

**AXIAL AND RADIAL VARIATION  
IN THE PROPORTIONS OF SAPWOOD AND HEARTWOOD  
IN STEMS OF COMMON OAK (*QUERCUS ROBUR* L.)  
DEPENDING ON SITE TYPE, AGE CLASS  
AND SOCIAL CLASS OF TREE POSITION**

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**Abstract.** The study presents radial and axial variation in the proportions of sapwood and heartwood in stems of common oak growing under varied growth conditions. Collected material was analyzed in order to find factors affecting irregularity in sapwood and heartwood zones in stems of trees representing investigated populations. The proportion of sapwood and heartwood in the stem and the rate of heartwood formation are influenced by crown size and transpiration efficiency of trees, social class of tree position as well as site conditions. The proportions of sapwood and heartwood vary also between age classes of trees. A considerable effect on the width of the sapwood zone in trees was found for crown size. In this case correlations were positive in both analyzed age classes, although in age class III they were weaker than in age class IV.

**Key words:** common oak (*Quercus robur* L.), sapwood, heartwood, fresh mixed forest (LMśw), fresh broadleaved forest (Lśw), timber

**INTRODUCTION**

Forest site types of fresh mixed and fresh broadleaved forest in Poland in 2005 jointly accounted for 22.5% forested area [Raport... 2005]. Under these forest site type conditions common oak is found at varying quality, both as the main tree species as well as an admixed tree species in the upper and lower storeys [Siedliskowe... 2003]. Common oak grows in relatively fertile forest site types and reaches considerable dimensions. Sale of common oak timber yields large profits. For example the highest bid price of oak veneer wood in 2007 at the international auction in Krotoszyn was PLN 3300.00 per 1 m<sup>3</sup> [Raport... 2005].

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Wood still remains the fifth major commodity in world trade. Moreover, in the future the dynamically developing world pulp and paper and chemical industries are likely to replace many sectors of the petrochemical industry. For these reasons appropriate utilization of wood is of paramount importance for the entire modern civilization [Plomion et al. 2001].

Specific properties of sapwood and heartwood, depending on the tree species and potential wood application, may be positive or negative. This is connected with a characteristic feature of sapwood, which is its higher permeability and lower stability than those of heartwood [Krzysik 1978]. Thus, knowledge on the proportions of individual wood types in the stem is of great importance both for the producer and the end buyer [Pazdrowski 1992].

The study was an attempt to determine the variation in the proportions of sapwood and heartwood at the radial and axial sections in stems of common oak (*Quercus robur* L.) representing age classes III and IV, growing in fresh mixed and fresh broadleaved forests. Variation in the width proportions of these two wood zones in stems was analysed.

When analysing the above mentioned problems it was attempted to identify factors affecting the irregularity of sapwood and heartwood zones in stems of trees representing investigated populations.

The study was to determine interdependencies between selected biometric properties of the crown and the width of the sapwood zone at the radius of the cross stem section.

Analyzed correlations were investigated in relation to Kraft's classification of social class of tree position in the stand, in terms of age classes and forest site types.

## MATERIAL AND METHODS

Experimental material consisted of wood of common oak (*Quercus robur* L.) growing in fresh mixed and fresh broadleaved forest sites in the Łopuchówko Forest Division, a part of the Regional Directorate of State Forests in Poznań (Fig. 1).

Analyses were conducted in stands of age classes III and IV (in terms of age from the forest management plan), in which oak was the main tree species. The percentage of oak in the species composition ranged from 8 to 10, with an admixture of such tree species as common beech, European hornbeam, silver birch, Norway maple, sycamore maple, black alder, European aspen, European ash, wild cherry, Scots pine, European larch and Norway spruce.

In four selected sample plots (of 1 ha each) breast height diameter and height were measured on all trees and they were presented in terms of 2-cm diameter subclasses. On the basis of the recorded height and diameter characteristics a total of 12 model trees were selected (three for each sample plot) according to the Ulrich I method [Grochowski 1973].

Next those trees were found and marked on site. When identifying trees on site it was determined whether they may be definitely classified to a specific Kraft's class of tree position in the stand. Tree no. I according to Kraft belonged to class III, tree no. II belonged to Kraft's class II, while tree no. III – to Kraft's class I. Terminology connected solely with Kraft's social position classification will be used in the further parts of the study.



Fig. 1. The area of the Łopuchówko Forest Division, the Regional Directorate of State Forests in Poznań

Rys. 1. Zasięg terytorialny Nadleśnictwa Łopuchówko, RDLP Poznań

For each model tree selected on the sample plot their crown projection area was determined (from the four cardinal and four intermediate directions) prior to felling. After felling stem length and the length of live crown were measured.

The stem was divided into 2-m sections, from the centres of which discs were cut in order to determine selected traits of wood macrostructure, with the volume of the sapwood ring and the heartwood cylinder being calculated in each 2-m section of individual trunks. Next a disc was cut from the breast height diameter and from the saw cut.

On collected discs radial widths of sapwood and heartwood zones were determined in the four directions corresponding to the cardinal points. When analysing results for individual discs and trees arithmetic means for the widths of analysed wood zones were used.

Results of analyses are presented in the form of tables and figures.

## RESULTS

Results show considerable variation in the proportions of sapwood and heartwood in the volume of trees in individual Kraft's classes growing in fresh mixed and fresh broadleaved forests, coming from two age classes.

Moreover, axial variation (along the stem) and radial variation were also observed in terms of the share of heartwood at the cross stem section, both in individual forest site types and in Kraft's classes.

Trees included in the study were characterized by a larger proportion of heartwood volume in relation to sapwood volume. Among trees representing age class IV the predominance of heartwood in the total volume was more marked than it was the case in trees from age class III.

In trees from age class III growing in fresh mixed forest the mean proportion of heartwood in stem volume was 60.19%, while in trees from fresh broadleaved forest it was on average 58.07% heartwood. In trees from age class IV the mean proportion of heartwood volume in the stem for trees from fresh mixed forest was 62.78%, while for those from fresh broadleaved forest it was 61.30%.

An even more marked variation was recorded in the proportion of the mean sapwood and heartwood volumes in individual Kraft's classes of trees, representing analysed populations. The highest proportion of heartwood in the mean volume of trees was found in trees from Kraft's class I coming from age class IV in fresh mixed forest (67.96%), while the smallest proportion of heartwood was recorded in trees from Kraft's class III growing in fresh broadleaved forest and representing age class III (47.88%). In Kraft's class II the proportions of sapwood and heartwood volumes were intermediate in relation to Kraft's classes I and III. The trend in the proportion of sapwood in the volume of trees in individual Kraft's classes in relation to the share of heartwood was the opposite. The numerical characteristics of the relative proportions of sapwood and heartwood in the volume of common oak trees from the investigated populations are presented in Table 1.

Table 1. Mean percentages of sapwood and heartwood volumes in stems of common oak  
Tabela 1. Średni procentowy udział miąższości bielu i twardego w pniach dębu szypułkowego

Kraft's class Klasa Krafta	Age class III – III klasa wieku				Age class IV – IV klasa wieku			
	LMśw		Lśw		LMśw		Lśw	
	heartwood twardziel	sapwood biel	heartwood twardziel	sapwood biel	heartwood twardziel	sapwood biel	heartwood twardziel	sapwood biel
I	59.35	40.65	63.12	36.88	67.96	32.04	67.88	32.12
II	59.66	40.34	63.20	36.80	60.88	39.11	56.25	43.75
III	61.55	38.45	47.88	52.12	59.49	40.51	59.78	40.22
Standard deviation Odchylenie standardowe	0.97		7.20		3.70		4.87	
Mean Średnia	60.19	39.81	58.07	41.93	62.78	37.22	61.30	38.70

When investigating variation in the proportions of sapwood and heartwood at the radius of the cross stem section in relation to age classes in individual forest site types considerable diversification needs to be stressed in analysed stands. Heartwood rather than sapwood accounts for a larger proportion at the radius in case of all age classes.

Common oaks representing age class III are characterized by a larger proportion of sapwood at the radius than trees from age class IV. Among analysed trees from age class III a slightly higher share of sapwood at the radius was found for trees coming from fresh broadleaved forest (28.19%) than for those from fresh mixed forest (27.82%). The proportion of heartwood at the radius in age class III was 72.18% for trees representing fresh mixed forest and 71.81% for those representing fresh broadleaved forest.

In case of trees from age class IV there are bigger differences in the proportions of sapwood and heartwood at the radius in individual investigated forest site types. A higher share of sapwood was recorded for trees from fresh broadleaved forest (27.21%), while in stems of trees from fresh mixed forest sapwood accounted for 24.54% at the radius. The percentages of heartwood were 72.79% at the radius in stems of trees growing in fresh broadleaved forest and 75.46% in stems of trees from fresh mixed forest. Trees from age class IV were characterized by a higher share of heartwood at the radius than those trees which represented age class III. Described dependencies are shown in Figures 2 a and b.

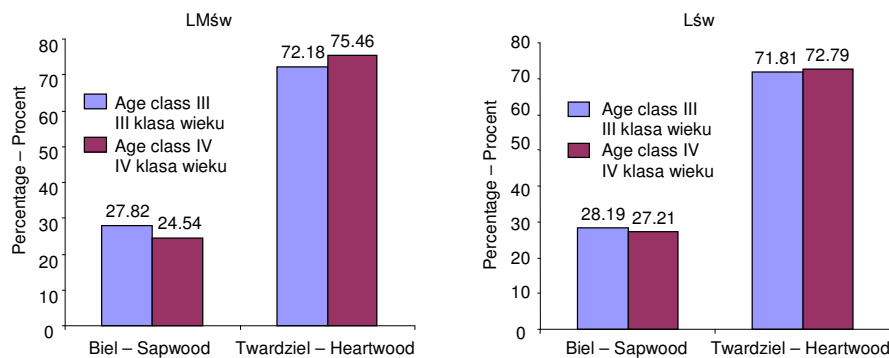


Fig. 2. Mean relative proportions of sapwood and heartwood at the radius of cross stem section in stems of oak in age classes III and IV growing in fresh mixed forest and fresh broadleaved forest

Rys. 2. Średni względny udział bieli i twardzieli na promieniu przekroju poprzecznego pni u dębu w III i IV klasie wieku wyrosłych w warunkach LMśw i Lśw

A considerable variation was found in the mean contents of sapwood at the radius in individual Kraft's classes. Maximum mean share of sapwood at the radius in age class III was recorded for Kraft's class III (32.47%), an intermediate one in Kraft's class II (26.12%), while the lowest share was found in Kraft's class I (25.43%). The proportion of heartwood at the radius in trees from age class III exhibited an opposite trend than for sapwood, amounting in Kraft's class III to 67.53% (the least among trees from age class III), in Kraft's class II to 73.88% and in Kraft's class I to 74.58% (the most among trees from age class III).

Differences between trees in age class IV were slightly less marked. The highest share of sapwood was found in trees from Kraft's class II (27.75%). The lowest proportion of sapwood was recorded for Kraft's class I (22.48%), while an intermediate content for Kraft's class III (27.40%). The content of heartwood in Kraft's class II was

72.25% (the least among trees in age class IV), in Kraft's class III it was 72.60% (an intermediate value), while in Kraft's class I it was 77.52% (the highest figure among analyzed trees of age class IV). The proportions of sapwood and heartwood at the radius in trees from individual Kraft's classes in terms of age classes are presented in Figures 3 a and b.

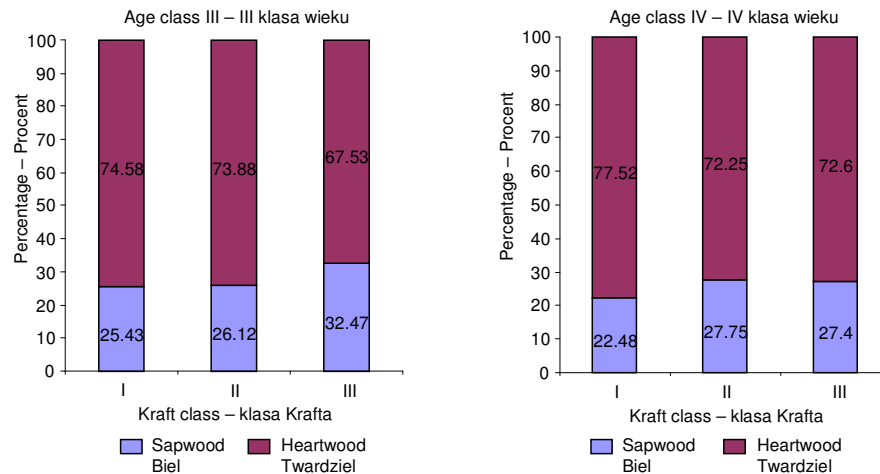


Fig. 3. Mean percentages of sapwood and heartwood at the radius of cross stem section in Kraft's classes of oak trees in age classes III and IV

Rys. 3. Średni udział bielu i twardzieli na promieniu przekroju poprzecznego pnia w klasach Krafta u dębu w III i IV klasie wieku

In the study the effect of crown size on the occurrence and quantitative variation of sapwood and heartwood was analyzed at the stem profile and cross stem sections of common oak trees representing age classes III and IV, coming from fresh mixed forest and fresh broadleaved forest. Considerable irregularity and variation was recorded in crown size in individual mean sample trees in terms of their respective forest site types.

It was observed that trees representing Kraft's class I generally have bigger crown volumes than trees from Kraft's classes II and III (means from all mean sample trees representing a given Kraft's class of social tree position in the stand). In case of trees from Kraft's class I crown volume calculated as the volume of a paraboloid of revolution was 142.5 m<sup>3</sup>, whereas in trees from Kraft's class II the mean was 129.5 m<sup>3</sup> and those from Kraft's class III it was the least, i.e. 42.25 m<sup>3</sup>.

When analysing individual trees included in the study it was found that in all trees representing examined populations the highest crown volume was recorded in a tree from Kraft's class II and age class IV, growing in fresh mixed forest (298 m<sup>3</sup>), followed in terms of volume by a tree from Kraft's class I and age class IV growing in fresh broadleaved forest (crown volume of 218 m<sup>3</sup>). Two trees with the smallest crown volume were a tree from Kraft's class III and age class III from fresh mixed forest and from fresh broadleaved forest (their volume was 21 m<sup>3</sup> and 32 m<sup>3</sup>, respectively). The other trees were characterized by an intermediate crown volume.

In terms of the circular crown projection area the highest figures were also recorded for trees representing Kraft's class I (33 m<sup>2</sup>), with intermediate values for crowns of trees from Kraft's class II (22 m<sup>2</sup>) and the smallest for those from Kraft's class III (11.5 m<sup>2</sup>).

Among individual measured trees the highest circular crown projection area was recorded for a tree from Kraft's class I from age class IV, growing in fresh mixed forest (45 m<sup>2</sup>), followed by a tree from Kraft's class I and age class III, also from fresh mixed forest (31 m<sup>2</sup>).

Numerical variation in crown volume and crown projection area are given in Tables 2 and 3.

Table 2. Crown characteristics of common oak trees growing under diverse site conditions, coming from two age classes, variation in Kraft's classes in terms of age classes and forest site types among trees representing the analysed population

Tabela 2. Charakterystyka koron drzew dębu szypułkowego wyrosłych w zróżnicowanych warunkach siedliskowych, pochodzących z dwóch klas wieku, zróżnicowanie w klasach Krafta z rozróżnieniem klas wieku i typów siedliskowych lasu wśród drzew reprezentujących badaną populację

Characteristic Charakterystyka	Kraft's class I – I klasa Krafta				Kraft's class II – II klasa Krafta				Kraft's class III – III klasa Krafta			
	LMśw	Lśw	SD	mean średnia	LMśw	Lśw	SD	mean średnia	LMśw	Lśw	SD	mean średnia
	Age class III – III klasa wieku											
Pk	31	30	0.5	30.5	19	17	1	18	8	11	1.5	9.5
Vk	129	143	7	136	60	71	5.5	65.5	21	32	5.5	26.5
	Age class IV – IV klasa wieku											
Pk	45	26	9.5	35.5	29	23	3	26	19	8	5.5	13.5
Vk	218	80	69	149	298	89	104.5	193.5	87	29	29	58

Vk – crown volume understood as the volume of a paraboloid, Pk – crown projection area understood as the area of a circle, SD – standard deviation.

Vk – objętość korony jako objętość paraboloidy, Pk – pole powierzchni korony rozumiane jako pole koła, SD – odchylenie standardowe.

Table 2. Crown characteristics of common oak trees growing under diverse site conditions, coming from two age classes, mean values of crown parameters for Kraft's classes

Tabela 2. Charakterystyka koron drzew dębu szypułkowego wyrosłych w zróżnicowanych warunkach siedliskowych, pochodzących z dwóch klas wieku, średnie wartości parametrów korony dla klas Krafta

Social class of tree position Klasa biosocjalna	Kraft's class I I klasa Krafta		Kraft's class II II klasa Krafta		Kraft's class III III klasa Krafta	
Parameter	SD	mean średnia	SD	mean średnia	SD	mean średnia
Pk	7.2	33	4.6	22	4.5	11.5
Vk	49.5	142.5	97.8	129.5	26.1	42.25

Explanations as in Table 2.  
Objaśnienia jak w tabeli 2.

Figures 4 and 5 present radial proportions in the distribution of sapwood and heartwood along stems of common oaks, depending on age classes in relation to their social

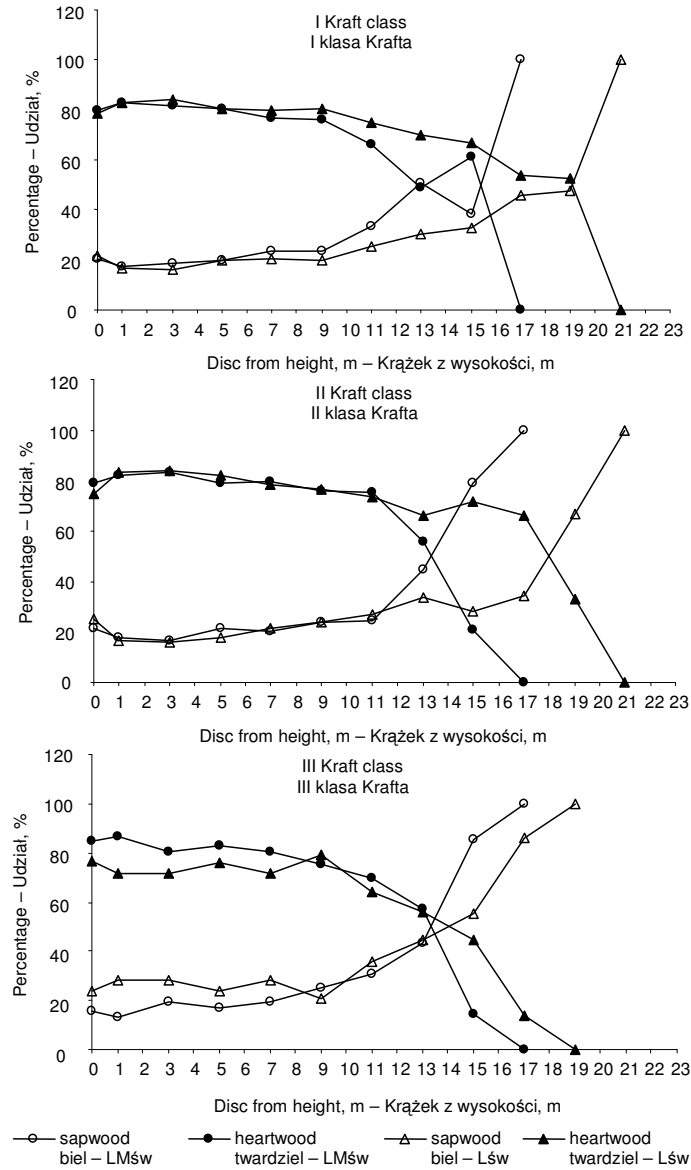


Fig. 4. Characteristics of radial distribution of sapwood and heartwood along the stem depending on tree position in the stand and forest site type in age class III

Rys. 4. Charakterystyka promieniowego rozmieszczenia bielu i twardzieli wzdłuż pnia w zależności od stanowiska biosocjalnego i typu siedliskowego lasu w III klasie wieku



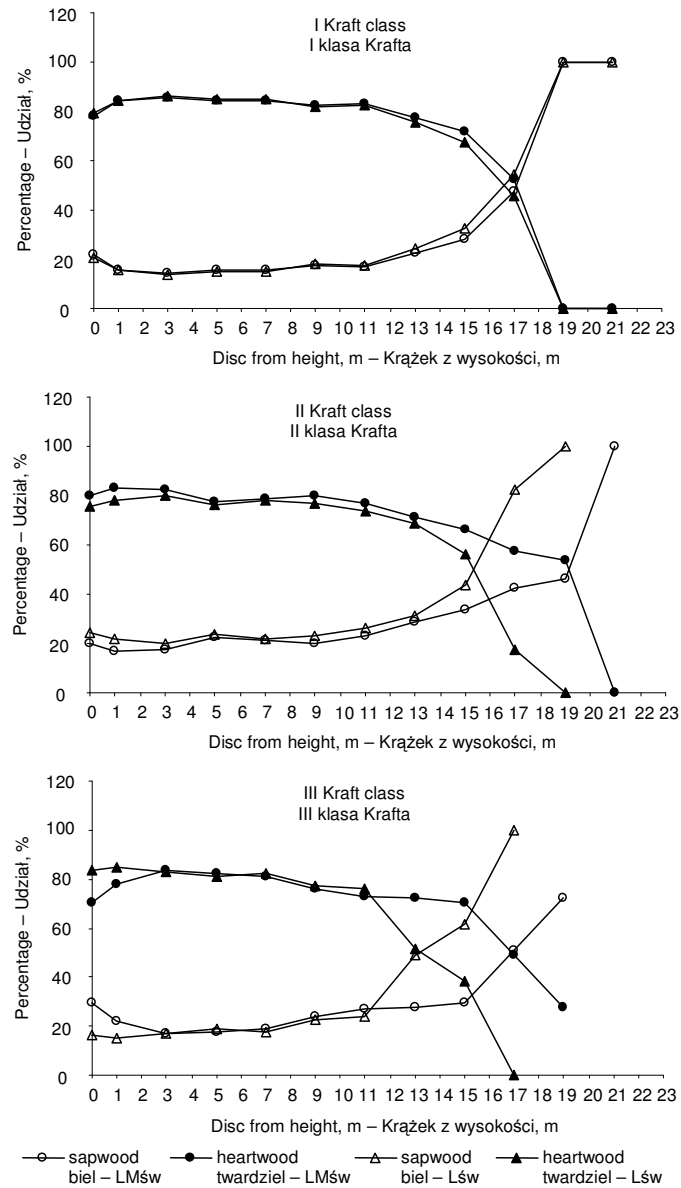


Fig. 5. Characteristics of radial distribution of sapwood and heartwood along the stem depending on tree position in the stand and forest site type in age class IV

Rys. 5. Charakterystyka promieniowego rozmieszczenia bielu i twardzieli wzdłuż pnia w zależności od stanowiska biosocjalnego i typu siedliskowego lasu w IV klasie wieku

class of tree position in the stand. An especially marked variation was found in age class III, especially in Kraft's classes I and II in case of the fresh mixed forest site. The proportions of sapwood and heartwood at the radius in relation to the diameter at the site of measurement was strongly disturbed at a height from 11 m to 13 m. Below and above these boundary height values the axial variation of the sapwood:heartwood ratio at the radius was more uniform.

Apart from the above mentioned differences found in individual cases of Kraft's classes considerable variation was also recorded between the two investigated forest site types in the comparison of the axial ratio of sapwood and heartwood at the radius. One of the characteristic features was the earlier occurrence (i.e. at a lower height on the trunk) of the point where the proportion of sapwood and heartwood became equal in age class III among analyzed trees coming from fresh mixed forest than it was the case for trees from fresh broadleaved forest. In analyzed trees of age class IV the shares of sapwood and heartwood became equal faster in case of trees from fresh broadleaved forest than fresh mixed forest (in contrast to age class III).

In age class III a varied proportion of sapwood at the radius along the trunk is observed in both forest site types, while in age class IV the variation in the share at the radius is more regular and sapwood predominates in the ratio in tree trunks from fresh mixed forest sites over those from fresh broadleaved forest.

Correlations between selected crown parameters of common oak and mean sapwood width in individual age classes are presented in Figures 6 and 7 below. It turned out that investigated crown parameters, i.e. crown projection area and crown volume as the volume of a paraboloid, show a positive correlation with the width of the sapwood zone. In case of both analyzed crown parameters a stronger relationship with the width of the sapwood zone was found in age class IV than in age class III.

Linear correlation coefficient between crown volume and mean width of the sapwood zone in trees representing analysed populations in age class III was +0.649, while in age class IV it was +0.725. Correlations between circular crown projection area and the mean width of the sapwood zone amounted in age class III to +0.723, whereas in age class IV to +0.866.

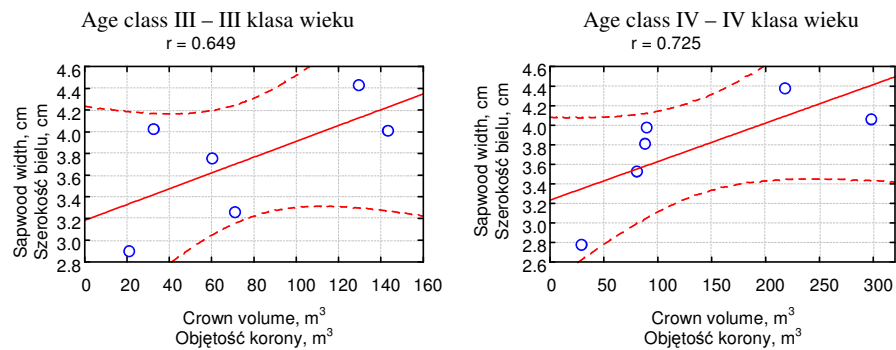


Fig. 6. Linear correlation between crown volume and mean width of sapwood zone in common oaks representing two age classes (95% confidence interval)

Rys. 6. Korelacja liniowa pomiędzy objętością korony a średnią szerokością strefy bielu u dębu szypułkowego reprezentującego dwie klasy wieku (95-procentowy przedział ufności)

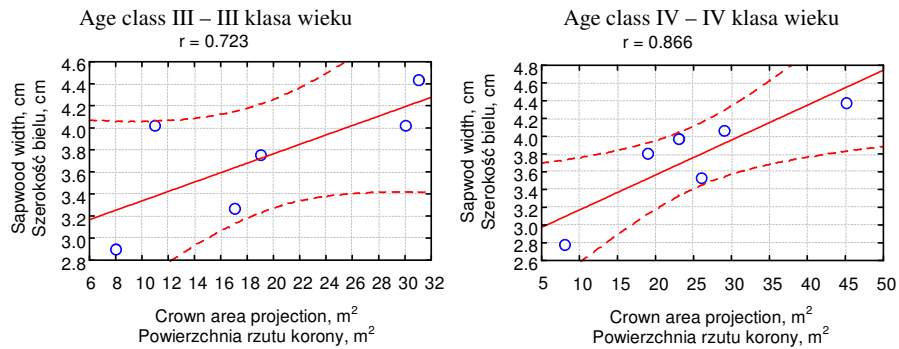


Fig. 7. Linear correlation between mean width of sapwood zone and crown projection area of common oaks representing two age classes (95% confidence interval)

Rys. 7. Korelacja liniowa pomiędzy średnią szerokością strefy biału a polem rzutu korony dębu szypułkowego reprezentującego dwie klasy wieku (95-procentowy przedział ufności)

## DISCUSSION

Internal wood structure is considered to be of great importance in wood industry. According to Jakubowski [2004], major elements of wood macrostructure affecting wood utilization include e.g. sapwood and heartwood. They are crucial both in case of softwood and hardwood species.

Many authors illustrate the proportions of sapwood and heartwood on the basis of the proportions of the volume of these wood macrostructural elements in tree stems [Krzysik 1978, Pazdrowski 1992, Jakubowski 2004]. Another important element, which may be useful in the quality appraisal of timber, is the radial proportion of sapwood and heartwood along the axis of a tree stem [Jelonek et al. 2006].

Jakubowski [2004] found that the volumetric share of heartwood in the tree stem in coniferous species increases markedly with the age of trees. A similar dependence was observed in this study where the share of heartwood volume in age class IV was bigger than in age class III.

A proportion of heartwood volume similar in terms of numerical values, although varying in individual cases, was observed in trees growing in fresh broadleaved forest in comparison to those from fresh mixed forest. The recorded slightly higher share of heartwood volume in stems of trees from fresh mixed forest is difficult to explain and differs from the results reported in studies on pine [Jelonek et al. 2006].

The irregular trend at different heights along the stem at the radius for sapwood and heartwood, observed in case of age class III, may result from the fact that common oak is a species which reaches the culmination of height and volume increments late and matures late. As it was reported by Jaworski [2004], the culmination of the current increment in height for oak takes places at the age between 30 and 40 years. Thus trees from age class III were cut during the most intensive increment in height and the biggest changes in terms of the affiliation to individual Kraft's social classes of tree position in the stand.

Time is undoubtedly a crucial factor in heartwood formation (a much more regular variation at the radius along the stem in age class IV than in age class III), which is consistent with observations reported by Hejnowicz [2002], although obviously other factors also play a role. These factors include the volume and efficiency of the assimilating organ, social class of tree position in the stand, tree genotype, latitude, forest site type as well as species-specific and individual traits, etc. This is manifested, among other things, in positive values of linear correlations between crown volume (a strong correlation) and the circular crown projection area (a strong correlation) and mean sapwood width at the radius in stems of common oaks.

Thus, between the conducting area (sapwood) and physiologically active crown there is a balance, which ensures the stability of the system, in which columns of water are moved in the xylem under tension caused by transpiration [Kacperska 2002]. Jelonek et al. [2006] found a strong effect of crown volume and area on the radial proportion of sapwood in Scots pine by calculating coefficients of determination.

Apart from the importance for pure science, the problem investigated in this study is also crucial for forest and wood sector practice. In-depth knowledge on factors affecting the formation of these two types of wood in stems of forest-forming species, especially still little investigated broadleaved species, may be used in the optimization of the utilization of timber and the size of both zones inside the stems in individual selection, and to promote further propagation of economically useful tree ecotypes.

## CONCLUDING REMARKS

1. A considerable irregularity was observed both in the proportions of sapwood and heartwood in volume and in the radial and axial distribution of these zones. This is manifested in major disproportions in the ratios of individual wood zones in stems.

2. In age class IV the proportion of heartwood volume and the share of heartwood at the radius were bigger than in age class III.

3. The highest share of sapwood at the radius in analyzed forest site types was recorded in trees from age class III growing in fresh broadleaved forest (28.19%), while the smallest in trees from age class IV growing in fresh mixed forest (24.54%).

4. The highest share of sapwood at the radius in individual Kraft's classes (32.47%) was found in common oaks from age class III representing Kraft's class III, while the lowest (22.48%) was recorded in trees from age class IV representing Kraft's class I.

5. A strong positive correlation was shown when analyzing the interdependence between mean width of the sapwood zone and crown volume in age class IV (+0.725). In age class III the interdependence of analysed traits was characterized by a lower power of correlation (+0.649).

6. A very strong correlation was observed when investigating the interdependence between mean width of the sapwood zone and the circular crown projection area in age class IV (+0.866), while in age class III it was a slightly weaker positive correlation (0.723).

7. Radial and axial variation was found in the proportions of both wood zones in stems of oaks growing in fresh mixed forest and fresh broadleaved forest, representing two age classes in view of Kraft's social classes of tree position in the stand.

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**ZMIENNOŚĆ OSIOWA I PROMIENIOWA UDZIAŁU BIELU I TWARDZIELI  
W PNIACH DĘBU SZYPULKOWEGO (*QUERCUS ROBUR* L.)  
W ZALEŻNOŚCI OD SIEDLISKA, KLASY WIEKU  
I POZYCJI BIOSOCJALNEJ**

**Streszczenie.** W pracy wykazano zmienność promieniową i osiową udziału bielu i twardzieli w pniach dębu szypulkowego wyrosłego w zróżnicowanych warunkach wzrostu. Analizowano uzyskany materiał badawczy, szukając czynników wpływających na nieregularność kształtowania się stref bielu i twardzieli w pniach drzew reprezentujących badane populacje. Na udział bielu i twardzieli w pniu oraz szybkość procesu twardzielowania wpływają rozmiary koron i efektywność transpiracji drzew, pozycja biosocjalna i warunki siedliskowe, na których wzrastają drzewa. Zróżnicowanie udziału bielu i twardzieli

występuje również pomiędzy klasami wieku. Wykazano duży wpływ rozmiarów koron na szerokość strefy bielu u drzew. Korelacje w tym wypadku były dodatnie w obu badanych klasach wieku, jednak w III klasie wieku słabsze niż w IV klasie.

**Słowa kluczowe:** dąb szypułkowy (*Quercus robur* L.), biel, twardziel, las mieszany świeży (LMśw), las świeży (Lśw), surowiec drzewny

*Accepted for print – Zaakceptowano do druku: 8.04.2008*

*For citation – Do cytowania: Szymański M., Pazdrowski W., Kaźmierczak K., Mańka K., Nawrot M., 2008. Axial and radial variation in the proportions of sapwood and heartwood in stems of common oak (*Quercus robur* L.) depending on site type, age class and social class of tree position. *Acta Sci. Pol., Silv. Colendar. Rat. Ind. Lignar.* 7(2), 45-58.*