A STRATEGY FOR INDIGENOUS WOOD ARCHITECTURE

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ABSTRACT

The wood architecture narrative is an important link in carbon reduction of the building sector. However, upscaling wood production and shifting to high-value application is impeded by poor resilience and quality of coniferous production forests in the Netherlands. This research aims to explore the potential for indigenous deciduous wood production and application in load-bearing constructions. A pilot location was chosen, for which through a literature study, an ideal indigenous forest prototype could be theorized. Recommended management methods helped to infer the resulting yield and wood dimensions for such a forest. With technical literature and a comparative analysis of mechanical properties, the resulting wood types (Black Alder, European Ash, European Beech, Hornbeam and Summer Oak) were attributed various possible applications in construction. It was concluded that there is potential for a strategy for indigenous wood architecture.

KEYWORDS: *Timber construction, Indigenous trees, Production forestry, Deciduous wood, Architecture*

I. INTRODUCTION

1.1. Problem Statement

Wood construction is an important pathway to reduce the carbon emissions of the building sector. The unilateral standardization of the wood chain however impedes the aspirations to upscale wood production and shift more resources to high-value applications.

Most wood construction methods in the Netherlands are adapted to coniferous wood, provoking local forestry of exotic tree species such as spruce, douglas and larch. As a consequence, Dutch forests are less resilient in the face of climatic extremes and therefore more susceptible to calamities (Van Kemenade et al., 2021). In addition to the resulting ecological impact due to poor resilience, annual reports by Oldenburger et al. (2022; 2023) and Teeuwen et al. (2024) show a 35% decline in national wood production since 2016, which can partly be attributed to drought and disease (Staatsbosbeheer, 2022). Moreover, our forests tend to yield lower quality coniferous wood, as such species are not well adapted to the Dutch climate (Fraanje, 1999), which may also explain why the Netherlands is barely 6% self-sufficient in its material wood production, and relies mostly on import (Probos, n.d.). Meanwhile, there is little attention for production of quality indigenous deciduous wood, making high-value application difficult. For example, approximately 80% of locally cut deciduous wood is currently used as firewood (Oldenburger et al., 2020).

To conclude, within the existing wood production framework, upscaling local production is undesirable and a mass shift to higher-value applications is unlikely. To overcome this obstacle, it is necessary to rethink the framework and to explore the potential for indigenous wood production and - construction.

1.2. Scope

This thematic research is part of a larger graduation project. In this project, the *national termination policy of livestock farms with peak loads* is proposed as an opportunity to increase local wood production, create public recreational space and simultaneously regenerate nature. The *Stedendriehoek* region in Gelderland was chosen as a pilot location, because its policy documents (Regio Stedendriehoek, 2023) align with the scope of this graduation project and because of its proximity to vulnerable Natura-2000 reserves, where by definition most peak polluters reside. The thematic research is also limited to this location, although the methodology ought to be replicable in other locations.

The goal of this thematic research is to investigate the potential of an alternative strategy for indigenous wood production, suitable for implementation on the project location, based on an ecosystem-to-building-system approach. Firstly it is essential to know the parameters of a desirable ecosystem for the location, which will be the starting point for this approach. From this, it should be possible to infer productive qualities, such as rotation period, and product volume. This would contribute to resolving the problems associated with upscaling national wood production. Finally, the possible applications for the resulting wood products in construction will be explored, in order to illustrate the potential for a high-value indigenous wood chain. Engineered wood products (EWP) are left out of scope.

One dilemma in this project is the slower growth-rate of some indigenous tree species compared to exotic species, limiting the feasibility of an alternative wood production strategy. This obstacle will not be ignored in this paper, however the exact solution, if there is one, will be further developed in the overall design. This paper will focus mainly on the production and use of quality indigenous wood.

1.3. Research Questions

To what extent is there potential to create new production forests with an alternative strategy for wood production and - application, adapted to the properties of indigenous tree species?

This research question can be divided into four sub-questions, each representing a link in the wood chain:

1. *What are the parameters of a desirable indigenous forest on the project location?*
2. *What are the appropriate management methods for such a forest?*
3. *What types, volumes and dimensions of wood can such a forest yield, and in what timespan?*
4. *How can these wood types be efficiently utilized in load-bearing constructions?*

II. METHODS

2.1. Developing the Forest

The desired composition of an indigenous forest will be derived from a comparative analysis of field research and inventories on old indigenous forests close to the project location. The first referenced source is a review of historical documentation of plant findings in the last primeval forest of the Netherlands, the *Beekbergerwoud*, by vegetation scientist Eddy Weeda (2014). Secondly, Maes & Van Loon (2011) inventoried seed sources of indigenous species within proximity of the former *Beekbergerwoud*. Rövekamp & Maes (2002) previously did a similar inventory across the *Veluwe*. Both reports were aimed at exploring the potential for reinstating indigenous nature close to the project location, and thus provide valuable recommendations on forest recovery and - management. Lastly a map from the *Atlas van Nederland* shows the potential natural vegetation through succession (Stichting Wetenschappelijke Atlas van Nederland, 2001).

Species that were mentioned in at least three of the referenced sources are labeled as characteristic species for the desired indigenous forest prototype. If useful, these species can be felled as part of the new strategy. Species that were mentioned in only two of the sources, or deemed threatened by an attention list by Van Kemenade & Maes (2024), are included solely for ecological purposes. Herbaceous plants, grasses and mosses are mostly left out of scope for this research. The origin of all species is double-checked with an online tool by Royal Botanic Gardens Kew (n.d.).

With a list of indigenous species, it is possible to construct a forest complex suitable for the project location. The encyclopedic website of Ecopedia (n.d.a; n.d.b) and additional sources are consulted to determine the required abiotic factors and landscape qualities. This section concludes with an indigenous forest prototype as an answer to the first sub-question.

2.2. Finding Appropriate Management Methods

In this section, appropriate management methods will be selected for the prototype forest, taking into account the desired multifunctionality for the graduation project. Methods for stocking, thinning and harvesting, will be chosen based on literature by forestry experts such as Simon Klingen (2021), as well as other complementary sources and silvicultural guides.

2.3. Inferring the Yield and Dimensions

The yield and dimensions of the different wood types that result from the chosen management methods are hard to determine accurately, as they depend greatly on environmental qualities. Therefore, assumptions will be made, based on literature by Peter Fraanje (1999), data from the wood database of Centrum Hout (n.d.), and other sources. Through the theoretical mean annual volume increments (MAI) and the rotation periods of the tree species, the yield in cubic meters usable wood can be calculated. Additionally, several forestry reviews were found that give insight into the dimensions of the felled trees.

2.4. Wood Application in Construction

Peter Fraanje (1999) ends his book, *Natuurlijk bouwen met hout*, with a matrix for possible applications of 33 types of wood. Construction is mentioned as a relatively unspecified option in this matrix. The goal of this last section is to expand upon this matrix, and add more specific load-bearing construction applications for the different wood types.

To this end, the literature by Fraanje (1999) will be used alongside complementary research on wood application, archeological research, and an analysis of mechanical properties based on data derived from the Granta EduPack 2024 by ANSYS (2024) and the wood database of Centrum Hout (n.d.). Mechanical properties taken into account for this analysis are: Young’s modulus, bending -, tensile -, compressive - and (parallel and perpendicular) shear strength. This analysis will indicate what loads the different wood types can or cannot resist, which in turn implies specific applications in construction. Limitations such as durability and dimensions, will also be considered.

III. RESULTS

3.1. Forest

The former 1,5 km^2 *Beekbergerwoud* is a reliable source for selecting truly indigenous vegetation for the project location, as it reached its climax ecosystem isolated from human intervention (Weeda, 2013). Weeda (2014) categorizes the collected documentation into three forest systems: Alder swamps, humid deciduous forests and dry deciduous forests on horsts. Species within these systems comply with theorized climax systems on the project location as mentioned in *Atlas van Nederland* (Stichting Wetenschappelijke Atlas van Nederland, 2001), as well as more modern inventories by Rövekamp & Maes (2002) and Maes & Van Loon (2011). By comparing these sources, a list of species could be created for an indigenous forest on the project location.

The characteristic species that have been selected for production purposes through the criteria mentioned in paragraph 2.1 are: Black Alder (Alnus glutinosa), European Ash (Fraxinus excelsior), Hornbeam (Carpinus betulus), European Beech (Fagus sylvatica) and the Summer Oak (Quercus robur). These species can be categorized with affiliated species, into three forest types, ranging from wet, light forests (Type 1) to dry, shady forests (Type 3), similar to the structure by Weeda (2014). These systems, summarized below, can also be found in the appendix (appx. A).

Type 1
Forest type 1 is characterized mostly by Alder. Due to similar growing conditions, the Ash, the indigenous Bird Cherry (Prunus padus) and the Black Currant (Ribes nigrum) are found there as well. This system is preferably situated near flowing water, on lower rich soil types (Ecopedia, n.d.a; n.d.b). Alder and Ash, both fast-growing and light-demanding species, can be felled for production (Fraanje, 1999). Black Currant can be harvested in early stages of development.

Type 2
The Ash is also found in forest type 2, in combination with the Summer Oak. This forest is mostly a gradient between forest type 1 and type 3. It also houses Bird Cherry, as well as Ivy, Honeysuckle, and the Hazel from the dryer forest type 3. Other species include Dogwood, Hawthorn, Spindle, and Guelder Rose. The soil must be humid, rich and well-draining (Ecopedia, n.d.a; n.d.b). Ash and Oak can be felled for production (Fraanje, 1999) and hazelnuts can be harvested in earlier stages of development. The European Maple (Acer pseudoplatanus) may also belong in this forest type, although due to its disputable origin (Weeda, 2014; Royal Botanic Gardens Kew, n.d.) it will not be further included in this research.

Type 3
The dry deciduous forest consists of Oak, Beech and Hornbeam. The Winter Oak (Quercus patraea) is also added to this landscape as recommended by Rövekamp & Maes (2002), although this threatened species will not serve for production. Other species include the Hazel, Ivy, Holly, Honeysuckle and Dog Rose. The forest is situated on higher, dryer grounds, as in the *Beekbergerwoud* (Weeda, 2014; Ecopedia n.d.a; n.d.b). A high density is recommended for tall and straight Beech trees (Fraanje, 1999). The Summer Oak, Beech and Hornbeam can be felled, and hazelnuts can be gathered in earlier stages.

3.2. Management

Development
Veen & Berris (1994) reviewed the approach of *Natuurmonumenten* for the recovery of two reserves on farmland, including the new *Beekbergerwoud*. Although *Natuurmonumenten* prefers spontaneous development from nearby seed-sources, they do not rule out planting when necessary. The Common Ash (Fraxinus excelsior) for example has insufficient seed-sources in proximity to the project location, and must be gathered elsewhere (Maes & Van Loon, 2011). Additionally, undesirable species or varieties may naturally spread into the forest (Veen & Berris, 1994), which can be another reason to prefer planting over spontaneous development. Other than that, *Natuurmonumenten* limits its intervention to the creation of appropriate abiotic qualities, by damming up draining ditches and removing fertilized topsoil (Veen & Berris, 1994).

Stocking
Production forests are stocked with thousands of stems per hectare and thinned until only a hundred *potential crop trees (PCTs)* remain before felling. PCTs are selected for their health, vigor and form, ensuring optimal qualities for the final harvest (Short & Radford, 2008). Ash and Alder can be initially stocked with 2500-3300 stems/ha, Oak with 2000-5000 stems/ha, and Beech around 4400-6600 stems/ha (Löf et al., 2015; Short & Radford, 2008; SWS Forestry Services, 2016). No information could be found on Hornbeam stocking (or thinning).

Thinning
Thinning limits natural losses (Tomter et al., 2016), benefits the health of the stand, ensures optimal conditions for the PTCs, promotes diameter growth, and provides periodic income (Short & Radford, 2008). Tending (removal of unfavorable trees) takes place when a stand reaches an average height of 8 meters. Thinning occurs upward from 10-15 meters (Short & Radford, 2008), or at 30-40 years old (Fraanje, 1999), depending on the species. After about 40 years and several

thinning operations, at least for Oak species, only around 500 stems/ha should remain (Löf et al., 2015). Before the final felling, 60-80 Ash (and probably Alder) and 100 Oak (and probably Beech) stems should remain. (Dobrowolska et al., 2011; Löf et al., 2015).

Cutting

Selective cutting is often deemed the most ecologically friendly method compared to clearcutting. Simon Klingen (2021) however poses that group-cutting may offer the best of both worlds, as it negates organizational complexities of selective cutting, whilst limiting the negative ecological impact of areal cutting. Additionally, this method mimics the naturally occurring landscape due to windthrow or disease. Mohren et al. (2015) analyzed different cutting methods, and drew similar conclusions. They claim that cutting groups of >0,25 hectares results in rejuvenation of more light-demanding species, whilst smaller groups result in rejuvenation of shade-demanding species. Due to its flexibility, this cutting method is chosen as an appropriate method for the indigenous production forest prototype.

3.3. Yield

Ranges for productive qualities and dimensions of the five different tree species were retrieved from several sources, and compiled into Table 1. These values will vary greatly based on growth conditions in practice.

Table 1. Rotation period, volume increment and dimensions for five wood species

Species	**Rotation period**	**Increment**	**Stem height (m)**	**Diameter (m)**
Black Alder *A. glutinosa*	40-60 [y] [1]	6,0-8,4 [m^3/ha/y] [1]	15-25 [1,6] Clear: 6-12 [1,6]	0,3-1,2 [1,6]
European Ash *F. excelsior*	60-75 [y] [1,2]	7,4-8,6 [m^3/ha/y] [1,2]	20-30 [1,2] Clear: 15-20 [1]	0,3-0,6 [5]
European Beech *F. sylvatica*	50-80 [y] [1]	5,0-5,7 [m^3/ha/y] [1,4,5]	20-30 [1,5,6] Clear: 9-15 [1,6]	0,2-0,5 [1,5,6]
Hornbeam *C. betulus*	30-80 [y] [1]	4,4-6,8 [m^3/ha/y] [5]	10-25 [1,5,6] Clear: 5-13 [1,5,6]	0,2-0,4 [1,5,6]
Summer Oak *Q. robur*	120-150 [y] [1,3]	4,0-6,3 [m^3/ha/y] [1,4]	25-30 [1,3,6] Clear: 6-8 [3]	0,6-0,7 [1,3]

Note: 1. (Fraanje, 1999) ; 2. (Dobrowolska et al., 2011) ; 3. (Löf et al., 2015) ; 4. (Baeté et al., 2002) ; 5. (Iliev et al., 2022) ; 6. (Centrum Hout, n.d.)

The *increment* in Table 1 refers to stemwood with bark, measured from ground level to the end node, excluding branches (Lerink, 2023). These numbers likely refer to the final felling volume, divided by the rotation period. Given the stem dimensions, this roughly complies with the approximate 100 PCTs after all thinning operations (Short & Radford, 2008). The Gross Annual Increment (GAI) consists of the final felling, thinning operations and natural losses. Natural losses can be kept as low as 5% of the GAI, with heavy thinning of 35% (Tomter et al., 2016). This means that the volume of the final felling, the *increment* in Table 1, is around 60% of the GAI.

With the numbers above, it is possible to estimate the yield per tree species per hectare of our forest prototypes. This yield also depends on the share that each tree species has in the total area. The formulas and an example calculation will be presented below.

$V_F = I \cdot t \cdot A_{sp}$ & $V_T = V_F \cdot 35/60$

Where V_F is the volume of final felling in [m^3], V_T is the volume of all thinning operations in [m^3], I is the annual increment in [m^3/ha/y] (see Table 1), t is the rotation period in [y] (see Table 1), and A_{sp} is the share of that species in the total area in [%]. The term *35/60* (may also be *35/55*) is derived from the share each volume has in the GAI, as stated by Tomter et al. (2016).

Example
Given forest type 2, with an assumed 50% Ash and 50% Oak under optimal growing conditions, the yields can be estimated. After 75 years, 320 m^3 (V_F = 8,6·75·0,5) Ash wood can be felled, which is approximately 60-80 logs with a diameter of 0,55-0,6 m, and a length of 17-19 m. In those 75 years, thinning resulted in another 180 m^3 (V_T = 320·35/60) Ash wood with smaller dimensions. After 150 years, 470 m^3 (V_F = 6,3·150·0,5) Oak wood can be felled, which is roughly 100 logs with a diameter of 0,7 m, and a length of 12 m. Thinning operations resulted in another 270 m^3 (V_T = 470·35/60) Oak wood with smaller dimensions. With a sustainable management cycle, this would result in an annual yield of 6,7 m^3/ha Ash wood, and 4,9 m^3/ha Oak wood. Similar calculations with other assumptions can be found in the appendix (appx. B).

A sustainable management cycle takes time to establish, as the time for rejuvenation should be considered. If harvests in forest type 2 take place every 25 years, then each harvest only 1/3 of the Ash area and only 1/6 of the Oak area can be felled to allow for the required regrowth time before the next felling. This limitation should be carefully considered in the planning of the project, as it affects the timespan for the return of investment.

3.4. Application

As mentioned in paragraph 2.4, the goal is to explore potential applications of the resulting wood types in construction. The matrix by Fraanje (1999) is taken as a starting point, and expanded upon with newer literature and a comparative analysis of mechanical properties. For this analysis, data from ANSYS (2024) and Centrum Hout (n.d.) is plotted in graphs (appx. C), together with the Eurocode strength classes retrieved from an information sheet by Centrum Hout (2017). These classes define property values based on rigorous testing and appropriate safety margins. The raw test data from ANSYS (2024) and Centrum Hout (n.d.) merely serves to compare individual properties of the wood types. They are by no means suitable as design guidelines. The findings are presented per wood type below, and compiled in a matrix in the appendix (appx. D).

Black Alder (Alnus glutinosa)
Alder wood is best suited for production of particle boards or poles and foundation piles. For millennia, it was used in mines, foundations and waterworks (Fraanje, 1999). Round and square piles up to 35 cm have been found on Roman military sites (Hänninen, 2019). In Ireland, fish-weirs were made from 40 year old Alder (Daly, 2024). Alder should be cut in winter and ventilated in storage. Its lack in strength can be compensated by making plywood (Reh et al., 2024). The wood itself is soft, has a high moisture content, and is quickly affected by fungi and insects, ruling out exterior application (Centrum Hout, n.d.). However, Alder can be watered for up to a year after felling, resulting in easier processing, increased durability and hardness, and fewer defects after drying (Fraanje, 2000). Results from the comparative analysis (appx. C) show that Alder has the worst mechanical values of the five wood types. Especially bending - and shear strength are low. Tensile - and compressive strength are comparable to Ash wood. For functions subjected to bending - and shear loads, such as for long-spanning beams or joints, Alder wood is not an ideal choice. For smaller elements in trusses, loaded in pure tension or compression and especially for zero-force members, Alder seems a fine option.

European Ash (Fraxinus excelsior)
The European Ash can be felled with large dimensions, although a short rotation period is recommended to prevent defects (Dobrowolska et al., 2011). The wood is underappreciated in construction, as its potential, especially for joists and beams, was surpassed by steel. In fact, metal

parts of tools and vehicles were previously often made from ash wood (Fraanje, 1999; Medović, 2021). It is also relatively affordable and easy to process, although it is less durable and susceptible to fluctuations in humidity and exposure to sunlight (Elkhaddar, 2024; Lignoma, n.d.). These issues depend on the drying process, the time of cutting, and may be overcome by watering the Ash first (Fraanje, 1999; 2000). The comparative analysis (appx. C) shows that the tensile - and compressive strength of Ash wood is comparable to that of Oak and Beech. Ash however excels in its elasticity, bending - and shear strength. It therefore seems ideally suited for long-spanning beams, lintels and floor joists, as well as for joints and dowels.

European Beech (Fagus sylvatica)
The comparative analysis (appx. C) shows that Beech wood performs well in all mechanical properties. It can be labeled as a universalist, although its utility is limited by low durability and high deformation (Pramreiter & Grabner, 2023). Both issues can however be avoided by steaming or watering the wood for up to a year after felling in the winter (Fraanje, 1999; 2000). It is also possible to improve the properties of the wood with high pressure and temperature (Centrum Hout, n.d.; Fraanje, 1999). It was used by the Romans in construction and shipbuilding as a lighter and more regular alternative to Oak (Medović, 2021). For good quantity and quality, Beech should be quarter-sawn or cant-sawn (Popadić, et al., 2014; Vilkovský, et al., 2023). Beech may be especially suitable for elements loaded in compression, for which a slenderness ratio of 1:50 (radius / effective length) is recommended (Koczan & Kozakiewicz, 2016).

Hornbeam (Carpinus betulus)
Before iron and steel, Hornbeam was used in parts for machinery and vehicles. It is still used as dowels and joints, however its use in construction is up for debate. (Fraanje, 1999). The analysis of mechanical properties (appx. C) shows that Hornbeam is tougher than the other wood types, especially excelling in bending, compression and tension. Moreover, it does not split or splinter easily (Centrum Hout, n.d.). Hornbeam however is claimed to be of poorer quality than Beech or Oak, due to its twisted trunk and many branches (Medović, 2021; Fraanje, 1999). Tests with representative samples resulted in mechanical performances slightly below that of Beech wood (Taj et al., 2009). Nevertheless, Hornbeam was used in the structure of a Roman theater (Medović, 2021), in traditional Romanian timber frame houses (Dutu, 2021), and as floor joists and bearers in 19^{th}-century houses in Istanbul (Ergun & Schuller, 2021). It is concluded that Hornbeam is suitable for heavily loaded elements of small dimensions.

Summer Oak (Quercus robur)
Of the five wood types, Oak is the most common in foundations and construction. This can be attributed to its aesthetics, low number of defects and high durability, which can increase even further by watering for up to four years (Fraanje, 1999; 2000). Oak was used often in corbels and (curved) beams in floors, trusses and roof construction. Many examples exist in monumental buildings in Amsterdam. However, the wood was partly outcompeted by Pine (Van Tussenbroek, 2022). Quarter-sawing Oak wood with the Slovenian method offers the best value yield (Smajic et al., 2023). Pre-drilling is recommended, and in contact with metals, corrosion can occur. According to the comparative analysis (appx. C), Oak, just like Beech, slightly outperforms most coniferous wood types. It is universally suitable for many applications (Centrum Hout, n.d.).

IV. CONCLUSIONS

4.1. Answering the Research Questions

There appears to be great potential for an alternative strategy for wood production. Comparing historical and contemporary documentation and inventories proved to be a successful method to identify a list of indigenous species and landscape types. Additional atlas material, articles and online encyclopedias helped to describe the species combination and abiotic qualities for three forest prototypes (appx. A). It was concluded that five tree species would exist within these forests, that can be felled for production: Black Alder, European Beech, European Ash, Hornbeam and Summer Oak. Based on further research into silvicultural literature, it was possible to select appropriate management methods and to theorize the rotation period, dimensions and maximum yield for each tree, and thus for each forest prototype (see Table 1 and appx. B). The resulting numbers are slightly proud of current gross volume increment of existing forest stands in the Netherlands. An explanation is that these maximum yields (appx. B) simulate pure production forests with 100% felling. In reality, to be considered a multifunctional forest, these yields need to be reduced to 80% felling (Schelhaas et al., 2018).

Efficient theoretical construction applications were found for each resulting wood type, based on extensive technical and archeological literature and a comparative analysis of the mechanical properties (appx. C). The results were compiled in a matrix (appx. D), which can be seen as an expansion upon an already existing matrix by Peter Fraanje (1999). It can be concluded that Beech and Oak wood can be applied relatively universally. Ash and Hornbeam perform exceptionally well in joints or as elements under bending loads, although the Hornbeam will most likely not produce large dimensions. Alder wood is most suitable for foundation, waterworks and sheet material. Additionally it was suggested that Alder may be a good candidate for elements in trusses.

4.2. Discussion and Recommendations

Qualities and applications of several wood types, especially Hornbeam, were hard to determine for construction purposes. It can be concluded that there is a knowledge gap and lack of appreciation for Dutch deciduous wood in construction, which can for a great part be attributed to low durability and high warping and shrinkage. Processing methods such as watering and steaming however are claimed to significantly limit these problems (Fraanje, 1999). Watering would also reduce cracking whilst drying the wood, resulting in a higher valued yield and possibly in better characteristic mechanical properties (Fraanje, 2000; Van Benthem & Teeuwen, 2018). Thorough testing of this method is therefore recommended. Perhaps it is even desirable to include a new strength class category, similar to the category for laminated wood, for watered wood in the Eurocode.

Another aspect that can be considered when applying indigenous hardwood species in construction is the time factor. In order to be fully circular, the lifespan of the structure should ideally match or exceed the increment of the forest it came from. For example, if a structure contains 240 m^3 processed Ash wood (final felling), milled with 80% efficiency, originating from a small 5 hectare Alder swamp forest Type 3 b (appx. B), this wood should be in use for at least 27 to 32 years, (300 m^3 divided by 5 times the annual increment of 1,9-2,2 m^3/ha). During that time, the forest would theoretically be able to re-accumulate that material. If this lifespan cannot be reached, the designer ought to think about challenges such as disassembly, reuse and the possible cascading pathways of the material.

When designing a load-bearing structure with indigenous wood species, Table 1, Appendix B and Appendix D can be used as a guide. From these matrices it is possible to derive indicatory dimensions, increments and suggestions for the efficient application for the five wood species that were studied in this research.

Lastly, due to time constraints, this research was focused on one specific area within the Netherlands. Analyses of other areas will likely yield different results, based on their respective desirable indigenous forests and the qualities of the resulting wood. My hope is that, in the future, other areas will be studied in a similar way. Additionally, this research remains purely theoretical, based on existing literature and data. Due to the many variables within wood production, processing and utilization, more practical studies are required to assess the potential for large-scale implementation of this new strategy for indigenous wood architecture.

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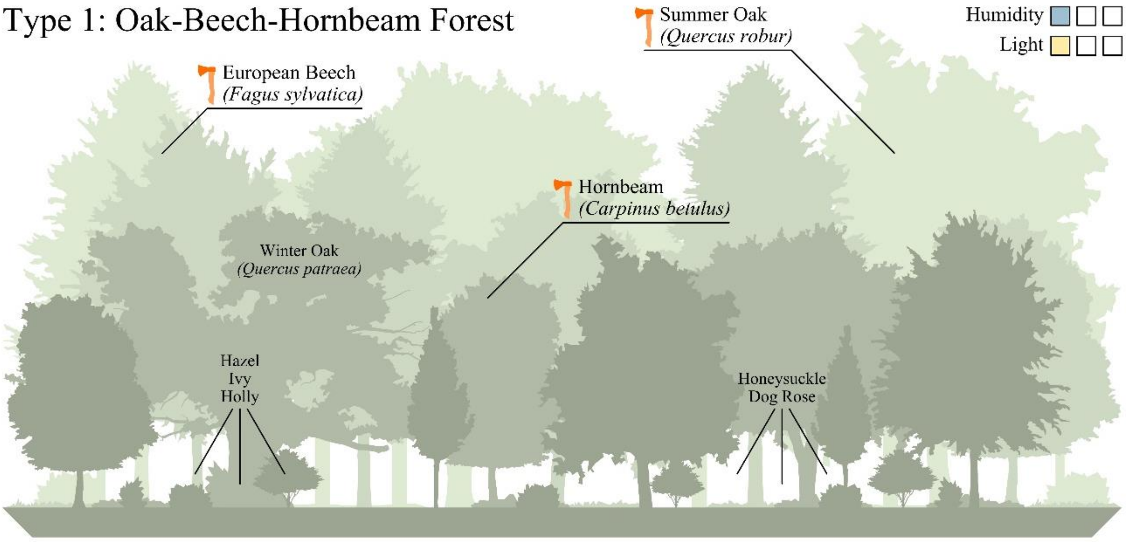
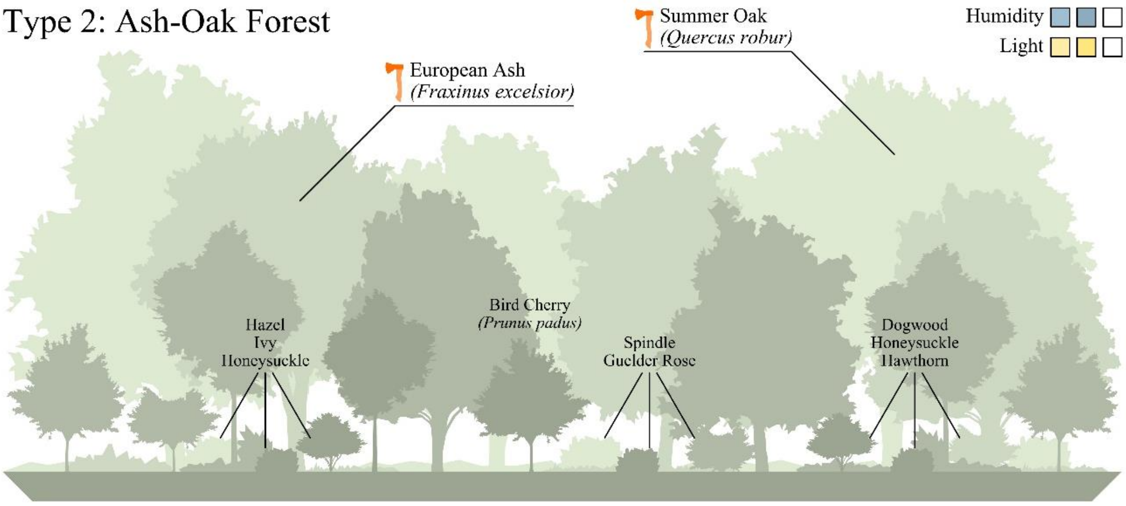
APPENDIX A

Forest Prototypes

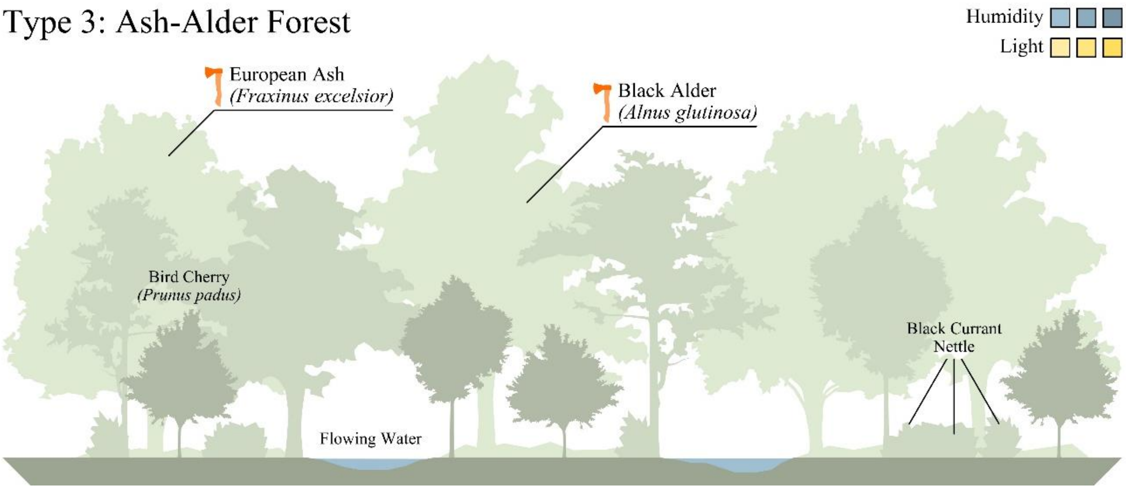
Type 1: Oak-Beech-Hornbeam Forest



Type 2: Ash-Oak Forest



Type 3: Ash-Alder Forest



APPENDIX B

Theoretical yield per forest prototype

Prototype *Share in area* *V_T/V_F = 35/60*	**Yield V_F** [m³/ha] *(at rotation period)* 60% of GAI	**Yield V_T** [m³/ha] *(at rotation period)* 35% of GAI	**Annual yield** Felling & Thinning [m³/ha]
Type 1 a: *Cb/Fs/Qr* *30/30/30%*	Cb: 106-163 *(at 80 y)* Cb: 44-68 *(at 30 y)* Fs: 120-137 *(at 80 y)* Fs: 75-86 *(at 50 y)* Qr: 180-284 *(at 150 y)* Qr: 144-227 *(at 120 y)*	Cb: 62-95 *(at 80 y)* Cb: 26-40 *(at 30 y)* Fs: 70-80 *(at 80 y)* Fs: 44-50 *(at 50 y)* Qr: 105-166 *(at 150 y)* Qr: 84-132 *(at 120 y)*	V_F Cb: 1,3-2,3 V_T Cb: 0,8-1,3 V_F Fs: 1,5-1,7 V_T Fs: 0,9-1,0 V_F Qr: 1,2-1,9 V_T Qr: 0,7-1,1
Type 1 b: *Cb/Fs/Qr* *50/25/15%*	Cb: 177-272 *(at 80 y)* Cb: 73-113 *(at 30 y)* Fs: 100-114 *(at 80 y)* Fs: 63-72 *(at 50 y)* Qr: 90-142 *(at 150 y)* Qr: 72-114 *(at 120 y)*	Cb: 103-158 *(at 80 y)* Cb: 43-67 *(at 30 y)* Fs: 58-67 *(at 80 y)* Fs: 37-42 *(at 50 y)* Qr: 53-83 *(at 150 y)* Qr: 42-66 *(at 120 y)*	V_F Cb: 2,2-3,8 V_T Cb: 1,3-2,2 V_F Fs: 1,3-1,4 V_T Fs: 0,7-0,8 V_F Qr: 0,6-1,0 V_T Qr: 0,4-0,6
Type 2 a: *Fe/Qr* *50/50%*	Fe: 278-323 *(at 75 y)* Fe: 222-258 *(at 60 y)* Qr: 300-473 *(at 150 y)* Qr: 240-378 *(at 120 y)*	Fe: 162-188 *(at 75 y)* Fe: 130-151 *(at 60 y)* Qr: 175-276 *(at 150 y)* Qr: 140-221 *(at 120 y)*	V_F Fe: 3,7-4,3 V_T Fe: 2,2-2,5 V_F Qr: 2,0-3,2 V_T Qr: 1,2-1,8
Type 2 b: *Fe/Qr* *75/25%*	Fe: 417-485 *(at 75 y)* Fe: 333-387 *(at 60 y)* Qr: 150-237 *(at 150 y)* Qr: 120-189 *(at 120 y)*	Fe: 243-282 *(at 75 y)* Fe: 195-227 *(at 60 y)* Qr: 88-138 *(at 150 y)* Qr: 70-111 *(at 120 y)*	V_F Fe: 5,6-6,5 V_T Fe: 3,2-3,8 V_F Qr: 1,0-1,6 V_T Qr: 0,6-0,9
Type 3 a: *Ag/Fe* *50/50%*	Ag: 180-252 *(at 60 y)* Ag: 120-168 *(at 40 y)* Fe: 278-323 *(at 75 y)* Fe: 222-258 *(at 60 y)*	Ag: 105-147 *(at 60 y)* Ag: 70-98 *(at 40 y)* Fe: 162-188 *(at 75 y)* Fe: 130-151 *(at 60 y)*	V_F Ag: 3,0-4,2 V_T Ag: 1,8-2,5 V_F Fe: 3,7-4,3 V_T Fe: 2,2-2,5
Type 3 b: *Ag/Fe* *75/25%*	Ag: 270-378 *(at 60 y)* Ag: 180-252 *(at 40 y)* Fe: 139-162 *(at 75 y)* Fe: 111-129 *(at 60 y)*	Ag: 158-221 *(at 60 y)* Ag: 105-147 *(at 40 y)* Fe: 81-94 *(at 75 y)* Fe: 65-76 *(at 60 y)*	V_F Ag: 4,5-6,3 V_T Ag: 2,6-3,7 V_F Fe: 1,9-2,2 V_T Fe: 1,1-1,3

Note:

Own work, based on (Baeté et al., 2002; Dobrowolska et al., 2011; Fraanje, 1999; Iliev et al., 2022; Löf et al., 2015; Tomter et al., 2016)

Ag = Black Alder ; Cb = Hornbeam ; Fe = European Ash ; Fs = European Beech ; Qr = Summer Oak.

V_F = Volume (yield) of final felling. V_T = Volume of all thinning operations up to the final felling.

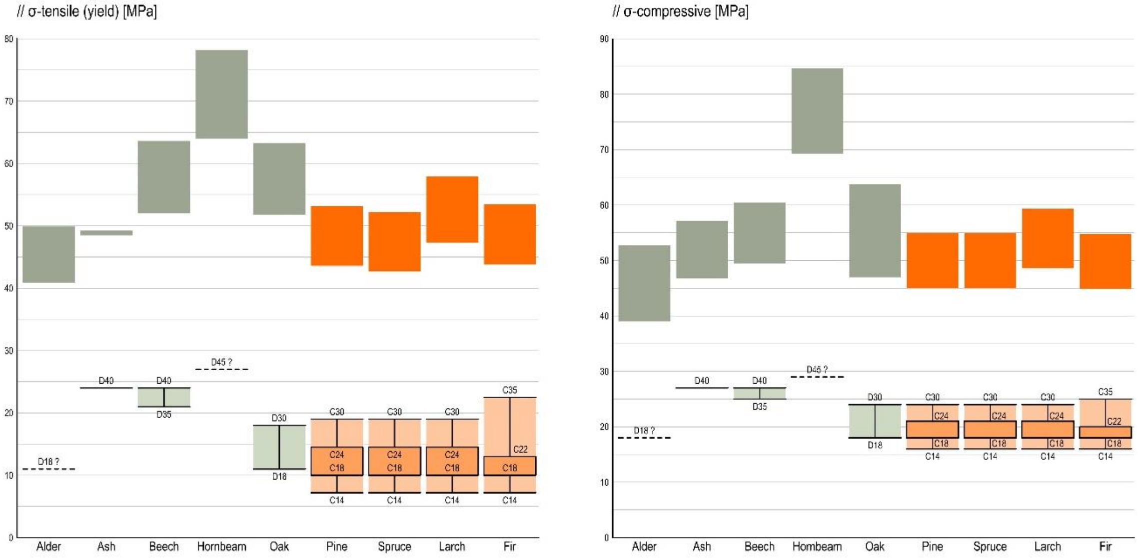
Calculations were based on the range of increments for each species as given in Table 1, thus results are presented in a range as well. The results simulate a production forest with 100% felling. In reality, to be considered a multifunctional forest, felling must be reduced to 80% (Schelhaas et al., 2018).

For forest type 1, 10% of the total area is reserved for the threatened Winter Oak (Q. patraea), the yield of which is not included in calculations.

Appendix C

Comparative analysis of mechanical properties for nine wood types

Continue on the next page…



Note:

Own work, based on (ANSYS, 2024; Centrum Hout, 2017; n.d.)

Raw test values (the higher, darker-colored values) for all properties are retrieved from Granta EduPack 2024 by ANSYS (2024) and complemented with values retrieved from the wood database of Centrum Hout (n.d.). These tests were performed under ideal circumstances with close-to-perfect wood samples. Characteristic values, such as those provided in the Eurocode, may be as low as 20-50% of the test values (ANSYS, 2024).

The Eurocode strength classes (the lower values in labeled boxplots) were retrieved from an information sheet by Centrum Hout (2017) as well as the wood database of Centrum Hout (n.d.).

Missing Eurocode strength classes for Alder and Hornbeam wood (dotted lines) were estimated by lowering the lowest mean raw test value by the same factor as the other wood types, for the worst of the six mechanical properties. These estimations should by no means be relied upon, because they did not result from rigorous research like the Eurocode (NEN-EN)

Appendix D

Application ranking matrix for five wood types in load-bearing constructions

		Black Alder	**European Ash**	**European Beech**	**Hornbeam**	**Summer Oak**
Truss construction	Top chord (rafter)	B	G	G	M (limited size)	G
	Bottom chord (tie)	M	G	G	M (limited size)	G
	Web member (strut)	M	G	G	**E**	G
	Web member (tie)	G	G	G	**E**	G
	Zero-force members	G	G	G	G	G
	Nodes, joints, pegs	B	**E**	G (as dowels)	**E**	G
Post & beam constr.	Posts & columns	B	G	G	M (limited size)	G
	Beams & purlins	B	**E**	G	M (limited size)	G
	Braces	B	G	G	M (limited size)	G
	Knee braces	B	G	G (universalist)	G	G (universalist)
Platform-frame construction	Sills or Soles	B	G (if durable)	B (moisture)	M (limited size)	**E** (durability)
	Studs (vertical)	M	G	G	M (limited size)	G
	Top plates	M	G	G	M (limited size)	G
	Headers & lintels	B	**E**	G	**E** (short span)	G
	Floor joists	B	**E**	G	**E** (short span)	G
	Rim joists	M	G	G (universalist)	M (limited size)	G (universalist)
	Sheathing	**E**	G	G	G	G
Misc.	Foundation piles	**E**	M	B (moisture)	M	G
	Foundation beams	B	M	B (moisture)	M	**E**

Note: **E** = Excellent ; G = Good ; M = Moderate ; B = Bad

The appreciations in the matrix are based on the literature as discussed in the thematic research paper (paragraph 3.4), the comparative analysis of mechanical properties (see appx. C), as well as personal communications with Max Salzberger from Cologne University of Applied Sciences (M. Saltzberger, personal communications, January 7 2025).