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Application of a New Method to Select the Most Suitable Wood Species for Surface Densification

Benedikt Neyses[1], Dick Sandberg[2]

ABSTRACT: Surface densification improves many properties of solid wood, and opens up new applications for low-density species e.g. flooring or wooden structures, and adds value to these species. Research into the surface densification of wood has been focused mainly on Scots pine, Norway spruce, aspen and poplar. In order to propagate the use of surface densification techniques, it is necessary to find more wood species that have a particularly high potential for an increase in value through such a treatment.

The purpose of this study was to select wood species which are suitable for surface densification and for use in a specific product, by applying a systematic and quantifiable selection method. The method that was presented in detail in an earlier work, is designed around a workflow consisting of multiple stages, takes into account weighted selection criteria and provides a quantified ranking of the most suitable species.

The results suggest that several species such as alder, basswood, cedar, and obeche that have not previously been considered for surface densification may be suitable candidates. Aspen, poplar and pine were confirmed as suitable, being among the top species in the ranking.

KEYWORDS: Multivariate Data Analysis, House of quality, product development, Quality Function Deployment, wood

1 INTRODUCTION

Surface densification increases the hardness, bending strength, stiffness and surface abrasion resistance of solid wood, and the improvement of these properties increases the value of the wood, opening up new fields of application for low-density wood species, such as high quality wood flooring or specialty components for construction.

Research into the surface densification of wood has mainly focused on the densification process itself, testing different approaches or optimizing the parameters of the densification process. Rautkari carried out extensive studies into different methods to densify the surface of solid wood [1]. Even though a surface densification method that used friction was studied [2], most researchers densified wood in a non-continuous hot press. Laine studied the effect of the process parameters on the density profile and surface hardness [3] and other researchers showed that it is possible to reduce the moisture-induced set-recovery of the densified wood by adding a hydrothermal post-treatment stage [4-5].

Other studies investigated the moisture-related properties of surface-densified wood. Kutnar and co-workers [6] compared the wetting properties of densified and non-densified wood by contact angle measurements and calculations of the surface free energy.

Even though the literature contains many publications about surface densification, or the densification of wood in general, the variety of densified wood species is rather low. The majority of the studies focused on common low-density wood species such as Scots pine or Norway spruce. Other studies tested surface densification on aspen, poplar, or Douglas fir [7-10]. Although it is not a low-density species, densified beech was the subject of many studies,

[1] Benedikt Neyses, PhD student, Luleå University of Technology, Wood Science and Engineering, Skellefteå, Sweden Email: benedikt.neyses@ltu.se

[2] Dick Sandberg, Chaired professor, Luleå University of Technology, Wood Science and Engineering, Sweden. Email: dick.sandberg@ltu.se

in some cases as densified veneer rather than as solid wood [11-15]. In order to propagate the use of surface densification techniques, it is necessary to find more wood species which have a particularly high potential for an increase in value through such a treatment. However, it appears that studies focusing on this subject simply do not exist.

In a previous study by Neyses et al., a new approach was presented for the selection of suitable wood species for wooden products in a systematic and quantifiable manner [16]. The approach combines quality function deployment (QFD) and multivariate data analysis (MVDA) methods in a step-wise process that assesses the suitability of a variety of wood species with regard to the requirements of a specific product.

The objective of the present study was to adopt this wood species selection method to identify those hardwood and softwood species which are the most suitable for surface densification from a technological and economic perspective, and to evaluate in a quantitative way how the well-established wood species for surface densification perform.

2 MATERIALS AND METHOD

The wood species selection method consists of several steps: (1) determination of the relevant product/process requirements, (2) determining which wood properties are relevant with regard to the requirements, (3) preliminary selection of wood species that fit the relevant wood properties, and (4) benchmark scoring of the wood species to obtain a quantifiable ranking of the most suitable wood species, (Figure 1).

The second and fourth steps of the method are based on the so-called house-of-quality (HOQ) approach presented by Hauser and Clausing [17]. Technically, the third step is not necessary to obtain the benchmark ranking of the most suitable wood species. However, it shows the interactions between the relevant wood properties in a graphical way that makes it easier to understand why certain wood species reached a higher benchmark score than others. The benchmarking of the wood species is based on a large wood species dataset, containing the properties of 100 wood species. The specific values were taken from the literature.

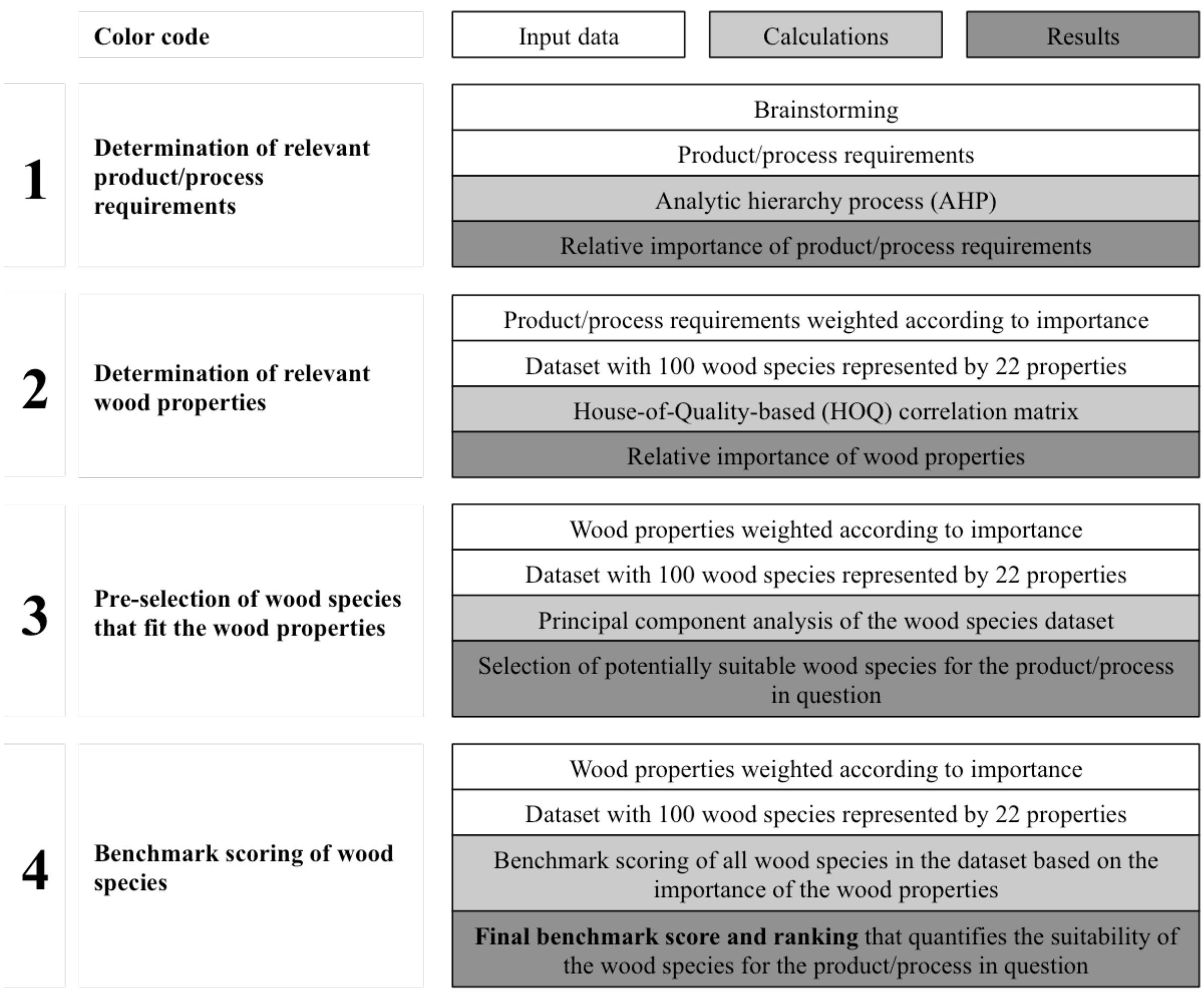

Figure 1: *Workflow of the wood species selection method*

In the following sections, the procedure for selecting the most suitable wood species for surface densification will be outlined in detail. Neyses et al. [16] presents the full description of the method.

2.1 WOOD SPECIES DATASET

The original wood species dataset used for the wood species selection method presented by Neyses et al. consisted only of hardwood species [16]. However, in the present study the goal was to select both hardwood and softwood species, and different wood properties than those found in the original dataset needed to be included.

For this reason, a new dataset was created for this study consisting of 100 commercially available hardwood and softwood species, represented by 22 properties. The data were taken from the Holzatlas by Rudi Wagenführ and from an online wood database [18, 19]. The data are based on average values for each species (Table 1). It was only possible to acquire data about the compressive strength parallel to the grain, even though the compressive strength perpendicular to the grain should be more relevant as it is the preferred direction of densification. The scales of all qualitative properties, such as “Texture”, “Availability”, or “Price”, were assigned so that a high value indicates a favourable manifestation of the property. Hence, a low-priced wood species receives a high value for the price property.

2.2 DETERMINATION OF THE MOST RELEVANT PROCESS REQUIREMENTS

In the first step, ten possibly relevant process requirements were determined through brainstorming. To assess the relative importance of each requirement, the so-called analytical hierarchy process (AHP) was applied. It consists of a matrix in which the importance of each requirement is assessed in comparison with every other requirement [20]. Different scales can be used to assess whether a certain requirement is more important to the densification process than another, and these can yield somewhat different results. For this reason, the AHP method was applied using a simple three-step scale (0, 1, 2), and a more complex seven-step scale (0.2, 0.33, 0.5, 1, 2, 3, 5). The final relative importance of each requirement was determined by calculating the average of the results from both assessment scales.

2.3 DETERMINATION OF THE MOST RELEVANT WOOD PROPERTIES

To determine the relevance of the wood properties, a correlation matrix as used in the well-established HOQ method was applied. With the help of a matrix, it is possible to assess how a certain wood property affects a certain process requirement. The assessment is made for all combinations of wood properties and process requirements. Countless different assessment scales can be used. In this study, a simple two-step scale (1= correlation or 0 = no correlation), a progressive scale (9 = strong correlation, 3 = moderate correlation, 1 = weak correlation, 0 = no correlation), and the average of the two scales were used.

2.4 PRELIMINARY DETERMINATION OF SUITABLE WOOD SPECIES WITH PRINCIPAL COMPONENT ANALYSIS

The third step of the wood species selection method has no influence on the final benchmark score. It is however useful to understand the interaction between the wood properties and to obtain a quick overview of those wood species which are potentially suitable for surface densification. This is achieved by performing a principal component analysis (PCA) on the wood species dataset and visualizing the scores and loadings via two-dimensional scatter plots. Superimposing the loading and score plots makes it possible to detect wood species that have favourable properties with regard to the surface densification process. The graphical presentation of the PCA data supports the understanding of how certain species reached their final score.

2.5 BENCHMARK SCORING AND RANKING OF THE WOOD SPECIES

To rank the wood species in a quantifiable manner according to their suitability for surface densification, a HOQ-based matrix system was used, as shown in Table 2. The properties of each species are normalized on a scale from 0 to 10. The minimum and maximum values of a certain property found among the species in the dataset are set to 0 and 10, respectively. The values of the other species for that property are adjusted accordingly. To calculate the final score, each normalized property value is multiplied by the importance of that property, and then added up row-wise. For example, the score of species A in Table 2 is calculated as: 9 x 20 + 6 x 10 + 2 x 30 + 5 x 40 = 500. After all scores have been calculated, the final ranking can be determined: the higher the score, the higher the final rank. The final scores were normalized, so that the highest scoring wood species had a score of 100.

Missing data for certain wood properties and wood species were assigned the lowest value found in the dataset for that property.

Table 1: *Overview of the properties by which the wood species are presented in the dataset*

Property	**Unit/scale**	**Description**
Origin	Continent	The continent on which the species is most frequently grown.
Vulnerability	Yes or No	Wood species that are vulnerable, endangered or close to extinction
Density	kg/m^3	Average dry density
Log diameter min	mm	Average minimum diameter of a harvested log
Log diameter max	mm	Average maximum diameter of a harvested log
Ratio max/min diameter	1	Ratio of the “Log diameter max” to the “Log diameter min”
Block size	mm	Average size of rectangular blocks/boards that are commercially available
Lignin content	%	Average percentage lignin content
Fibre orientation	1-5	1 = mostly irregular grain, 5 = generally straight grain
Texture	1-3	1 = coarse texture with open pores, 3 = fine texture
Pore arrangement	1-3	1 = ring porous, 3 = diffuse porous
Early-/latewood border	1-4	1 = distinct, 4 = invisible
Hardness	N	Average Janka hardness
Hardness/density	Nm^3/kg	“Hardness” divided by “Density”
Compressive strength	MPa	Average compressive strength parallel to the grain
Movement V	%	Average volumetric shrinkage between fibre saturation point and MC=0%
Movement T/R	1	Ratio of the shrinkage in the tangential to that in the radial direction between the fibre saturation point and MC = 0%
Drying properties	1-3	1 = difficult to dry, 3 = easy to dry
Surface treatment	1-3	1 = difficult to paint, stain, dye, etc., 3 = Easy to paint, stain, dye, etc.
Impregnation	1-3	1 = impossible to impregnate, 3 = easy to impregnate
Availability	1-4	1 = almost not available at all, 4 = regular availability in large quantities
Price	1-3	1 = expensive, 3 = cheap

Table 2: *Example of a benchmarking matrix. The properties of each species are normalized to a scale from 0 to 10. To calculate the final score, each normalized property value is multiplied with the importance of the respective property, and then added row-wise*

	Property 1	**Property 2**	**Property 3**	**Property 4**	**Score**	**Rank**
Importance of property [%]	20	10	30	40		
Species A	9	6	2	5	**500**	**3**
Species B	6	7	10	1	**530**	**2**
Species C	3	5	7	8	**640**	**1**

3 RESULTS

100 commercially available hardwood and softwood species were assessed according to their suitability for surface densification. In the following sections, the results from each step of the wood species selection method are presented.

3.1 DETERMINATION OF THE MOST RELEVANT PROCESS REQUIREMENTS

Table 3 shows the relative importance of the process requirements after brainstorming and application of the AHP method. The requirement of low material acquisition costs is the only one exhibiting a large difference between the two assessment scales used. For all other requirements, the two assessment scales yielded only slightly different results.

3.2 DETERMINATION OF THE MOST RELEVANT WOOD PROPERTIES

Table 4 shows the relative importance of the seven most important wood properties. In the case of “Vulnerability”, “Density”, “Lignin content”, “Hardness/density”, and “Price”, the two assessment scales gave significantly different results. For this reason, it was decided to run the benchmarking procedure with both scales and to average the scales. Because of its low importance and incomplete data, the property “Block size” was excluded from the calculation. The property “Hardness” was also excluded as it would yield misleading scores during the benchmark calculations. Instead, the ratio of hardness to density is more relevant.

3.3 PRELIMINARY DETERMINATION OF SUITABLE WOOD SPECIES WITH PRINCIPAL COMPONENT ANALYSIS

Figures 2 and 3 show the loading and score scatter plots of a simplified PCA model that excludes several wood properties that have a low importance. The model has a R^2 value of 0.533 and a Q^2 value of 0.251, meaning that it is of low quality and high uncertainty. However, the density, strength properties, price, availability and lignin content are modelled rather well with R^2 and Q^2 values of more than 0.5.

The strength-related properties are strongly correlated to the density, whereas “Price” and “Availability” are inversely correlated to the density. Hence, potentially suitable wood species are most likely located in the left-hand half of the score plot with a tendency towards the lower quadrant.

3.4 BENCHMARK RANKING OF THE WOOD SPECIES

The benchmark scoring was done several times in order to evaluate how the two different wood property assessment scales affect the final benchmark score (Table 5). With the average of the two scales, three runs of benchmark scoring were carried out initially. Additional scoring runs were carried out with the properties “impregnation” and “vulnerability” excluded. The former was excluded because of largely incomplete data, and the latter because it may have a strong effect on the final score without actually affecting the densification process from a technological and economic perspective. The simple assessment scale was misleading in a few cases, as weak correlations between certain requirements and wood properties have the same weight as very strong correlations. For this reason, this simple assessment scale was not considered for the scoring runs with excluded wood properties. Figure 4 shows an overview of the benchmark scores for some of the most suitable and most common wood species for surface densification of the six scoring runs.

Red alder had a perfect score in all the scoring runs, being ranked number 1 regardless of the assessment scale or the exclusion of wood properties. A comparison of the first three and last three scoring runs and an examination of the raw data show that the largely missing data of the property “Impregnation” has a strong effect on the final score. Some of the species that were used in previous studies into densification, such as beech or spruce reached rather low scores compared to the top-scoring species, such as red alder, incense cedar, and Scots pine.

Table 2: *Relative importance of the surface densification process requirements. Percentages greater than 10% indicate at least a moderate importance of the requirement*

Requirement	Relative importance, two-step scale [%]	Relative importance, seven-step scale [%]	Relative importance, average of the two scales [%]
High densification potential	15	16	**16**
High potential for hardness increase	15	17	**16**
High material consistency within species	2	4	**3**
High material homogeneity within one piece of wood	4	5	**5**
Low acquisition costs	14	9	**11**
Material easy to acquire	7	7	**7**
High shape stability in changing climate conditions	4	3	**3**
Low environmental impact when using the material	15	17	**16**
High potential for plastic deformability	15	14	**15**
Easy to stabilize the compressed wood cells	9	9	**8**

Table 3: *Relative importance of the seven most relevant wood properties*

Wood property	Relative importance, simple scale [%]	Relative importance, progressive scale [%]	Relative importance, average of the two scales [%]
(Low) Vulnerability	12	7	**9**
(Low) Density	24	14	**19**
(High) Lignin content	6	10	**8**
(High) Hardness/density	8	14	**11**
(Easy) Impregnation	7	5	**6**
(High) Availability	8	9	**9**
(Low) Price	8	5	**7**

Table 4: *Overview of the benchmark scoring runs. The lowest score of all the wood species gives an indication of the variation within the benchmark scores. The lower the value, the higher/better the spread*

Benchmark scoring run	Wood property assessment scale	Excluded wood properties	Lowest score of all wood species
1	Average of the two scales	-	46
2	Simple scale	-	54
3	Progressive Scale	-	38
4	Average of the two scales	Impregnation	50
5	Average of the two scales	Impregnation, Vulnerability	59
6	Progressive Scale	Impregnation, Vulnerability	51

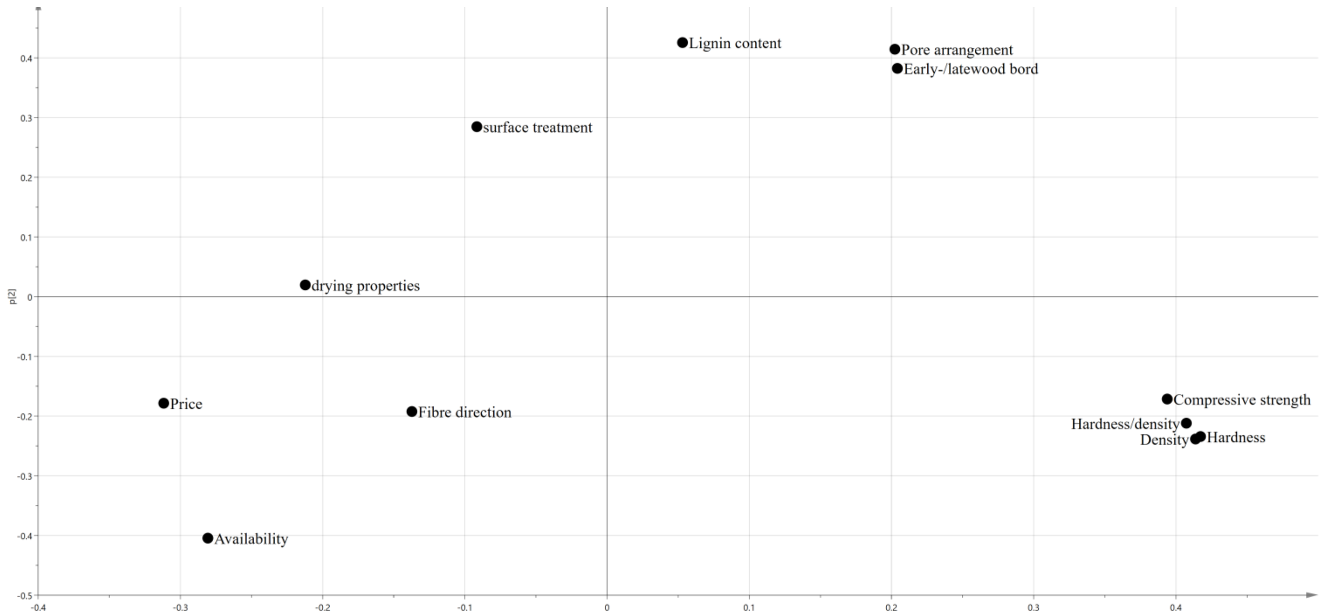

Figure 2: Two-dimensional loading scatter plot of a simplified principal component analysis (PCA) model with several wood properties excluded. Wood properties close to each other are strongly correlated

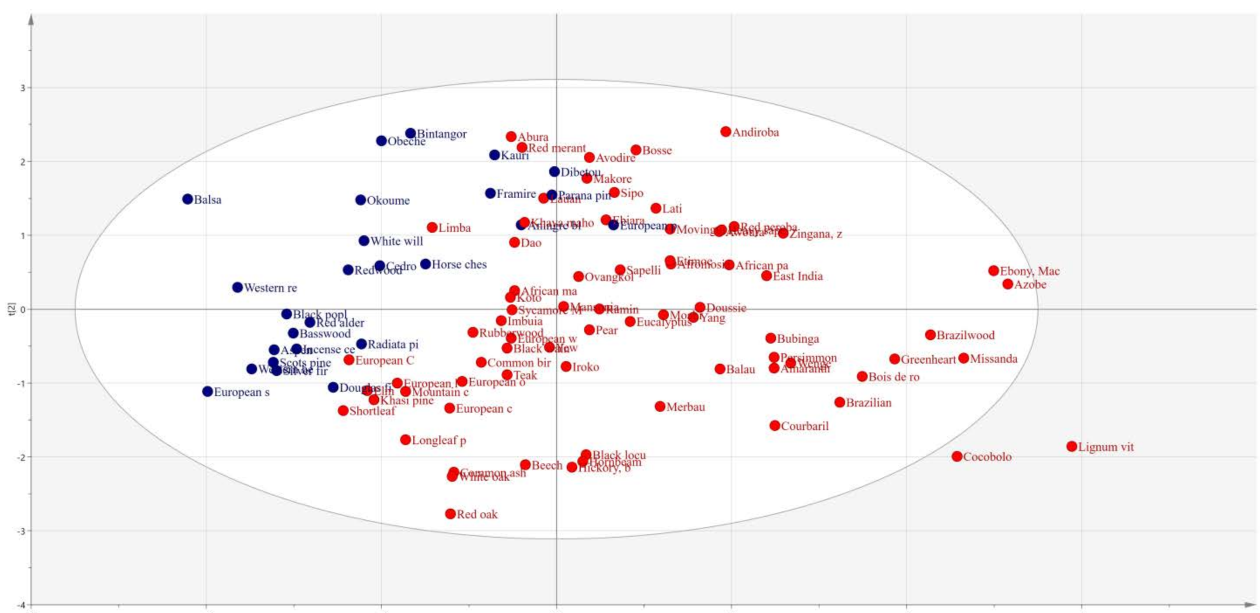

Figure 3: *Two-dimensional score scatter plot of a simplified principal component analysis (PCA) model with several wood properties excluded. The wood species are coloured after density. Blue dots indicate a density of 550 kg/m^3 or less, and red dots a density greater than 500 kg/m^3*

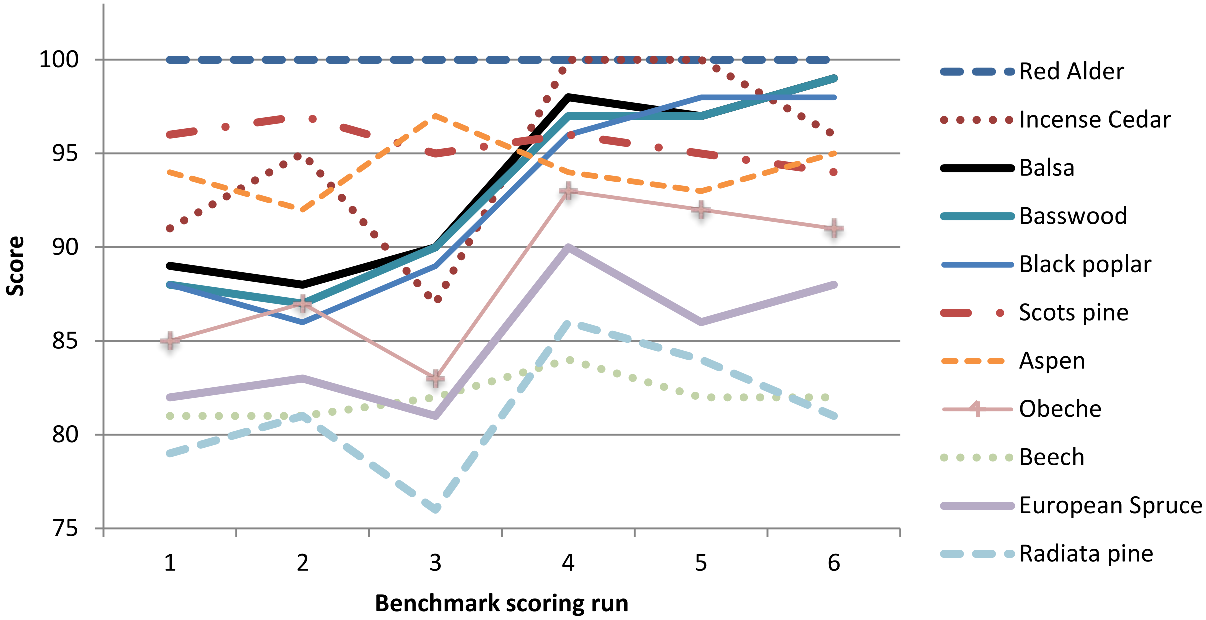

Figure 4: *Benchmark scores of some of the most suitable wood species for surface densification for the tested benchmark scoring runs listed in Table 5*

4 DISCUSSION

The assessment of the suitability of hardwood and softwood species for surface densification yielded moderately robust results. With one exception, the two scales used to determine the importance of the process requirements provided almost identical results. Even though the impact of different assessment scales on the importance of the wood properties was strong, the final benchmark scores were not affected as severely. Red alder reached the highest score during all scoring runs. Other species such as Scots pine, cedar, and aspen reached different ranking positions in different scoring runs, but were always among the top scoring species. An examination of the raw data in the wood species dataset revealed that the top ranking species scored consistently well for the most important properties and had at least moderately good scores for all other properties. Several exotic species, such as Avodire suffered from their vulnerability. Once this property was excluded, these species reached significantly higher scores.

Some species, which were used for surface densification in previous studies, scored moderately well, but perhaps not as high as expected. Examples are beech and spruce. Especially in the case of spruce, this may seem to be surprising. An examination of the raw data reveals that the species has a low ratio of hardness to density and a low lignin content. Beech suffers mainly from its high density. Several top-scoring species, such as alder, cedar and basswood, cannot be found in the literature in the context of surface densification.

An examination of the effect of the wood property assessment scales on the final ranking of the wood species showed that the progressive scale results in a larger spread of the benchmark scores than the simple scale. Generally, a wide spread of the scores is desired to establish a clear ranking of the wood species. However, wrong assessments of the wood properties with the progressive scale have a greater chance of leading to misleading benchmark scores. The simple scale has the problem that is favourer weak correlations between the wood properties and process requirements and may misrepresent reality. A wood property that is weakly correlated to many requirements achieves a greater importance than a wood property with strong correlations to only a few requirements. For this reason a *best of both worlds* approach was chosen by calculating the final benchmark score from the average results from the two wood property assessment scales.

The most difficult part of the wood species selection process was deciding how to handle some of the wood properties. The property “Impregnation” was moderately important according to the wood property assessment, but data was missing for many wood species. As species with missing data were assigned the lowest value found in the dataset for that property, the final benchmark ranking did not accurately represent reality. Collecting the missing data from other sources can resolve the issue in the future.

The property “Vulnerability” was also problematic. On the one hand, it is fairly important, and is generally an important aspect to consider in the world we live in. On the other hand, it has no impact on the process and the resulting product, either from a technological, or from an economic perspective. One can argue that even vulnerable or threatened wood species can be used legitimately if care is taken to ensure that the wood is harvested in a sustainable way. For this reason, two scoring runs were executed after excluding the property from the dataset.

Using PCA to make a preliminary selection of potentially suitable wood species was almost superfluous, due to the rather low quality of the PCA model. Nevertheless, it was valuable to show that a low price and high availability are inversely correlated to the strength properties.

5 CONCLUSIONS

The objective of this study was to find new species which are suitable for surface densification and the resulting products, and to evaluate the suitability of well-established species in this context. Based on the result of the wood species selection method, the following conclusions can be drawn:

- All of the well-established wood species for surface densification achieved a fairly high score, confirming their general suitability. However, beech and spruce were outside the top-ten scoring species.
- Several alternative wood species, some of them easily available in the developed parts of the world, reached high benchmark scores, suggesting their suitability for surface densification.
- Throughout the wood species selection method, several scale-based assessments are carried out. To increase the robustness of the results, it is necessary to examine the impact of different assessment scales on the final results.
- The PCA-based preliminary selection of wood species should be viewed as a supplementary but non-essential step in the wood species selection method.
- The whole approach presented in this study can be improved by adding more data to the wood species dataset, both by filling in missing data and by adding more wood species.

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