discs). Also, the measurements were based on a 25-mm flitch thickness and the reconstruction of the heartwood part was a new feature added to the model. Therefore, for a few trees the heartwood diameter at the highest tree height levels was less or slightly more than 25 mm and accurate reconstruction was not possible.

The knots in four logs, of one stem (total of 245 knots), were analysed manually in order to evaluate the accuracy of the reconstruction program in the identification of the knot origin position and of all segments of the same knot (I). The number of reconstructed knots in each analysed log differed from the reality only by 2 and the calculated positions for the knot origin on the stem pith showed a mean deviation of 7.8 mm.

5.2.2 Sawing simulation results

The sawing yields simulated by WoodCIM® closely followed the ones measured in industrial environment (III and IV). The results on study V showed that, for the sawing patterns tested, the program showed similar output yields when sawing only boards (57%) and over-estimated the industrial yields when sawing lumber and boards (45% vs. 53%). These production yield values remained almost the same when the number of virtual logs input as raw material increased. Also, it was possible for the pool of 35 virtual maritime pine stems to supply a good quantity of logs within the range of the industrial consumed ones (129 out of 218). However, the results should be analysed considering the numerous factors that can influence sawing yields and comparing the industrial and virtual environment conditions. The dispersion of the sawing yields for industrial logs was much higher than for the simulated ones as virtual conditions related to the raw material and sawing process are less complex than in reality. The simulation of sawing with fixed position of the log might also create differences as in the industrial sawing the log was rotated by the operator to the best position. Previous studies showed 6% average differences in yields between worst and best rotation angles (Usenius et al. 1989). However, in the industrial environment the operator optimises more easily the sawing of smaller logs than of larger ones. Therefore for bigger logs the highest absolute differences occur when the sawing simulated yield was higher than the industrial one.

5.3 Study of raw material characteristics

5.3.1 Stem and log shape

The results in study I described the stem shape for the maritime pine trees sampled from S1 relating it with the forest production. In studies III and IV, the 35 virtual stems were crosscut into 2.6 m logs which were characterised as raw material for the sawmill industry.

The stem shape of the 20 S1 trees was analysed by studying the original 4 logs (5 m long) of each tree. Top diameters decreased with log position in the tree from an average 36 cm for butt logs to 24 cm for top logs, with 56% of the logs showing top diameters between 25 and 35 cm. Butt and top logs have the highest taper values, 13 and 11 mm/m respectively, while middle logs have taper values of 6 and 7 mm/m. The taper increases in the top log as this height level (15–20 m) is included in the dead crown zone. Maritime pine has a weak natural pruning and the death crown depth (often with big branches) is an important cause for depreciation of top logs (Tavares 1999).

The sampled trees showed different sizes in the four sites (Table 2). This resulted in logs with different average characteristics when stems were bucked to supply raw material for sawing simulation (III and IV). Figure 6 shows the average top diameter, taper, and curviness for these logs. The logs from S1 showed the highest average top diameter and lowest taper and pith curviness, as a result of the growing conditions referred to above (chapter 5.1). Site 2 showed the worst site growth (Table 2) and the logs obtained from the sampled trees had the smallest diameters. Overall, a large variation for log top diameter between different logs was found, ranging from 5 to 50 cm top. Most logs were included in the 30–35 cm (24%), 25–30 cm (21%), and 20–25 cm (20%) diameter classes. A study made on the characterisation of maritime pine logs in sawmills of different regions showed an average log diameter of about 25 cm (Reimão et al. 1994). This means that, although the sizes of S1 trees were above average, a large proportion of the bucked logs were within the range consumed by the industry.

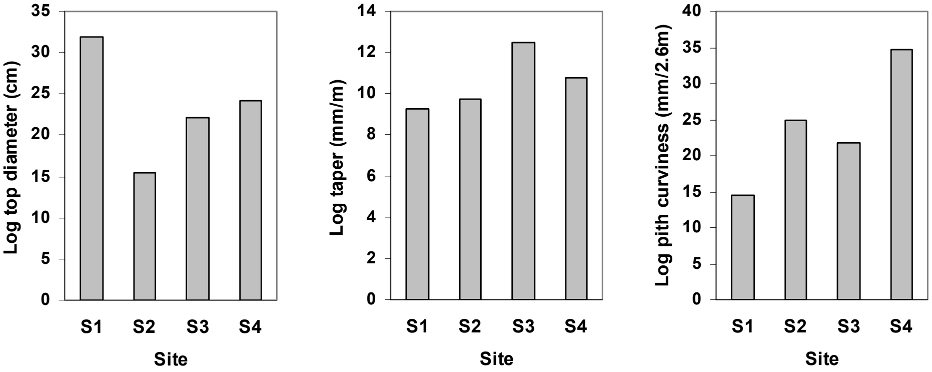


Figure 6. Average values of top diameter, taper, and pith curviness of logs from the different sites.

5.3.2 Knots

The within-tree variation of knot dimensions was studied for the 20 S1 trees up to 80% of total tree height, in average (I). This represents the commercial section of the stem and therefore the most important in terms of value yield for timber products. Although not representative for the diversity of the species, due to the small sample size, the results are indicative of the potential maritime pine knottiness and reflect the growing conditions described in chapter 5.1.

The volume proportion of knots within the stem varied from 0.07% of the butt log volume to 1.95% of the top log volume (5 m logs). The highest proportion of dead knots (38%) was found in the 3rd log (10–15 m of tree height). The proportion of the tree cross-section covered by the knot core increased linearly from the stem base (28% of the tree radius) to 55% of total tree height and thereafter remained rather constant (around 85% and 65% for the total and sound knot core, respectively) until the top of the stem. The sound knot core showed same kind of variation but the rate of increase with tree height was slower when compared to the total knot core. This stable zone corresponded approximately to the top log included in the dead crown (the first visible dry branch was located on average at 55% of total tree height). The lower part of the stem had the smallest knot core and the lowest proportion of dead knots. This stresses the importance of pruning maritime pines at early stages since this species has well branched first crown whorls and a weak natural pruning as referred to above (Tavares, 1999).

The influence of the silvicultural history of S1 trees on their knottiness was also reflected in the variation of knots' individual dimensions. The increase rate of knot dimensions was higher in the height level of 50–60% of total tree height, especially for diameter and volume (Fig. 7). Knot length and diameter increased along the stem attaining at these levels maximum average values of 12.4 and 3.2 cm respectively. These maximums are probably a response to the thinnings that

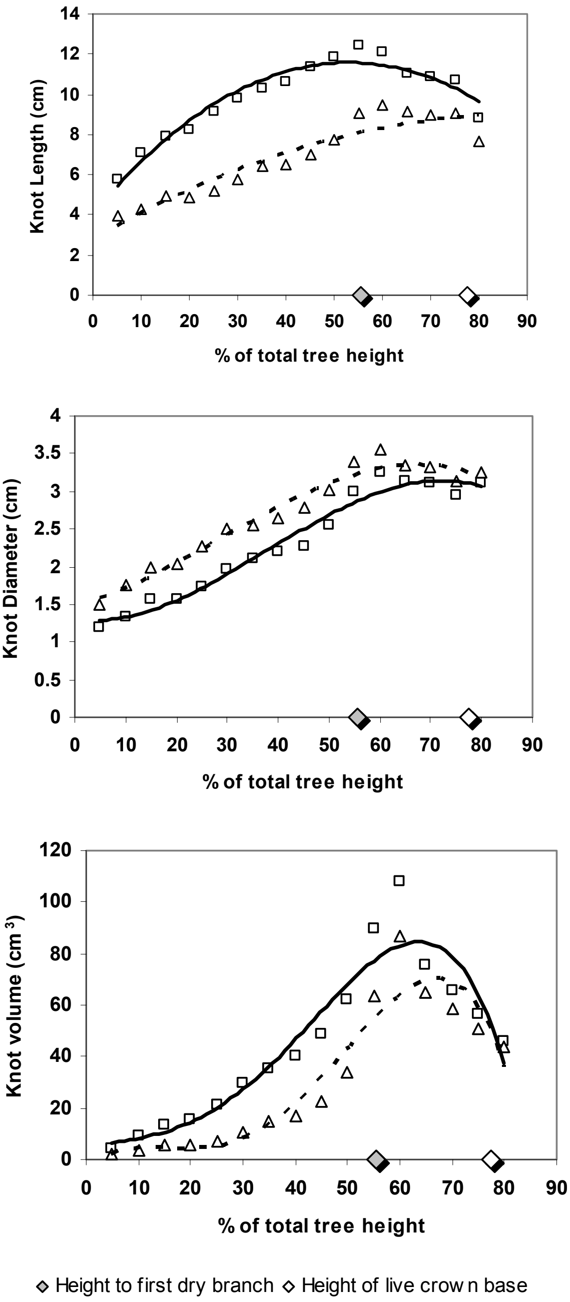


Figure 7. Average total (□) and sound (Δ) knot lengths, diameters, and volumes as a function of relative tree height. The corresponding polynomial fitted curves are indicated by (solid line) for total knot dimensions and by (dashed line) for sound knot dimensions.

occurred when the tree height corresponded approximately to the levels of 54 to 63% of the final total tree height. According to studies on mean annual height increments for this species (Paulo and Tavares, 1996), the thinnings were made when height increments were already in the decreasing phase allowing the tree to invest more in crown and diameter growth.

5.3.3 Heartwood and sapwood

The within and between-tree variation of heartwood and sapwood found in study II for the maritime pine stems follows the results reported in the literature for pine species. The heartwood content increases with tree age and various studies found evidence that, after a certain initiation age, heartwood is formed at a constant annual ring rate (Hazenberg and Yang 1991; Wilkes 1991; Sellin 1994; Björklund 1999; Gjerdrum 2002). In study II, the age of heartwood initiation was estimated to be 13 years through extrapolation of the second-degree polynomial fitted to the number of growth rings included in the heartwood with cambial age. Early heartwood formation phases were observed in the measured samples between 13 and 38 years. Esteves (2000) estimated heartwood initiation age for maritime pine to be around 20 years based on observations of stem discs at various height levels. For other pine species, this age is indicated in the literature to be between 9 and 30 years (Björklund 1999, Climent et al. 2003, Gjerdrum 2002, Mörling and Valinger 1999). The age of heartwood formation is usually lower when estimated by fitted models than by observation of wood discs. For the studied maritime pine trees, the heartwood formation rate was slower in younger ages with 0.5 rings per year for ages under 55 years and 0.7 rings per year between 55 and 83 years. For trees with similar ages (S2–S4), the variability in the number of annual rings within heartwood at a certain height level was quite low which supports the theory that heartwood progresses at a constant rate along the stem diameter.

In accordance with the findings for this species (Stokes and Berthier 2000) as well as for *P. sylvestris* (Björklund 1999), maritime pine sapwood width was much higher at the stem base than further up in the stem where it stabilised at an almost constant value after 2–3 m height. The sapwood width values were similar among trees in the same site except for S3 where between-tree variability was higher. This higher amount of sapwood at the tree basis might be connected to a decrease in specific conductivity in this region that is compensated by a higher sapwood area (Stokes and Berthier 2000).

The variability of heartwood dimensions was quite high, both between trees and between stands, in contrast to sapwood width which showed lower variation for trees belonging to the same stand. The heartwood diameter either decreased with stem height level or presented a maximum value at a specific height decreasing afterwards until the top of the tree (Figure 8). The latter was the typical pattern for the majority of the sampled maritime pine trees (63% of the total) and the maximum heartwood diameters were found between 1.4 m and 6.8 m. Similar profiles have been found for maritime pine in France, Spain, and Portugal

(Stokes and Berthier 2000; Berthier et al. 2001; Esteves 2000; Ezquerra and Gil 2001; Ferreira 2002) and for other pine species such as Scots pine (Björklund 1999; Mörling and Valinger 1999), Canary Island pine (Climent et al. 2003), and radiata pine (Wilkes 1991). The reason for these two patterns of heartwood vertical profile is not known although some hypotheses have been formulated in previous studies. The hypothesis made by Climent et al. (differences in crown depth result into earlier or faster heartwood formation) was not confirmed in Study II. The irregular heartwood profiles are likely to be caused by other factors, i.e. as a consequence of the increased sapwood volumes and butt swell at the stem basis. Also, it might be related with the height level of the heartwood initiation. In S1 trees, the maximum proportion of heartwood in the stem cross-section was found at 8.8 m (42% of the diameter and 18% of the cross sectional area) which corresponded to a total tree height at about 13 years of age, the age that was estimated here for heartwood initiation.

Tree variables as stem diameter, DBH and tree total height were found to correlate significantly with the heartwood content. The stem diameter was the best predictor of heartwood diameter. The fitness was done through a second-degree polynomial indicating that heartwood will be present for stem diameters above 6.8 cm and will increase in diameter by approximately 0.5 cm for each cm of stem diameter increase. Up to 50% of tree height, heartwood represents 17% of stem volume in 83 year-old trees and 12–13% in 42–55 year-old trees. Total tree height and DBH showed the highest correlation with heartwood and sapwood total volume within the tree. However, the correlations found are only indicative about the use of these two variables to predict heartwood volumes in maritime pine as the number of sampled trees was low and the variability between trees and stands as well as in heartwood contents was high. The hypothesis of predicting heartwood diameters based on stem diameters and heartwood volumes based on tree height and DBH can be very useful for the utilisation of the raw material in the wood-based industry. When the target is to maximise heartwood content in the products, the trees can be selected by DBH and height at harvest and stem bucking can be optimised taking into account the within-stem variation of heartwood (V).

5.4 Maritime pine sawing simulation

The 35 reconstructed stems were cross-cut into virtual logs to provide raw material data for the sawing simulations. Results explored in studies III to V showed the potential of the WoodCIM® sawing simulation module to study the impacts of raw material properties on the sawing yield of the conversion of maritime pine into solid wood products.

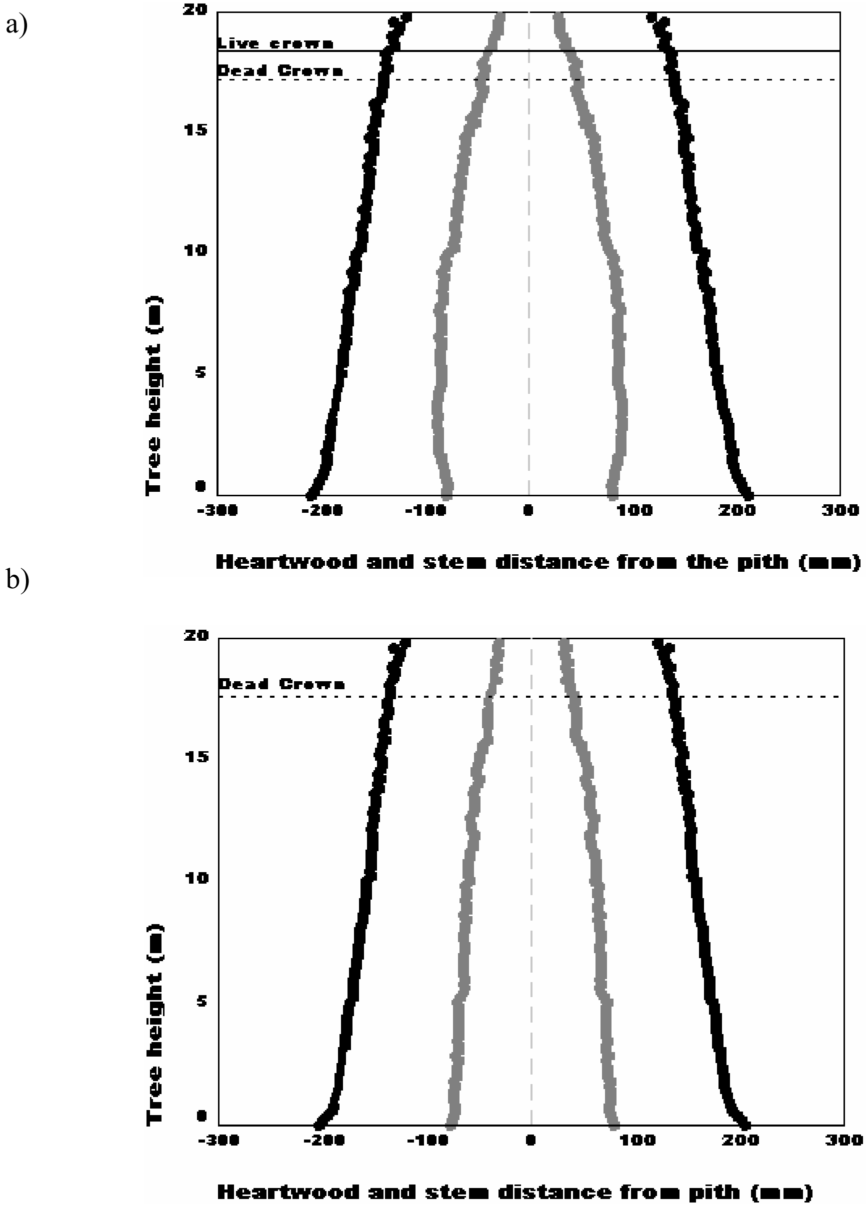


Figure 8. Symmetrical presentation of axial variation of stem and heartwood profiles in two trees showing the two different patterns: (a) heartwood with a maximum diameter at a specific height and (b) decreasing heartwood diameter along the stem.

5.4.1 The impact of log shape and internal knots on sawing yield

With the information from the sawing simulation, it was possible to evaluate volume and value yields of sawing and the impact of log characteristics, knots, and process parameters (III). The variability of the raw material characteristics described above in Section 5.2, mainly the differences of log shape and internal knottiness with sampled site and along the tree height, was reflected in the results.

When no specific quality requirements or prices were defined, the volume yield for a batch of 216 2.6m logs was 51.6%. The volume yield increased with diameter to maximum values of 59% corresponding to the sawing of logs in the 40–45 cm and 45–50 cm top diameter classes. The variability of the values inside each diameter class was high, especially in the range of diameters between 10 and 25 cm due to the different origin of the trees and the variability in log taper and curviness. When the sawing of a batch of logs from the same site was simulated, the best yield (52%) was obtained with the logs from Leiria (S1) in accordance with the larger diameters and lower pith curviness and taper as shown in Figure 6.

The software searches for a solution maximising the total value of the products received from the same log by taking into account each single knot inside the log and the rules for the grading of products. Product grades are defined by number, size, and quality of knots and proportion of wane allowed. The final sawing solution is very much dependent on the prices of products defined by dimensions and grades. In spite of small differences in volume yield using determined quality specifications for the boards (51.6% vs. 50.9%), the value yield (sawn products and by-products) increases strongly with log diameter class from a value of 35 € per log m^3 for the 5–10 cm diameter range to 105 €/m^3 – 107 €/m^3 for the 40–45 and 45–50 cm diameter ranges.

Figure 9 shows the grade distribution of the sawn boards. First grade boards were 79% of the total volume of boards when all the logs were sawn together. A higher proportion of 1st grade boards was obtained from logs from site S1 where 80% of the board's volume were included in the best grading class while for logs from the other sites first grade boards corresponded to only 58% of the total boards volume. This large difference in the yields for first quality boards between sites is a result of the long rotation, pruning, and thinning program in site S1 that allows obtaining large logs with a low proportion of knots (I). Concerning the log position in the stem, the yield decreased from butt to top logs due to the diameter decrease and knot volume proportion increase, as shown in study I. In the case of S3 trees, the yield of butt logs was similar to middle logs. For these trees, butt swell was very evident and taper values were high. A sawing simulation was done with the same input data however cross cutting of the first log started 1m from the normal stump height in order to avoid butt swell influence. In this case the results showed 8% increase on average in the sawing yields for butt logs.

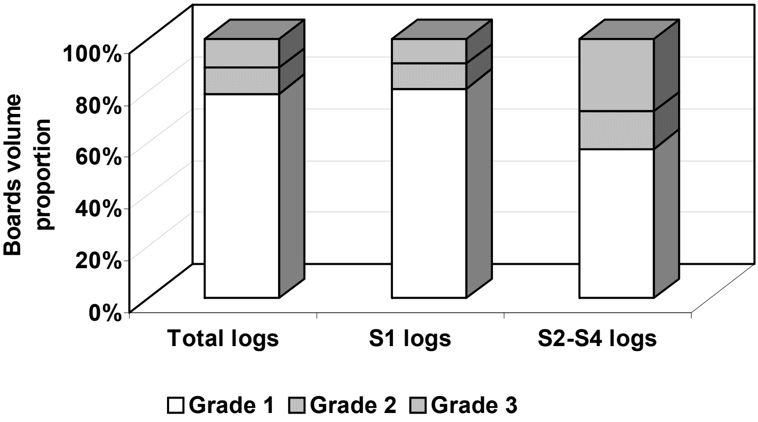


Figure 9. Volume proportion of 25 mm boards by quality grades in value optimised sawing simulations for the total of the logs, for S1 logs, and for S2, S3, and S4 logs. Relative selling prices of boards: 1st grade 100, 2nd grade 73, and 3rd grade 57.

5.4.2 The impact of resin tapping on sawing yield

The estimation of the impacts caused by the resin tapping of maritime pine trees was possible by comparing the sawing yields of resin tapped logs with the sawing simulation performed on a sample of virtual logs matching the dimensions to the industrial ones (IV). Resin tapping resulted in a loss of 11% on the sawing yields (44% vs. 55%). This loss was higher in the larger logs as they normally suffer more severe tapping. In most cases the stem area affected by the resin tapping is outside the knot core zone. Thus, one should expect an even higher value yield loss as this waste zone corresponds to the best board grades.

5.4.3 Production of heartwood containing components

Study V provided an overview of the potential to produce heartwood products from maritime pine and variables influencing it. At this stage, the results should be analysed in a theoretical context due to limitations of the simulation software to the sawing of heartwood. The WoodCIM® software was not designed to include heartwood as an input parameter or as a quality feature in the output (Usenius 1999, 2000). Therefore, the heartwood was taken in the input as an individual entity, separate from the log. The full utilization of the heartwood was possible by allowing wane in the products, i.e. at least one face of the component included in the heartwood being the remaining volume in the sapwood (Figure 5). This sawing procedure is a virtual concept and in a real industrial situation the process would be to saw the whole log and subsequently use the heartwood content of sawn products as a grading criteria option. This means that sapwood products will also be obtained and these have to be taken into account for an overall economic analysis. However, the differences between simulation and industrial reality are systematic for all logs and should not affect the impact analysis of the different variables in the sawing yield of heartwood products. Windows and glued laminated boards were chosen as products due to the potential of increasing benefits and market share in case their production would be based on heartwood components.

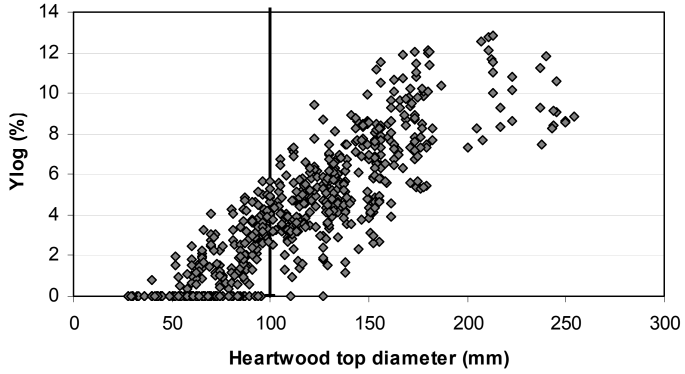
The results obtained showed that yields of heartwood products for some logs could attain 13% and 16% of log volume respectively for glued laminated boards and window components. The yield was highly variable with the log variables such as dimensions, original position in the stem and age, as well as with heartwood and product variables.

Correlation analysis indicated that log and heartwood top diameters and log position in the tree were the variables that had the greatest impact on the sawing yield (correlation coefficients of 0.73, 0.88, and -0.4 respectively). For the sawing simulation of glued laminated components, yield of heartwood products above 10% of log volume only occurred for logs from the S1 stand, corresponding to the older trees. Since in maritime pine heartwood tapers fast, the position of the log in the stem (e.g. being a butt or a top log) is very significant. The highest yields were obtained when sawing 3 m logs, with top diameter above 375 mm and from the first 9 m of the stem of these trees. This stresses the importance of including a special selection of raw material within the log quality grading when the target is the production of heartwood products. The yield obtained did not show significant differences with log length. The slightly better yields obtained for the 3 m logs (5.4% batch yield against 4.8% in 2 m logs and 5.0% in 4 and 5 m) probably resulted from the fact that these logs better fit the vertical heartwood profiles found for this species (II).

Figure 10 shows the yield of heartwood products in log volume (Ylog) for glued laminated boards as a function of heartwood top diameter (a) and log top diameter (b). The minimum diameter under which it was not possible to saw heartwood components (0% yield) or when the yields were low was around 300 mm of log top diameter and 100 mm of heartwood top diameter. These are in accordance with the function found in study II to relate heartwood and stem diameters. Also, Toverød et al. (2003) found log diameter as the most important variable for yield variation when sawing heartwood products. However, the logs for production of heartwood components should not be selected only based on the log and heartwood diameter, even if these were the variables with the highest influence. Log selection for heartwood products will produce the highest potential yields when all the above variables are considered. A good log grading targeting the sawing optimisation of these products will therefore be achieved through an efficient traceability system and by the adaptation of machine vision systems for detecting heartwood, *e.*g. x-ray (Oja et al. 2001, Grundberg 1999).

The study of the potential for producing heartwood products is particularly important for maritime pine. In fact, in the global wood market maritime pine cannot compete with other species for the mass production of sawn products. Production with high quality requirements and higher added value is needed to maintain the competitiveness of solid wood products from this species.

a)



b)

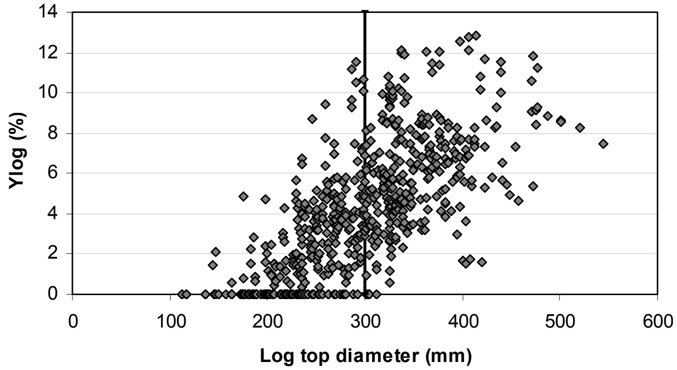


Figure 10. Yield of heartwood components in log volume (Ylog) for glued laminated boards as a function of heartwood top diameter (a, $R^2 = 77\%$) and log top diameter (b, $R^2 = 53\%$).

The results about the influence of the components dimensions on the sawing yields indicate that better yields were achieved with smaller components since these fit better the reduced heartwood volume. However, it was the change of quality requirements regarding the presence of knots that had the greatest impact on the yield and product dimensional assortment. The yield (Ylog) was drastically reduced with the increase of the number of defect-free faces in the component. It is possible to produce defect-free components though, in this case, 38% of the components had the smallest allowed width and length (75 and 400 mm, respectively). The results in studies I and II showed that most of the heartwood volume was included in the knot core volume. The production of knot-free components was then mainly dependent on the inter-whorl length. For S1 trees, the knot core varied from 28% of tree diameter at the stem bottom to 84% of tree diameter at 70% of total tree height (I). For the same trees, the proportion of heartwood varied from 34% of the stem diameter at the bottom, to 24% at the top (II). Finger-joining techniques might be applied in this case to produce defect-free components with the required dimensions.

6. Conclusions

The WoodCIM® stem/log reconstruction and sawing simulation software modules proved to be useful tools to increase the knowledge on maritime pine wood characteristics and to develop sawing studies for this species. This allowed to evaluate the impact of raw material and process characteristics on the production performance. The reconstruction provided a good description for log and heartwood shape with only small deviations between simulated and measured diameters and a good identification of individual internal knots. The sawing simulation showed potential to optimise the operating instructions in the sawing process and it was able to reproduce the industrial sawing of maritime pine.

Although not representative of the variability for the species, the pool of virtual stems constructed in this thesis is a powerful source of data to study maritime pine wood. This is important as there are very few studies available in the international literature concerning the characterisation of this species as a raw material to the wood industries. The stem reconstruction technique adapted for this species included the representation of stem shape and internal knots. The reconstruction of the heartwood part was a new feature added to the model and it was completely developed within this study. This allowed obtaining detailed data on heartwood and sapwood variability along stem height and also their radial variation in the cross-section. Also, it was possible to use the heartwood part as input raw material for the sawing simulation. Although developed here for maritime pine, this technique can also be adapted to the study of heartwood and sapwood in other species.

Specifically, this thesis analysed the evolution of stem shape, individual knot dimensions, and heartwood/sapwood contents with tree height as internal characteristics of the pine stems. The virtual stems were the raw material input for the sawing-simulation studies and the output results clearly showed the impact of these characteristics on value and volume yields. Production yields were higher for logs from the first half of the stem as diameters were large and the taper was smaller when compared to top logs, especially when butt swell was avoided. According to the knot core profile found, butt logs also showed the highest value yields. However, when the target was to maximise the production of heartwood containing components, maximum yields were obtained with logs bucked between 3 and 9 m height as this better fits the heartwood profile found for most of the studied trees. The results can contribute to better selection of the raw material in order to optimise the different wood yields for target products of this species. The study of the maritime pine potentialities for producing heartwood containing components showed that this is possible with an efficient log grading system and additional efforts for selecting heartwood pieces after the conversion. However, the general yields of heartwood products are low and the production should carefully integrate the remaining products from sapwood.

The results also showed the impact of the between-stand variability of wood characteristics on the sawing yields. Raw material harvested from stands with long rotation and management plans (especially pruning and thinning programs) showed the best results, mainly concerning high-quality grades output on sawing as well as the best heartwood sawing yields. Although the present studies did not include any economic analysis, the results are a clear indication that industry should press foresters to supply raw material from stands with longer rotations and better management when the target strategy is the production of high quality products.

The results in this study contribute to the basic scientific knowledge about maritime pine concerning the variations of wood characteristics and their influence on sawing yield outputs, namely within-tree and between-tree variability of stem shape, internal knot dimensions, and heartwood and sapwood development. Also, the results are a contribution to the improvement of this species' utilisation as a raw material for the solid wood industry and can support further development of industrial applications for defect detection and sawing simulation. The WoodCIM® sawing simulation program adapted in this study for maritime pine can support product development studies as well as the development of real-time applications for the sawmill and secondary conversion industries.

7. Further work

The conclusions of this thesis and the results found in the studies presented here suggest that further research is needed, especially concerning the following issues:

- Sampling of maritime pine trees should be increased in order to account for the observed between-tree and between-stand variability. The increase in the number of sample trees and sites should cover a wider range of reported growth conditions and silvicultural management programs. In this way, it would be possible to study the impact of specific forest variables, such as tree provenance, cambial age, density, thinning and pruning on the raw material characteristics and conversion value yield.

- Further analysis on larger samples is also required for a full validation of the accuracy of the reconstruction model, especially concerning dimensions of individual knots and sawing simulation output. Further work should be performed to validate the output quality grades of the sawn products.

- The data associated with the heartwood reconstruction supplies a detailed description for the cross-sections for each 50 mm of stem height. Therefore it will be possible studying the radial variation of this xylem zone in maritime pine. Also, in order to further study the age-based development process of heartwood, future studies should include measurements in a wider range of tree age and the upper parts of the stem with low heartwood contents. For the latter case, the reconstruction of the heartwood would require the use of thinner flitches for data acquisition.

- The results obtained support further development of the WoodCIM® sawing simulation program for research purposes and also for development of industrial applications. The new feature added in this thesis to the stem reconstruction model, the heartwood core, should be included as an input quality requirement for sawing simulation. Information concerning raw material characteristics other than knots, such as resin pockets and pith volume, was also stored and in the future this information could be included in the stem reconstruction and accounted for in the sawing simulation.

- Finally, another important task would be to connect the results with economic and marketing studies. The economic value of wood raw material and final products are very strongly connected. In a future work it is important to create knowledge in order to achieve a good balance between the different parts in the wood conversion chain. Also, research of potential sawing yields of new high added-value products, as for the heartwood containing components, should be developed within feasibility studies and including marketing research.

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Published by

Series title, number and report code of publication

VTT Publications 533
VTT–PUBS–533

Author(s)
Pinto, Isabel

Title

Raw material characteristics of maritime pine (*Pinus pinaster* Ait.) and their influence on simulated sawing yield

Abstract

The objective of this work was to study maritime pine (*Pinus pinaster* Ait.) wood characteristics and their impact on the sawing yield using virtual stem models and sawing simulation procedures. In the first part of the work, a characterisation of maritime pine as raw material for the wood industry was performed. The stem shape, distribution of knots, and heartwood/sapwood contents were studied. In the second part of this work, the virtual stems provided the raw material for sawing-simulation studies.

The stem reconstruction, bucking, and sawing simulation modules of WoodCIM® were used. WoodCIM® is an integrated optimising software system, developed at the Technical Research Centre of Finland (VTT), for the optimisation of the wood conversion chain. The software was adapted for maritime pine and validated. Thirty five maritime pine stems were randomly sampled from 4 sites in Portugal. These were mathematically reconstructed into virtual stems, based on image analysis of flitch surfaces. The 3D virtual stems included the description of external shape, internal knot architecture, and heartwood core. The reconstruction of the heartwood shape was a new feature added to the reconstruction module during this study. Input data concerning final products and process variables for sawing simulation were obtained directly from the wood-based industry.

The average volume percentage of knots in 83 year-old maritime pine trees, varied from 0.07% for butt logs to 1.95% for top logs. Heartwood diameter either followed the stem profile or showed a maximum value at the height 3.8 m, on average, while sapwood width was higher at the stem base and after 3 m remained almost constant along the stem height. Production yields were higher for logs with origin of the first half of the stem as diameters were large and taper reduced when compared with top logs. Butt logs showed the highest value yields because of the knot core profile. When the target was to maximise the production of heartwood containing components, best yields were obtained with logs bucked between 3 and 9 m height.

The results in this study increased the basic scientific knowledge about maritime pine concerning the variations of wood characteristics and their influence on sawing yield outputs. Also, these can contribute to further development of industrial applications of defect detection and sawing simulation tools.

Keywords
maritime pine, *Pinus Pinaster* Ait., 3D stem models, stem shape, knots, heartwood, sapwood, sawing simulation, production yields

Activity unit
VTT Building and Transport, Betonimiehenkuja 5, P.O.Box 1806, FIN–02044 VTT, Finland

ISBN
951–38–6373–5 (soft back ed.)
951–38–6374–3 (URL:http://www.vtt.fi/inf/pdf/)

Project number

Date
September 2004

Language
English

Pages
51 p. + app. 69 p.

Price
C

Series title and ISSN
VTT Publications
1235–0621 (soft back ed.)
1455–0849 (URL: http://www.vtt.fi/inf./pdf/)

Sold by
VTT Information Service
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