Material Flow Analysis of Wood in a Self-Sufficient Community

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General Research Profile, Minor Research Report

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Abstract

Wood is an essential natural resource that can be utilized in various ways, such as for construction, bioenergy, and paper production. The flow of wood from harvest to use has the potential to be optimized to achieve circularity and enhance sustainability through proper management and increased recycling rates. This objective is particularly interesting to “Orchid City,” a concept for a future-proof, self-sufficient community of up to 50,000 inhabitants. A material flow analysis was therefore conducted for Orchid City to determine whether the community could self-sustain its wood consumption based on own wood production. The recycling rates of the wood flow were evaluated to determine if efficiencies in the system could be increased to enhance the circularity of the wood. Next, recommendations were made for which tree species to grow and where the wood should be produced. The cascade-use principle of wood was evaluated to determine which order of uses is most efficient. Finally, the feasibility of an Orchid City in the Netherlands was evaluated in terms of geographical location and spatial requirements. This report concludes that an Orchid City of 50,000 inhabitants (occupying 19,700 ha in total) can be self-sufficient in terms of wood, given increases in efficiencies within the recycling system. The total amount of wood that needs to be produced is 24,275 tonnes per year and Orchid city exceeds this amount by 4,686 tonnes. The corresponding land claim, needed to fulfill these growth requirements is 2,410 ha for natural forest, 2,994 ha for agroforestry, and 9,039 ha for silvopasture. From a wood flow perspective, it is feasible that such a community could be placed in certain areas of the Netherlands with similar land use regimes and low population densities. However, further research is needed to consider more complex issues and potential constraints to implementation, such as land tenure and regulation, and current high land prices.

Layman's Summary

Wood has many uses in the built environment and is a crucial resource in many cities and communities. It can be used for construction of buildings, fencing and decorations, furniture making, paper and pulp production, and biomass for energy. However, it is important to optimize the use of wood, as the flow from harvest to use can sometimes be inefficient, resulting in a loss of both wood and energy. Therefore, it is essential to properly manage the harvest and uses of wood in order to create a productive wood flow system. This topic, in particular, is of great interest to “Orchid City,” a concept for a future-proof, self-sufficient community of up to 50,000 inhabitants (occupying 19,700 ha in total). Orchid City aims to create a community that is climate-adaptive and enhances resilience to environmental change through regenerative agriculture, increased biodiversity, and renewable energy. A material flow analysis was created and to evaluate the flows of wood in each sector (e.g., construction sector, energy production) and provided insight as to where the efficiencies could be increased within the system to promote circularity. This report also highlighted recommendations including which tree species to grow, in what type of land use systems they should be produced (e.g. natural forest, agroforest, etc.), as well as which flows could be made more efficient by enhancing recycling. The feasibility of Orchid City was also evaluated in terms of geographical location and spatial requirements. One of the potential locations is the Netherlands, and since this country is relatively small and the forest requirements to grow the wood are very high, it is important to consider if such a large space is available in the Netherlands for this purpose. It was concluded that Orchid City would be able to produce all of its own wood and meet the wood demands of each sector in a community of 50,000 inhabitants, if forests are properly managed and the recycling rate of the wood flow increases. The total amount of wood needed to be produced is 24,275 tonnes and Orchid city exceeds this amount by 4,686 tonnes. The corresponding land space, in hectares, needed to fulfill these growth requirements are 2,410 for natural forest, 2,994 for agroforestry, and 9,039 for silvopasture. The community would also be feasible in the Netherlands, but only in particular regions that have low population densities and use the land in similar ways as Orchid City plans to, so that natural areas aren’t converted to farmland or urban space. Additional research is needed to evaluate other important aspects of Orchid City’s feasibility, such as land prices, regulations, and laws that could affect where it can be located.

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Acknowledgments

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1. Introduction

1.1 Orchid City

Orchid City (OC) is a self-sustaining city blueprint, created by the company Except Integrated Sustainability, with a mission to reinvent how humans coexist with nature and each other. Self-sufficient communities or cities have been designed for numerous locations in many different circumstances. Bačelić Medić et al., 2013 emphasize the importance of integration of renewable energy sources and appropriate energy storage solutions if communities are to reduce their dependency on outside energy sources. Apart from energy self-sufficiency, Sreeharsha & Venkata Mohan, 2021 incorporate the concepts of circular economy, ecological engineering and biorefineries to achieve social and environmental self-sufficiency. Previous studies have also emphasized the importance of context when creating sustainable communities and the need for models to be scalable depending on culture and regions (Singh et al., 2019). Due to the multi-faceted problems of modern society, solutions need to be integrated and multi-dimensional. Potential solutions to include in a self-sufficient community are self-sustainable food production, maintenance of biological diversity and ecosystem stability, zero discharge and responsible consumption, and green architecture (Sreeharsha & Venkata Mohan, 2021).

OC in particular is aimed at creating an ideal living environment while providing the following services for its community:

- All energy, year-round, from renewable sources
- All food, aiming for net zero on the nutrient balance
- All reasonable daily services and program, including schools, workplaces, care, shops, culture, and entertainment.
- Minimalization of traffic, no need to use a car
- Climate adaptive, regenerative ecosystems, health and biodiversity boosting landscape
- Affordable housing, generation proof for seniors, starters, and students

- Meaningful job creation, from production to offices, bio-based products, construction materials, textiles, and ceramics

The OC blueprint applies an integrated strategy to produce systemic modeling to offer solutions for creating an inspirational and essential environment. To create a harmonious community, OC combines economic development with innovative solutions in agriculture, resource management, climate adaptation and bio-based construction and manufacturing. It ensures a financially feasible project with an inviting return on investment for investors. To ensure self-sufficiency, OC is driven by a closed-loop, circular approach powered by ecosystem services. It maximizes circularity with regards to building materials, transport and equipment, and agriculture and provides on-site workshops that create essential daily products (Fig. 1).

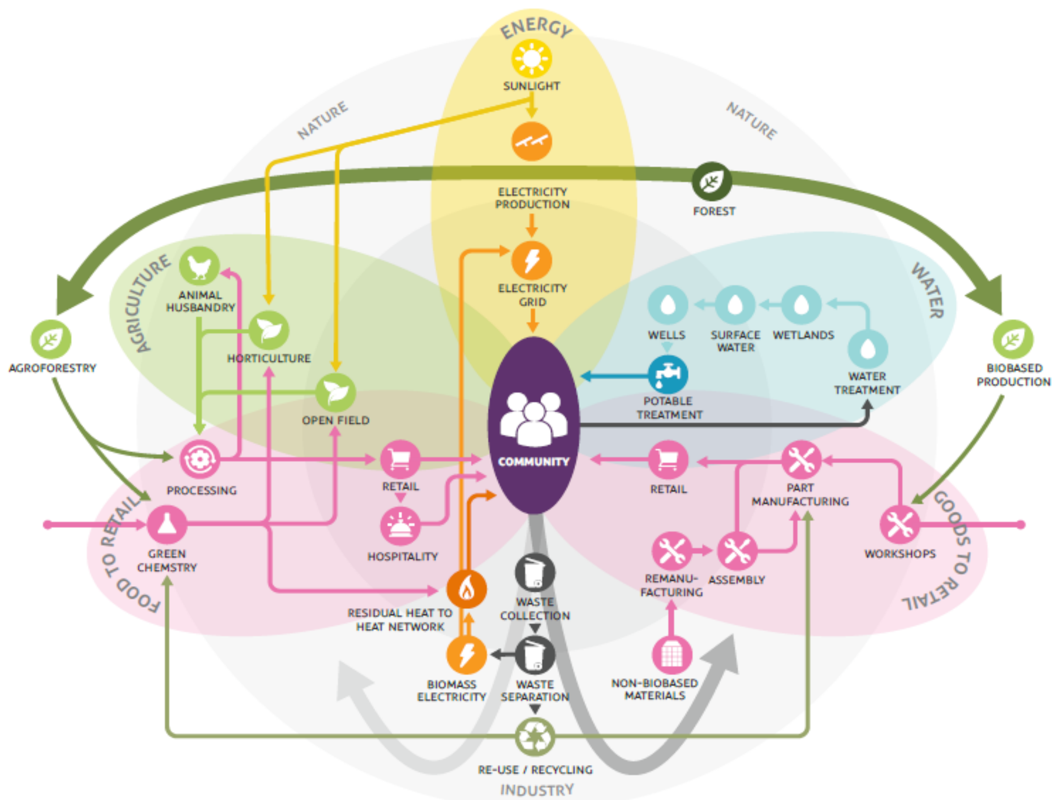


Figure 1. Resource circularity of Orchid City (*Orchid City: Reinventing the Future*, 2021).

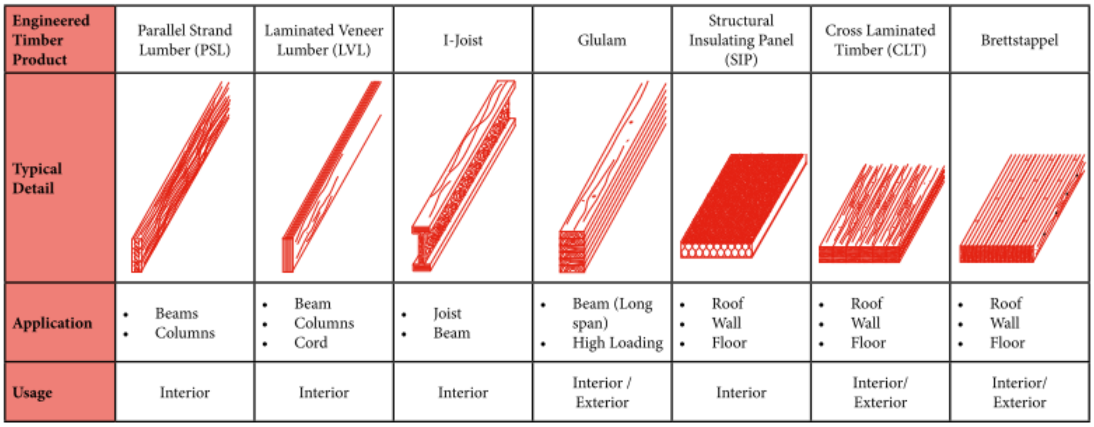
The blueprint of Orchid City is built in a scalable model which supports communities from populations of 500 to 50,000 inhabitants. The concept is built to be adaptable through a range of different climates, locations, and cultures as well as many types of economic activities (Fig. 2). It is able to acclimate to the availability of a particular space, the local demands, and the ambitions of partners. So far, its feasibility has been modeled for locations in Brazil, the Netherlands, and Vietnam, which illustrates its adaptability to diverse challenges. According to Except Integrated Sustainability, the benefits of a hypothetical OC are “A city of 15,000 residents is able to create over 8000 sustainable jobs and help channel more than €4.5 billion investment into surrounding regions for development. A community of this size will have 7500 houses in various typologies, plant approximately 1.1 million trees, and not only achieve carbon neutrality but become energy positive in operations” (*Orchid City: Reinventing the Future*, 2021).

Figure 2. Scalability and adaptation of Orchid City (*Orchid City: Reinventing the Future, 2021*).

1.2 Why timber?

To ensure self-sufficiency and a circular, closed-loop approach, a goal of OC is to utilize timber and other wood-based materials in construction as much as possible, opposed to other building materials coming from finite resources such as metals and cement. Wood is a lightweight material that is easy to process and repair and can be used in buildings both large and small (Goverse et al., 2001). It is a 'renewable' material that has a high strength-to-weight ratio and is therefore versatile and durable (Pérez Zerpa et al., 2017). Not only is timber renewable, recyclable, and biodegradable, but its production and processing are energetically efficient and products from timber construction can physically embody carbon (Hart & Pomponi, 2020; Zubizarreta et al., 2019). In fact, by substituting wood for concrete and steel in building construction, a 14% - 31% reduction in global CO_2 emissions could be realized (Himes & Busby, 2020). Wood used in construction of buildings can avoid emitting CO_2 by various pathways, including the storage of wood in buildings and products so it does not rot, burn or produce CO_2, displacing CO_2 produced by burning wood and using less energy in the manufacturing of wood than steel, concrete, and other building products (Oliver et al., 2014).

Along with the environmental and natural benefits, timber can also be highly functional in its use. Engineered wood products are created by laminating smaller boards into larger structural components, such as glue laminated (glulam beams) or cross-laminated timber (CLT) panels, which allow for the re-formulation of large structural timbers which address the natural inconsistencies of wood and can make its structural and mechanical performance more stable (Fig. 3) (Churkina et al., 2020). With CLT in particular, a minimum of three layers of sawn softwood are stacked on top of one another at right angles and glued to form a desired thickness and can be used for floors, roofs, and walls (Ramage et al., 2017). Due to the many structural benefits of CLT, such as its high strength-to-weight ratio and design flexibility, its application has a very broad range in construction (Laguarda Mallo & Espinoza, 2014). It can be utilized in not only single-family houses but also residential, multi-story, industrial, and commercial buildings and has even been used in the construction of high-rises (Wieruszewski & Mazela, 2017). Furthermore, CLT performs exceptionally well in its fire performance due to its unique charring properties and burns slowly and predictably (Laguarda Mallo & Espinoza, 2014).



Engineered Timber Product	Parallel Strand Lumber (PSL)	Laminated Veneer Lumber (LVL)	I-Joist	Glulam	Structural Insulating Panel (SIP)	Cross Laminated Timber (CLT)	Brettstappel
Typical Detail							
Application	• Beams • Columns	• Beam • Columns • Cord	• Joist • Beam	• Beam (Long span) • High Loading	• Roof • Wall • Floor	• Roof • Wall • Floor	• Roof • Wall • Floor
Usage	Interior	Interior	Interior	Interior / Exterior	Interior	Interior/ Exterior	Interior/ Exterior

Figure 3. Common structural engineered timber products in Europe (Ramage et al., 2017).

The use of timber in construction can also provide indirect benefits. By centralizing the production and processing of raw timber, production chains can be handled by small and medium-sized firms, creating new business opportunities that could uplift the local and regional economy. This centralization would also impact other branches, such as the woodworking industry and real estate business, and create structural changes in the overall economy, considering timber construction to be a branch of the emerging bio-economy (Hynynen, 2016). Furthermore, an emerging CLT industry can create opportunities to support local job growth and generate savings in construction time which can provide a greater rate of return for project investors (Scouse et al., 2020). Changing land use to increase forestry can benefit not only the timber industry, but can also create ecological benefits and help mitigate climate change (Ramage et al., 2017).

While there are many direct and indirect benefits to using timber in construction, there are also potential drawbacks. The question of whether sufficient land is available to meet the rapidly growing demands of timber use is important to consider. Meeting such demands will inevitably include displacing already existing consumers from the market or create a larger demand for importing tropical timber (Hart & Pomponi, 2020). Moreover, engineered timber products, such as CLT, can have negative impacts on the embodied energy burden compared to untreated wood. Wood is also vulnerable to moisture, as it can affect the mechanical properties and make wood vulnerable to attack by fungi or insects. Therefore, careful consideration must be put into the design, species, and treatment used (Ramage et al., 2017).

1.3 Wood flow analysis

A material flow analysis was conducted for OC to determine whether the community could self-sustain its wood consumption based on its own wood production. A material flow analysis (MFA) is the systematic assessment of flows and stocks of materials within a complex system defined in space and time (Cencic & Rechberger, 2008). It refers to accounts in physical units (i.e. tonnes) comprising the extraction, production, transformation, consumption, recycling, and disposal of materials (Hekkert et al., 2000). An MFA was chosen as the primary analysis due to its ability to obtain a precise understanding of systems and sub-systems thinking and provide relevant indicators of a systems or process' efficiency. While a general MFA was already created for woody biomass in 2019 by Probos Netherlands (Teeuwen et al., 2019), an additional one needed to be created for OC and the introduction of construction timber demands, to not only estimate the potential wood flow, but also optimize the efficiency of the system. Another assessment that could have been suitable is a Life Cycle Assessment (LCA). Compared to an MFA, an LCA is focused on the time of a life cycle of a functional unit within a value chain, taking on a micro-vision approach as it is typically product-oriented. While such an approach could be interesting in terms of analyzing the life cycle of one particular wood product, macro scale flows need to be understood before assessments on micro scale generates accurate insights. An MFA was therefore better suited as it looks at a particular material, in this case wood, and follows it through a variety of trajectories, such as production, use phase, and end-of-life and provides a macro-vision of the system (Birat, 2020).

Similar studies have conducted MFAs on timber in the past in various locations and times. For example, Lenglet et al. (2017) evaluated the wood flows in the upstream part of the wood sector in France to not only understand the wood flow but also evaluate potential consequences of various scenarios of raw wood export policies. The results from the MFA offered a solid base for analysis and opportunities for development prospects, and demonstrated the relevance of MFAs to reconcile highly heterogenous datasets. Moreover, the report combines the MFA with an economic modeling framework, which not only analyzes the wood flow, but proposes insights into policy recommendations. The report also mentions the difficulties in data collection, as large uncertainties prevail in existing databases where some data, especially regarding wood fuels, are under-reported in official statistics. Another study done by Parobek et al. (2014) investigated the raw wood flow in Slovakia using an MFA. The study analyzed wood resource balance, taking into account the uses of wood as a material, by-products and waste generated from the production, and further uses in wood processing or energy sectors. The analysis revealed the actual consumption of wood in its various forms and the relationships between resources, basic production indicators, foreign trade relations, and the use of raw wood materials in the domestic market. The report also acknowledged that the demand for roundwood is constantly changing in Slovakia and there are many specifics influencing production and consumption in the domestic market, therefore, the requirements of wood processing can vary over a relatively short time. Furthermore, Kayo et al. (2019) created an MFA in combination with an LCA to quantify the environmental impacts of wood consumption in Japan from 1970 to 2013. The study found that paper consumption was a large contributor to environmental impacts such as climate change and urban air pollution and that an effective measure in reducing overall environmental impact would be to reduce the greenhouse gas emissions from paper production. It also found that an increase in wood use for building construction, furniture materials, and energy production could lead to reductions in environmental impacts via carbon storage and material substitution.

In general, an MFA on wood is more focused on resources and systems as a whole, rather than specific products. To have a deep understanding of a wood system and all its parts, including inputs, outputs, production, consumption, disposal, imports, and exports, it is important to carry out an analysis based on a systems approach. While there may be limitations to this analysis, an MFA is a logical approach to understand the wood flow in OC. Such limitations could include gaps in data or fast-changing markets; therefore, assumptions will need to be made accordingly.

1.4 Main objectives and research questions

The main objective of this report was to create a material flow analysis for OC to determine whether the community could self-sustain its wood consumption based on its own wood production. This means that OC will not need to import (or export) any wood and instead, focus on reducing the amount of wood needed by creating a more efficient wood flow. The research aims to gain understanding on what sectors, or uses, of wood there will be in OC, the demands for each of these sectors, where the wood will come from and how much wood will need to be compensated for if there are no longer imports. Because OC aims to be self-sufficient, understanding the flow of wood in this report, from production to use to disposal, can provide insight into future plans of wood management of OC and determine if self-sufficiency in wood production is possible. Furthermore, this report also analyzes the feasibility of such a wood flow in the Netherlands. To be self-sufficient, it is crucial to have an efficient and sustainable wood flow and this report determines if such a wood flow can in principle be implemented. The reference location of OC for this report, a rural area in the Netherlands, is also an important factor to consider regarding the feasibility, given the regulations, costs, and space available in this location. Therefore, based on these objectives, the main research questions for this report are:

1. Can Orchid City be self-sufficient in its wood demand?
2. Is Orchid City feasible in rural areas in the Netherlands, in terms of wood flow and location?

The report will first analyze the current material flow analysis of wood in the Netherlands in order to extrapolate the data to a wood flow in OC. Based on this wood flow, it can then be determined if OC can be self-sufficient in its wood production. Further recommendations are given on which tree species to grow in OC, where the wood can be produced, and how the recycling rate can be optimized. Lastly, the feasibility of placing OC in the Netherlands is analyzed. The research conducted is based on literature review and a scalable model already constructed in Microsoft Office Excel within the company, Except Integrated Sustainability.

2. Methods

2.1. Wood flow in the Netherlands

In order to create a realistic MFA for OC, wood flow in the Netherlands needs to be understood. The main data used for the Dutch wood flow assessment was from Probos Netherlands, who created an MFA for wood production and use in the Netherlands in 2019 (Teeuwen et al., 2019) (Fig. 4). The analysis gave an overview of many different inputs and outputs, including imports, exports, and feedback loops within the system and gave a baseline to understand the average amounts of wood being used in different sectors. In order to later extrapolate this data for OC, the presented data was reverse engineered back to the original data, which was missing from the MFA. Once the dataset was usable, the MFA was simplified. First, the flow was reduced to 8 main sectors that are most relevant and will also be used in OC, including:

- “primary use”
- “secondary use”
- “old paper”
- “paper and cardboard production”
- “paper and carboard processing”
- “recycled wood”
- “material consumption”
- “energy production”

The main focus was to see how much wood needed to be produced in the Netherlands if imported wood was no longer used. In other words, how much wood needs to be produced in the Netherlands to create self-sufficiency at the national level?

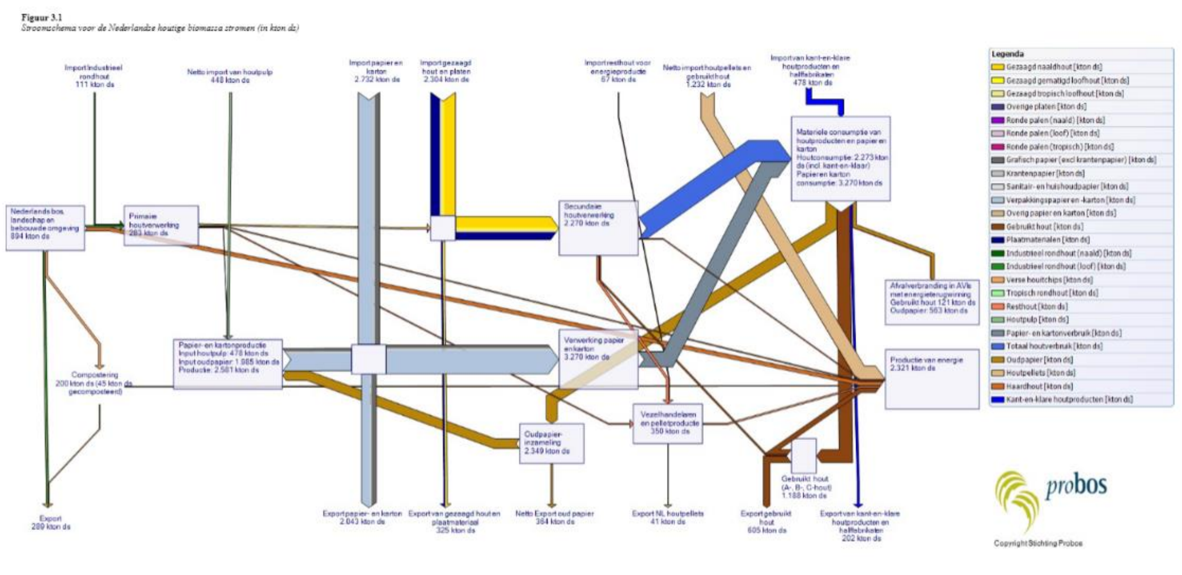


Figure 4. Material flow analysis on wood production, consumption, imports and exports in 2019. (Teeuwen et al., 2019).

To answer this question, the imports of wood coming from external sources needed to be accounted for. Each wood import has a corresponding amount of "forest equivalent" it requires, in other words, if the Netherlands is no longer accepting wood imports, that amount of wood needs to be compensated for in a Dutch forest. Therefore, the Dutch forest equivalent would need to be much larger than it was originally in order to grow the compensated wood. The sectors "secondary use" (processed wood and paper products such as packaging or wooden furniture) and "paper and cardboard production" had large forest equivalents, but the sector with the largest requirement needed to be determined. If this requirement was fulfilled, then all other sectors, which had lower requirements, should then also be fulfilled in terms of average usage. To calculate the average usage of these sectors, the amount of wood currently in that sector was normalized per person so it could later be extrapolated to OC. In the "secondary use" sector, for example, the per person usage was 133.5 kg per year, which was done by dividing the annual wood demand of the sector, 2270 ktonnes, by the population of the Netherlands, approximately 17,000,000.

Next, this value was multiplied by 98.3%, which is the percentage of “secondary use” wood that is coming from a Dutch forest annually and needs to be considered when calculating the forest equivalent. This calculation was done by dividing the input from recycled wood (38 tonnes) by the total wood in the sector (2,270 tonnes). This means that 3.2% of “recycled wood” goes into “secondary production”, in other words, only 3.2% of wood in the feedback loop is recycled. Next, the amount of wood coming from the Dutch forest directly, as opposed to imports, was calculated as this would give the amount of wood that needed to replaced, or compensated for, since imports will no longer be used. Of the wood being produced in the Dutch forest, 42% of it goes to “primary production,” and of that wood, 89.4% goes to “secondary production.” Therefore, the overall amount of the wood in the “secondary production” sector coming from the Dutch forest is 38%. The final calculation to determine the forest equivalent needed to meet the wood requirements for this sector is as follows: 133.5 kg times 17,000,000 (assumed Dutch population), multiplied by 98.3% and divided by 38%. In the example case of the Netherlands the forest equivalent for this sector would be 58.7 million tonnes.

2.2 Wood flow in Orchid City

After creating a simplified baseline of the wood flow in the Netherlands, this information could then be extrapolated to create an MFA for OC. However, changes were made in the system in order to optimize the efficiency of the wood flow, since the goal of OC is to not only be self-sufficient, but as sustainable as possible. The changes that were incorporated included prioritizing and increasing wooden construction, omitting the “incineration” sector and transferring its wood inputs to “energy production”, and optimizing the recycling loops between “secondary use” and “paper and cardboard processing.”

First, a consideration needed to be made for these sectors specifically, given the prospect of OC using more wood in the “secondary use” sector to build long-lasting, wooden houses. The assumption is made that currently in the Netherlands no significant fraction of homes are constructed in such a way, therefore the additional wood needed has to be added to the current footprint. To add the additional wood that would be needed to build wooden houses in OC, the total built area for housing (1,507,375 m^2) was taken from the OC model and divided by its 50,000 intended citizens to estimate the housing needed per person in OC. Next, the average amount of wood per unit of area in housing was found (0.26 m^3/m^2) in order to estimate the required amount of wood needed for the housing. This value was taken from Kapambwe et al. (2009) and Ramage et al. (2017). The unit conversion from m^3 to tonnes was then corrected for by multiplying this value by 1.5, the average density of wood. Next, this value was divided by the lifespan of a wooden house, which is, on average, 62 years (Kapambwe et al., 2009). This gave a per person per year estimate, as an additional wood footprint associated with wooden construction of houses. The calculated value was 189 kg of wood per person per year, which was then added to the original 133.5 kg, giving a total of 322.5 kg per person per year. After multiplying this value by 50,000 inhabitants and the respective amounts of wood coming from the forest as was done in the Dutch MFA, a total of 42,215 tonnes of forest equivalent is needed for OC. The same process was used to determine the forest equivalent for the "paper and cardboard processing" sector, which came to 41,378 tonnes, and while the requirements were similar, the "secondary use" sector was the higher by 837 tonnes. This makes "secondary use" the most demanding sector and currently determines the minimum forest size required to become self-sufficient.

The next adjustment was to increase the efficiency within the recycling loop of "secondary use" (since this is currently leading in forest demand, see section 2.1.1) as this was only 3.2%. The current Dutch system shows a low wood recycling rate, recycling only 3.2% of the used 133.5 kg per person. However, wood used for construction is generally of high quality, and the structural capacity of the wood can be largely maintained, which means the recycling potential of such wood, an additional 189 kg per person, is significantly higher. Reuse of wood requires no technical change in the application of wood in the Dutch building practice, as long as careful and selective demolition and pre-treatment of wood is considered (Goverse et al., 2001). As such, this needed to be reflected in the MFA. The first step was to increase the transparency of the wood flows between sectors by dividing the "material consumption" sector into two separate sectors; "material consumption (wood)" and "material consumption (paper)". According to the Dutch MFA, the portion of "secondary use" wood that is lower quality (6,675 tonnes) that goes to "energy production" is 36% and the portion that goes to "recycled wood" is 64%, which is the same ratio that will be used in the OC MFA. However, wood used for construction will not adopt the same ratio but use one that is more representable. The rates for construction are 90% of the housing construction wood (9,450 tonnes) will be recycled and only 10% will go to "energy production." This rate is based off the assumption that 90% of the wood from housing and construction is still salvageable and has the potential to be reused (Goverse et al., 2001). The 10% that goes to "energy production" reflects unforeseen losses, such as demolition incidents or damage to the house over its lifetime. The wood entering the "energy production" sector from both high- (construction use) and low-quality (general use) rates was added together, as well as the wood entering the "recycled wood" sector, and these combined values were the outputs from "material consumption (wood)" (see figure 5).

The next wood flow that could be adjusted within this loop was from the "recycled wood" sector to the "secondary use" sector. The amount of wood in this use sector that is low-quality is known (64% of the 6,675 tonnes that originally entered the "secondary use" sector), as well as the amount of high-quality wood (90% of 9,450 tonnes). These beginning amounts can be used to calculate the separated recycling rates. The original rate was once again used for the low-quality wood, which showed 3.2% of the wood being recycled in the loop and entering "secondary use" and 96.8% entering "energy production." The same assumption was made as before, with 90% of the high-quality construction wood being recycled and entering "secondary use" and 10% entering "energy production." After combing the two amounts, the final ratio of "recycled wood" entering energy production was 39% while 61% entered "secondary use." With the recycling rate of wood increasing from 3.2% to 61%, the forest equivalent requirement decreased drastically, as more recycled wood could be used that was already in the system. Considering that the actual demand for wood does not change and the "secondary use" sector still requires 16,125 tonnes for a population of 50,000 people, then the amount of wood coming from "primary use" could be determined by subtracting the recycled wood amount, 7,792 tonnes, from the 16,125 tonnes. Because the two forest equivalents were very close together the impact of the drastically lower forest equivalent of "secondary use" on the overall system efficiency is very low, due to the "paper and cardboard" sector remaining high and taking over in leading forest equivalence.

Another step that was taken to optimize the overall efficiency of the system was to minimize the difference between the forest equivalent requirement of "secondary use" and "paper and cardboard production." The assumption was made that the wood originally entering "secondary use" is of high quality, however, this wood could also be used for lower quality purposes, such as paper and cardboard production. Therefore, to decrease the requirement for the paper and cardboard sector, excess secondary wood could be sent to pulp instead, raising the fraction of low-quality wood towards paper production. This optimization was done mathematically, as the forest equivalent formulas of both sectors were set in an equation where they equaled each other with a variable x, the percentage of wood that would enter each sector from the "primary use" sector, was solved for iteratively. This resulted in the ratio of wood for the "secondary use" sector being approximately 81.7% and 18.3% for the "paper and cardboard production." These ratios then provided the optimal forest equivalent to supply both sectors, which was 24,275 tonnes. This also meant that the ratio of wood leaving the "primary use" sector and entering the "paper and cardboard production" sector almost doubled, as it was previously only 10.4%. Once the forest equivalent was known and the ratios adjusted, the amount of wood in each sector could be calculated for the final optimized wood flow in OC (Fig. 5). Additionally, a change was made by omitting the "incineration" sector from the flow and directing the inputs into energy production instead, since it is assumed that the wood entering both the "incineration" and "energy production" sector is of the lowest quality and can only be burned.

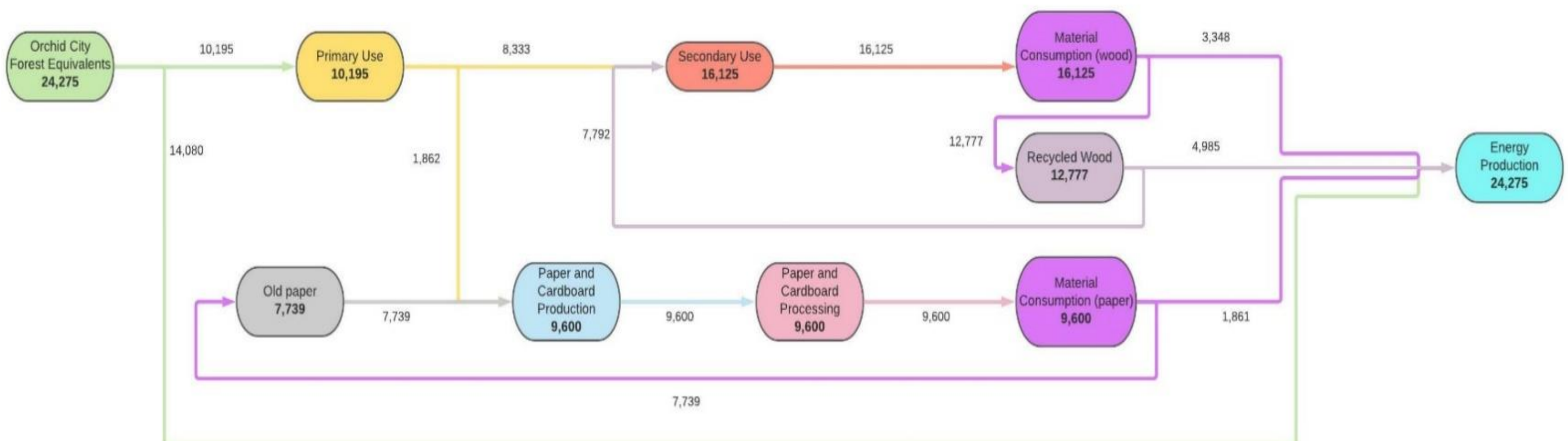


Figure 5. Material Flow analysis on wood production and consumption per year in Orchid City (Displayed in tonnes).

3. Results

3.1 Can Orchid City self-sustain its wood demand?

To determine if OC is self-sustainable in terms of wood production and consumption, the amount of wood coming from the forest and agricultural sectors needed to be calculated. The OC model was referenced here to find the sources of wood under the food scenario "Vegetarian MF", which means that OC will only raise livestock for dairy production and not for meat. The model consists of 3 main landscape typologies that will produce trees that will be used for timber, including the natural forest, agroforestry, and silvopasture. The orchard group was omitted from the wood production estimations as it is assumed that the trees will be used for fruit and nut production rather than focus on timber. The land space, in hectares, dedicated to each of these groups in a population of 50,000 people are 2410, 2994, 9039, respectively.

To determine the average amount of wood being produced in each hectare, a literature review was conducted. According to Duncker et al. (2012), a Central European forest ecosystem, with European beech (*Fagus sylvatica L.*) being the dominant tree species, produces 2.83 tonnes of wood per hectare per year. This is under the management system of low-intervention, or close-to-nature forestry, where the objective is to sustainably produce valuable timber while using natural processes as a guiding principle. This means that only the European beech species are harvested over a period of 40 years and 20% of the area is unmanaged. Additionally, E. Arets & Schelhaas (2019) states that in multifunctional forests in the Netherlands, harvesting rates are on average 5.7 m^3, or 2.01 tonnes, per hectare per year. The baseline production value used for OC was then the average of these values, 2.42 tonnes, and in total, the amount of wood coming from the natural forest in OC is 5,832 tonnes.

Next, the amount of wood being produced from the different agricultural typologies had to be calculated. In a silvopasture system described by Bird et al. (2010), 200 *Pinus radiata* trees, which can be used for both low and high quality uses, would produce approximately 57 tonnes per hectare at year 31, or, 1.84 tonnes per hectare per year in a period of 31 years when widely spaced (4 m x 9 m per hectare). It is assumed that agroforestry will have similar tree spacings and growth as the silvopasture system, therefore, 1.84 tonnes per hectare per year is multiplied by the hectares of agroforestry and silvopasture in OC. Agroforestry would then produce 5,509 tonnes of wood and silvopasture would produce 16,632 tonnes. Considering the wood produced in the natural forest, agroforestry, and silvopasture, OC would produce, in total, 28,961 tonnes of wood, which exceeds the wood requirements by 4,686 tonnes. Therefore, OC can theoretically be self-sustainable in terms of wood production.

4. Discussion

4.1 Wood self-sufficiency in Orchid City

Based on the results of the MFA, OC would be able to meet the wood demands for each sector from its own capacity, without importing foreign wood and be self-sufficient in terms of wood production. In fact, OC exceeds the wood requirements by 4,686 tonnes. While both agroforestry and silvopasture are already managed, the natural forest could remain unmanaged as much as possible and provide many other ecosystem services besides wood production, such as controlling floods and erosion, recreation, and sustaining biodiversity (Balloffet et al., 2012). Due to this overproduction of wood and the benefits of a natural forest, the amount extracted from the natural forest could be lowered while the amount from agriculture would remain the same. Therefore, agroforestry and silvopasture would produce wood to their full extent (22,141 tonnes) and the remaining 2,134 tonnes will come from semi-natural forest.

It is also important to take into account the assumptions made in order to create the MFA for OC and the corresponding uncertainties. There is a gap in data in the original Dutch MFA by Probos Netherlands, where the data for OC was extrapolated from. In this MFA, the wood amounts in the input and output flows were not specified, so the amount of wood in each sector needed to be calculated back from each of the flow inputs. However, some of the flows such as “energy production” and “recycled wood” were unclear and amounts were not specified, so the amounts estimated for these sectors are surrounded by larger uncertainties. Another uncertainty is the wood uses in the sectors “secondary use” and “material consumption (wood)” which were assumed to be for high-quality (construction) and low-quality (other wood products). However, more research could be done to investigate the specific wood uses in the sectors so that the wood flow would not be as undefined and the exact amount of each type of wood could be determined. Similarly, further optimization options could be investigated, such as the possible applications of recovered/recycled wood in sectors such as composting and fungi cultivation. However, these investigations were beyond the scope of this report.

The wood flow analysis from Hekkert et al. (2000) was also compared with the MFA from Probos Netherlands Teeuwen et al. (2019) to review any similarities or differences in the wood flow of the Netherlands. The two analyses were similar in the sense that they both showed the heavy dependence on foreign wood imports for the sectors pulp production, primary production, and wood products. Also, both analyses concluded that paper production is a substantial part of the total wood flow and consumes a large proportion of wood. Hekkert et al. (2000) states that about 35% of the total paper consumption is from paper packaging while Teeuwen et al. (2019) estimates that 33.5% of wood goes into paper and cardboard production. The main difference between the two analyses is that in Hekkert et al. (2000), the wood supply and use are only recorded when they have economic value, therefore, waste and recycling streams with no economic value are not present in the flow analysis, while in Teeuwen et al. (2019), this data was present. Lastly, Hekkert et al. (2000) do not indicate the mass-balance of paper and wood itself, but instead, only shows the amount of paper and wood products, while Teeuwen et al. (2019) indicate the mass-balance.

The wood flow analysis of OC shows similarities to other MFAs, specifically with regards to the use of wood. Kayo et al. (2019) determined that by promoting the use of wood in building construction, reductions in greenhouse gases could be made through carbon storage and material substitution. This follows the cascade-use principle that was used for OC of using wood for high quality and long-lasting purposes first in order to increase its lifespan and reduce waste. Additionally, the wood sectors indicated in Parobek et al. (2014) were also similar to those of the OC, including primary wood processing (sawn wood, pulp), secondary wood processing (furniture, construction), and wood fuel. However, the report specified how the wood in each sector would be used, which the OC MFA did not. For example, the report indicated that pulp wood was converted to particle and fiber board production and pulp and paper, while industrial residues like sawdust, chips, particles, and black liquor were converted to energy use in private households, industrial internal use, and energy biomass for heat and energy.

While scalable models have been introduced in previous studies as a way to create self-sufficient communities using an integrated approach, the one of OC is unique and innovative. It incorporates numerous aspects of sustainability (such as economic, social, and ecological) on a scale of up to 50,000 inhabitants while being able to adapt to the needs and desires of cultures and locations across the world. Ecovillage, in particular, is one initiative similar to OC that aims to be socially harmonious, economically practical, and ecologically sustainable. It emphasizes the need to scale the ecovillage model to incorporate regional, cultural, and natural aspects of sustainability (Singh et al., 2019). However, Ecovillage, along with other studies reviewed, did not provide a working scalable model like OC, but instead, only provided theoretical and conceptual models that could be used to create self-sufficient communities.

Furthermore, the OC MFA aims to promote sustainability and be self-sufficient in wood production and consumption, which is similar to the goals and findings of the report done by Sreeharsha & Venkata Mohan (2021). A circular bioeconomy was a main goal to achieve the United Nation's Sustainable Development Goals in the report, focusing on circular loops and eliminating waste and utilizing renewable resources to their full potential. While the report focused on sustainable food production, the same concept can be applied to wood, as it is another renewable resource and the OC MFA follows the same approach.

4.2 Species selection

The analysis of wood flow in OC considered the amount of wood required to fulfil the demands of each sector. However, the type of wood was generalized and the analysis did not consider the tree species. Instead, it was assumed that "generic species" would be functional for each sector. Another step could be taken to consider tree species which would provide further insight into the harvest times and management strategies, as well as specify which species could be used in which sector. By considering the variation according to different species, the forest requirement could change, since trees have different growth and harvest times depending on their species and this could require more or less space.

Two main categories of trees are the species that can be used in “secondary use,” which require the trees to be large and durable, while the other species can be used in all other sectors, such as “paper and cardboard production” and “material consumption (paper)” as they are typically lower quality and less durable. Potential species and their durability can be seen in Fig (6). The main trees species in Dutch forests are Scots Pine (*pinus sylvestris* L.) and Oak, both sessile (*Quercus robur* L.) and pedunculate Oak (*Quercus petraea*) (Mohren & Vodde, 2006; van der Maaten-Theunissen & Schuck, 2013). Due to the abundance and ability to grow in wet conditions, Oak could be a suitable choice for the durable species used in the “secondary use” sector for construction of houses. In fact, both sessile and pedunculate Oak are amongst the most economically important deciduous forest trees in Europe and have been used for the manufacturing of furniture, floor-boards, paneling, and veneer. They can live for up to 1,000 years and typically achieve a height of 30 m and diameters of up to 1 m (Eaton et al., 2016). The other most abundant species in the Netherlands is Scots Pine, which is a conifer that can reach 35 m in height with a lifespan of approximately 250 years. It is most commonly utilized in furniture and construction industries, such as for construction, fencing, crates, and pallets. It is typically slow growing and rotations in commercial plantations are between 50 to 120 years, based on

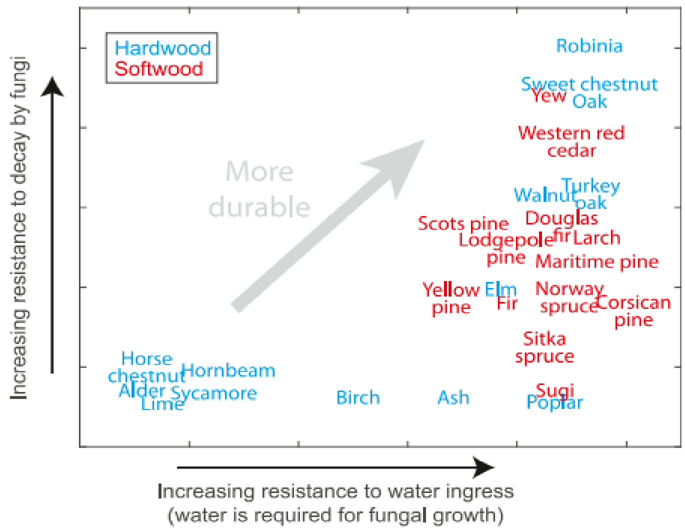


Figure 6. Durability of heartwood of important species grown in Europe. Species towards the top right of the axes are most durable, with those lower and further to the left less durable (Ramage et al., 2017).

climate (Roszyk et al., 2020). While Scots Pine is less durable than Oak, it could still be a viable option for some of the lower quality products in "secondary use." Moreover, the durability of wood products can be further improved by chemical and physical wood treatments to include dimensional stability, resistance to biological degradation, fire resistance, and thermal stability (Ramage et al., 2017).

The next category to consider is that of all the other wood sectors that require less durable wood. Fast growing hardwood species including Birch, Poplar, Eucalyptus and Acacia are mainly used for pulp and paper (Arets et al., 2011). Poplar and Willow, specifically, are fast growing and already present in the Netherlands and could, therefore, be viable tree species given their association with the Dutch landscape and their fast growth rate, creating shorter rotation cycles (Mohren & Vodde, 2006). Further, paper and board producing factories in the Netherlands produce paper and board almost entirely from recovered paper and/or pulp from Poplar and imported Norway Spruce (Unece, 2019). These species can also be utilized in the recycling loop if they are no longer able to be re-used. The reprocessed fibrous materials, or wood waste, can produce paper and packaging products.

Both "high-quality" and "low-quality" species can be utilized in the natural forest, agroforestry, and silvopasture. Especially for the agricultural methods, it could be useful to have a combination of both fast and slow growing species, not only for the diversification of income, but also for the benefits tree crops can offer depending on their species, such as soil health and stability, ecosystem services, and nutrient availability (Dollinger & Jose, 2018).

4.3 Cascade-Use Principle of Wood

Along with the selection of tree species, it is also important to consider the amount of wood entering the "energy production" sector. Theoretically, the burning of wood for energy production should be the last option if recycling and other uses are not possible within the system, according to EU Forest Strategy (European Commission, 2013). This is the so called cascade-use principle, and it suggests that wood be utilized in the following order of priority: wood-based products, re-use, recycling, bioenergy, and disposal (Ramage et al., 2017). It implies that that raw material from forests or agriculture should be first used for buildings, furniture, and others products with a long life span, while energy from biomass should preferably be derived from wood waste, residues, and recycled products (Ciccarese et al., 2014). According to the MFA for OC and the Netherlands, however, 58% of the wood produced is not going to the production of wood products, but instead, directly to energy production. This could be due to the fact that the amount of wood coming from the forest and agriculture does not only include roundwood used for construction and products, but also wood biomass coming from short-rotation cycles where trees are too small and not suitable for structural use (Ramage et al., 2017). Because of this, the large initial percentage of wood being directly used for energy production should not significantly impact the wood supply for construction and other uses. Managing the tree cycles efficiently in OC could further limit the amount of wood going directly to energy production and OC could then focus mainly on using other renewable energy sources, such as solar and wind power.

Regarding the wood entering "energy production" that is already in the system, it is shown that during the processing of roundwood, approximately 50% is recovered for viable wood products while the rest, such as wood residues or second grade trees infected by rot or fungus, is used for biomass fuel (Lindberg & Tana, 2012). Also, the wastes from "material consumption (wood)", "recycled wood", and "material consumption (paper)" all flow into the "energy production" sector in OC when the wood is no longer able to be re-used or recycled. During the processing of the wood, by-products such as remaining dust, shavings, and fibers can be used as biomass fuel, as well as logs and branches of small diameter that are not considered appropriate for constructional uses (Vasiliki et al., 2018). This also includes tree bark, as it is a common by-product from the sawmill and pulp industry and is currently one of the main solid wood fuel used in heat and power production in countries such as Finland (Routa et al., 2021).

In order for OC to have a feasible recycling system with such high rates, it is also important to have a well-designed and properly managed scheme. There needs to be an extra step in the waste separation process to divide reusable and low-quality wood. Additionally, the reusable pieces needs to be treated (i.e. removed of dirt and nails) and this step is often labor intense and can be costly (Goverse et al., 2001). Another important consideration in the end-of-life scenarios for wood concerns the disposal stage. Because it is assumed that OC will not be disposing any wood and instead, using the low-quality wood for energy, the disposal scenario is not incorporated into the MFA. However, some wood products contain hazardous components and cannot be used as biofuel but instead, need to be disposed in a landfill or incinerated at a special plant. This can be avoided in OC, however, with careful planning and management, such as applying biodegradable paints and using non-toxic wood treatments.

4.4 Is the location of Orchid City feasible?

While OC is an innovative and sustainable concept, especially with regards to the efficient wood flow, it is important to consider its feasibility in the Netherlands. The Netherlands is a relatively small country with a total surface area of 4.2 million hectares (including inland and open water) with half of the surface area being used in agriculture and a third for nature, water, and recreation (Statistics Netherlands, 2020). Therefore, land availability and population density may be an issue when considering the placement of an OC with 50,000 inhabitants. First, a region or space needs to be identified where the population density is less than 50,000 to ensure that no inhabitants will be displaced. As can be seen in Fig. 7, the northern and northeastern regions of the Netherlands have a lower population density than regions with large cities like Amsterdam, Rotterdam, and Utrecht. For example, the municipality of Westerveld in Drenthe is 278.4 km^2, has a population of 19,661 inhabitants, and a population density of 70.63/km^2. Considering that the space needed, both open and built, for an OC of 50,000 inhabitants is 19,700 ha (or 197 km^2), the municipality of Westerveld, for example, could be a viable option for the placement of OC.

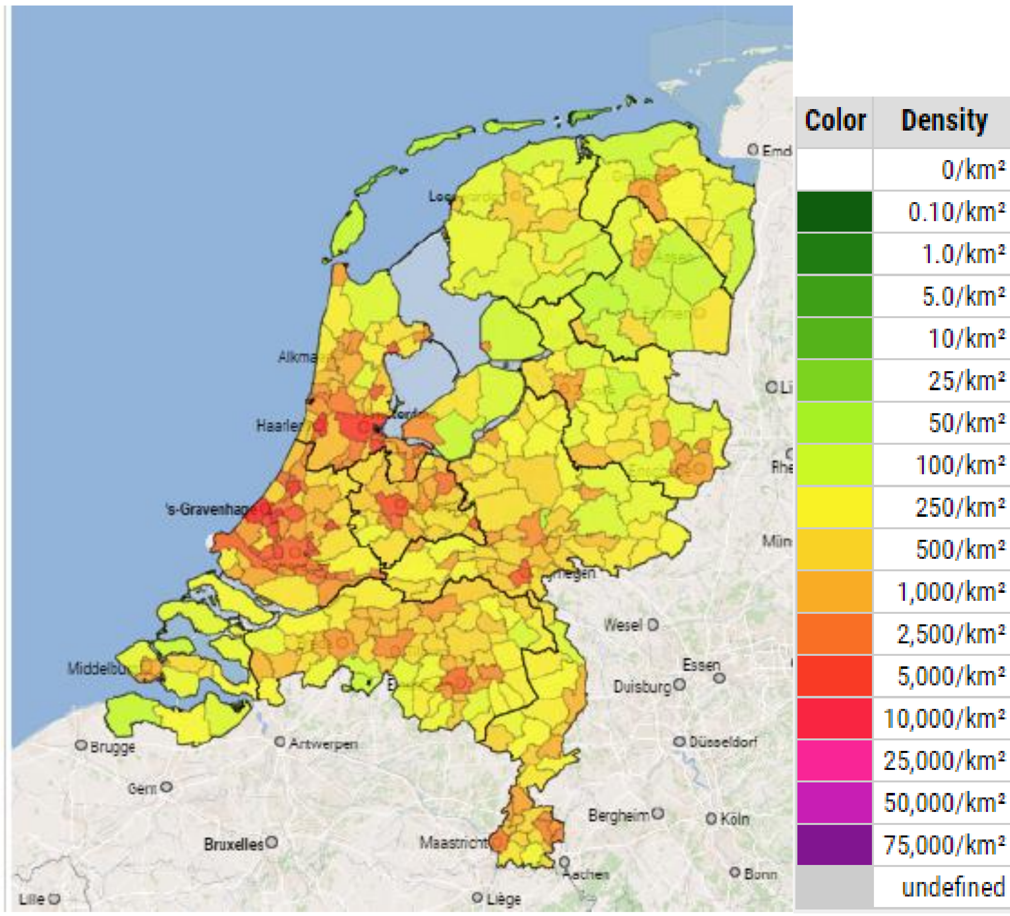


Figure 7. Population density of Dutch provinces and municipalities in 2021 (Brinkhoff, 2021).

It is not only important to consider the spatial and population feasibility, but also the land availability, given that the surface area in the Netherlands is used in various ways. In the province Drenthe, for example, 21.4% of the land is used for nature, water, and recreational areas, 9.1% is used for built-up area and road surface, and 69.5% is used for farmland (Schelhaas & Clerkx, 2015). In OC, 17.9% of land is used for nature and water, 2.6% is used for the built environment, and 78% is used for farmland. While the ratios between the two are different, they are relatively similar and could potentially be feasible from transitioning an average Dutch municipality to an OC community. However, not all Dutch provinces with low population densities have similar land uses. Flevoland, for example, has multiple municipalities with large land space and low population densities, however, the province is comprised of 53% natural areas, 6.1% built environment, and only 40.8% farmland. This could make it difficult to place an OC here due to its high farmland demand and the already present natural areas that contribute to the biodiversity of the Netherlands.

Other major contributions towards the feasibility of OC include land prices as well as regulations and policies. There are many stakeholders involved in the buying and selling of land in the Netherlands, including Dutch municipalities who are actively involved in order to pursue "active land policy" to achieve policy goals and acquire agricultural land before reselling it (van Oosten et al., 2018). Property developers have also become highly involved in the land market in recent years which has raised the pressure on the market as well as increased the land rents (Buitelaar, 2010). Many factors go into not only the ability to purchase land, but also the price, which depends on the location and what the land will be used for. Prices for arable land in the Netherlands has rose steeply in the last few decades, ranging from €40,000 to €120,000 per hectare (*Land - Boerengroep*, 2017). Except has been building a model to answer the financial questions for the last year. While initial indications look very positive, no conclusive answer has been indicated. It is therefore important to first indicate the location of OC and the feasibility of the project in order to maintain adequate forestry and agriculture techniques to meet wood demands within the community.

5. Conclusion

Orchid City is an innovative concept that aims to provide a resilient, self-sustaining community for both present and future generations. With sustainability as its core principle, it focuses on using renewable energy, promoting a circular economy, and providing health and happiness to its inhabitants while still being financially feasible. One material in particular that needs to be taken account when trying to promote self-sufficiency is wood, as it has great potential to be grown completely in OC as opposed to relying on imports. Therefore, the research questions "Can Orchid City be self-sufficient in its wood demand?" and "Is Orchid City feasible in the Netherlands, in terms of wood flow and location?" were proposed in this report and answered via an MFA and literature review. The MFA on wood showed that OC can produce its own wood via the natural forest, agroforestry, and silvoculture techniques while meeting the demands of each wood sector without importing foreign wood. Therefore, the total amount of wood needed to be produced is 24,275 tonnes per year and OC exceeds this amount by 4,686 tonnes. The corresponding land space, in hectares, needed to fulfill these growth requirements are 2,410 for natural forest, 2,994 for agroforestry, and 9,039 for silvopasture. Finally, the possibility of locating OC in the Netherlands was discussed and it was concluded that from a wood flow perspective, it is possible that an OC could be placed in the Netherlands. However, further research needs to be done on potential constraints related to current land prices, land regulations and policies. Future studies could further research the feasibility of OC in the Netherlands, as many factors besides just the geographical location and physical scale of the community are important to consider, such as the social, political, and financial aspects. However, these considerations were beyond the scope of this report. Additional research could also be conducted on the specific designs and layouts of the natural forests and agriculture in OC to have a better perspective on the growing, harvesting, and management abilities of the trees. Specific species require certain management styles, rotation cycles, and growing conditions and such factors could be specified as a recommendation for the further development of the OC concept.

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