THÜNEN

TiMBA - Timber market Model for policy-Based Analysis: Documentation of model structure, data, and parameters

TI-FSM - Thünen Institute Forest Sector Modelling

Thünen Working Paper 263

TI-FSM

TI-FSM is an authors’ collective that jointly developed and program TiMBA. The members of the collective in alphabetical order are Honkomp, Tomke; Morland, Christian; Schier, Franziska* (Lead Contact); and Tandetzki, Julia (former Thünen Institute of Forestry).

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Thünen Working Paper 263

Braunschweig/Germany, March 2025

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Preface

The Timber market Model for policy-Based Analysis - TIMBA - is a partial economic equilibrium (PE) model for the global forest products market. The model endogenously simulates wood and wood-based products' production, consumption, and trade across 180 countries. TIMBA computes the market equilibrium for each country and product in a given year by maximizing the social surplus in the global forest sector. During the equilibrium process, commodity production, consumption, and prices are recursively balanced for each simulation period. TiMBA is Python-based, with a modular structure built entirely using open-access libraries.

This work is the result of the collaborative efforts of the forest sector modeling team at the Thünen Institute of Forestry from 2018 to 2024. In recent years, several people have made significant contributions to this project. Without their support, reflection, and constructive criticism, this undertaking would not have been as successful as it is today. We want to express our gratitude to all of them. In particular, we would like to thank

- Pixida GmbH and especially Tobias Hierlmeier for professional support in revising and restructuring the model architecture and code and being a valuable help in programming tasks.
- Thünen Institute Service Centre for Research Data Management and especially Harald von Waldow for providing expertise, consultation, and support during the release process.
- Holger Weimar and Matthias Dieter for the trustful and cooperative working environment, rational support, critical discussion, and the opportunity to keep going.
- Johanna Schliemann for immediate technical support whenever needed.
- Johann Heinrich von Thünen Institute, and in particular the Institute of Forestry, and their representatives for providing financial resources, as well as acquiring third-party funding to support the development.

Summary

This working paper details the underlying structure of the Timber market Model for policy-Based Analysis - TiMBA - as well as the data and parameters used for modeling. TiMBA is a partial economic equilibrium model for the global forest sector. The market equilibrium is subject to market clearance and constraints, balancing raw materials, product manufacturing, and consumption while limiting international trade (Paul A. Samuelson 1952). The model structure distinguishes three types of roundwood (fuelwood, coniferous and non-coniferous industrial roundwood), two additional raw products for paper production (other fiber pulp and waste paper), two intermediate products (mechanical and chemical wood pulp) and eight finished products (coniferous and non-coniferous sawnwood, veneer sheets and plywood, particle board, fibreboard, newsprint, printing and writing paper, and other paper and paperboard). Except for sawnwood, intermediate and end products are produced from a mix of coniferous and non-coniferous industrial roundwood.

Scenario simulations with TiMBA are guided by certain parameters and assumptions depicting how the forest sector might unfold in the future. In the model framework, wood products are implicitly treated as perfect substitutes, regardless of their origin, as long as they belong to the same product. Thus, consumption of final wood products is merely shifted by changes in income and price (Murray et al. 2004), making the gross domestic product (GDP) an important model driver. The supply of roundwood depends on wood prices and forest development, which is determined by the growth dynamics of forest stocks, the change in forest area, and harvest volumes. Forest area development and timber supply are coupled to GDP per capita developments based on the concept of the environmental Kuznets curve (Panayotou 1993).

The base year for the scenario simulations with the current version of TiMBA is 2020. The input data used for simulation with TiMBA must be calibrated and provided in a source file before the model runs. This file is provided together with the model. The calibration procedure is described in Buongiorno (2015) and altered according to (Schier et al. 2018). The input data for calibrating the model are obtained from three global databases: The FAOSTAT Database on Forestry Production and Trade (FAOSTAT 2022), the FAO Global Forest Resources Assessment (FRA) (FAO 2022) and the World Bank Development Indicators (World Bank 2022). In its basic version , price and income elasticities of demand are mainly taken from Morland et al. (2018). TiMBA uses projections of GDP and population growth made in the Shared Socioeconomic Pathways scenario “Middle of the road” (SSP2) provided by Keywan Riahi et al. (2017). Technology developments (input-output coefficients and manufacturing cost) are estimated based on historical developments from 1993 - 2020, while information on trade inertia and cost is based on WTO data as provided in the Global Forest Products Model (Buongiorno 2015, 2021). All developments of exogenous parameters until 2050 are provided in an input file (“scenario_input.xlsx”). The model output comprises production, consumption, trade quantities, prices, and forest development information. The model concept is based on the formal description of Buongiorno et al. (2003) and Buongiorno (2015).

Table 1: Model characteristics overview

Model type	Dynamic and static equilibrium market model
Geographical scope	Global (180 countries)
Temporal Dimension	Recursive long-term analyses
Products	Raw-, intermediate, end products
Data sources	FAOSTAT, FRA, WDI, Comtrade, WTO, IIASA-SSP
Software Implementation	Python 3.9, 3.10, 3.11, 3.12.6
Current model version	TiMBA 1.0.3
Permanent link to code repository	https://zenodo.org/records/13842492
Code License	APGL3
Code versioning system used	GitHub, Zenodo
Solver environment and Solver	CVXPY, OSQP

Source: TI-FSM et al. (2024)

Keywords: Forest sector analysis, partial equilibrium model, wood product markets, forest-based production, international trade, python, programming, model documentation, policy impact assessment

Zusammenfassung

Dieses Working Paper beschreibt das Timber Market Model for Policy-Based Analysis (TiMBA) sowie die in dem Modell verwendeten Daten und Parameter. TiMBA ist ein partielles Gleichgewichtsmodell für den globalen Holzmarkt. Die Modellstruktur unterscheidet drei Arten von Rundholz (Brennholz, sowie Nadelholz und Laubholz für die industrielle Nutzung), zwei zusätzliche Rohstoffe für die Papierproduktion (andere Zellstoffe und Altpapier), zwei Zwischenprodukte (mechanischer und chemischer Papierzellstoff) und acht Endprodukte (Nadel- und Laubschnittholz, Furnier- und Sperrholz, Spanplatten, Faserplatten, Zeitungen, Druck- und Schreibpapier sowie sonstige Papiere und Pappen). Abgesehen vom Schnittholz können Zwischen- und Endprodukte aus einem Input-Mix aus Nadelholz und Laubholz hergestellt werden. Exogene Parameter und Annahmen geben einen Leitfaden, wie sich die Gesellschaft und der Forstsektor in der Zukunft entwickeln könnten. Innerhalb des Models werden Holzprodukte, unabhängig von ihrer Herkunft, als perfekte Substitute behandelt solange sie demselben Produkt angehören. Daher wird die Nachfrage nach Holzprodukten lediglich durch Änderungen von Einkommen und Preisen verschoben (Murray et al. 2004), wobei das Bruttoinlandsprodukt (BIP) ein wichtiger Treiber des Modells ist. Das Angebot an Rundholz hängt von Holzpreisen und der Wachstumsdynamik der Waldbestände die durch Veränderungen der Waldfläche und Erntemengen bestimmt wird. Basierend auf dem Konzept der Umwelt-Kuznets-Kurve (Panayotou 1993) sind die Entwicklung der Waldfläche und die Holzversorgung an die Entwicklungen des BIP pro Kopf gekoppelt.

In der aktuellen Version von TiMBA ist das Basisjahr für die Szenario-Simulationen 2020. Die für die Simulation verwendeten Eingangsdaten müssen kalibriert und in einer Quelldatei bereitgestellt werden. Diese Datei wird zusammen mit dem Modell bereitgestellt. Das Kalibrierungsverfahren ist in Buongiorno (2015) beschrieben und gemäß (Schier et al. 2018) erweitert. Die Eingangsdaten für die Kalibrierung des Modells stammen aus der FAOSTAT-Datenbank für Produktion und Handel von Forst- und Holzprodukte (FAOSTAT 2022), dem FAO Global Forest Resources Assessment (FRA) (FAO 2022) und den World Bank Development Indicators (Weltbank 2022). Die Preis- und Einkommenselastizitäten der Nachfrage werden hauptsächlich aus Morland et al. (2018) übernommen. Die Projektionen für das BIP und des Bevölkerungswachstums kommen aus denm Shared Socioeconomic Pathways-Szenario „Middle of the Road“ (SSP2) (Riahi et al. 2017). Weitere exogene Spezifikationen zu Technologieentwicklungen (Input-Output-Koeffizienten und Herstellungskosten) wurden auf Grundlage historischer Entwicklungen von 1993 - 2020 geschätzt, während Informationen über Handelshemmnissen und Kosten auf WTO-Daten basieren, die im Global Forest Products Model (GFPM) bereitgestellt werden (Buongiorno 2015, Buongiorno 2021). Alle Entwicklungen der exogenen Parameter bis 2050 werden ebenfalls in der Eingabedatei („scenario_input.xlsx“) bereitgestellt. Die Modellausgabe umfasst Produktions-, Konsumptions-, Handelsmengen, Preise und Informationen zur Waldentwicklung. Das Modellkonzept basiert auf der formalen Beschreibung von Buongiorno et al. (2003) und Buongiorno (2015).

Table 1: Modell Charakteristika

Model type	**Dynamic and static equilibrium market model**
Geographical scope	Global (180 countries)
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Products	Raw-, intermediate, end products
Data sources	FAOSTAT, FRA, WDI, Comtrade, WTO, IIASA-SSP
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Code License	APGL3
Code versioning system used	GitHub, Zenodo
Solver environment and Solver	CVXPY, OSQP

Quelle: TI-FSM et al. (2024)

Schlüsselwörter: Analyse des Forst- und Holzsektors, Partielle Gleichgewichtsmodell, Holmärkte, Forstwirtschaftliche Produktion, Internationaler Handel, Python, Programmierung, Modell-Dokumentation, Politikfolgeabschätzung

1 Introduction

This paper provides an overview of the data and parameters used in the **Timber market Model for policy-Based Analysis (TiMBA)** and gives an introduction to the model structure and specifications.

TiMBA is a multi-periodic partial economic equilibrium model for the global forest sector. The model simulates production, imports, exports, consumption quantities, and prices, as well as technological and forest development for 16 commodities and 180 countries. The prices of wood and wood-based products are endogenous to the model. The market equilibrium is subject to market clearance and constraints, balancing necessary raw materials and produced wood products and limiting the trade (Paul A. Samuelson 1952). In the model framework, wood products are implicitly treated as perfect substitutes, regardless of their origin, as long as they belong to the same product type. As the optimization of the market equilibrium in a given year does not include elasticity of substitution, demand is merely shifted by changes in income and price (Murray et al. 2004).

TiMBA distinguishes raw, intermediate, and end products (Figure 1). The model structure currently includes three types of roundwood (fuelwood, coniferous and non-coniferous industrial roundwood), two additional raw products for paper production (other fiber pulp and waste paper), two intermediate products (mechanical and chemical wood pulp, the latter including semi-chemical wood pulp) and eight finished products (coniferous and non-coniferous sawnwood, veneer sheets and plywood, particle board (including OSB), fibreboard, newsprint, printing and writing paper, and other paper and paperboard). Except for sawnwood, intermediate and end products are produced from a mix of coniferous and non-coniferous industrial roundwood. Products are determined by the definitions as applied for the FAO reporting (UNECE 2024). Production of intermediate and end products is modeled using input-output coefficients to determine the level of input needed to produce one unit of output. The production quantity depends on raw material prices, manufacturing costs, and commodity prices. While the prices of raw materials and intermediate and end products are simulated endogenously, the cost of manufacturing and transport are given exogenously.

Consumption of wood-based products is tied to country-specific income (GDP) and price levels via price and income elasticities taken from Morland et al. (2018). Demand for wood-based products is positively correlated to income; thus, an increase in income leads to an increase in demand, while demand decreases with increasing product price.

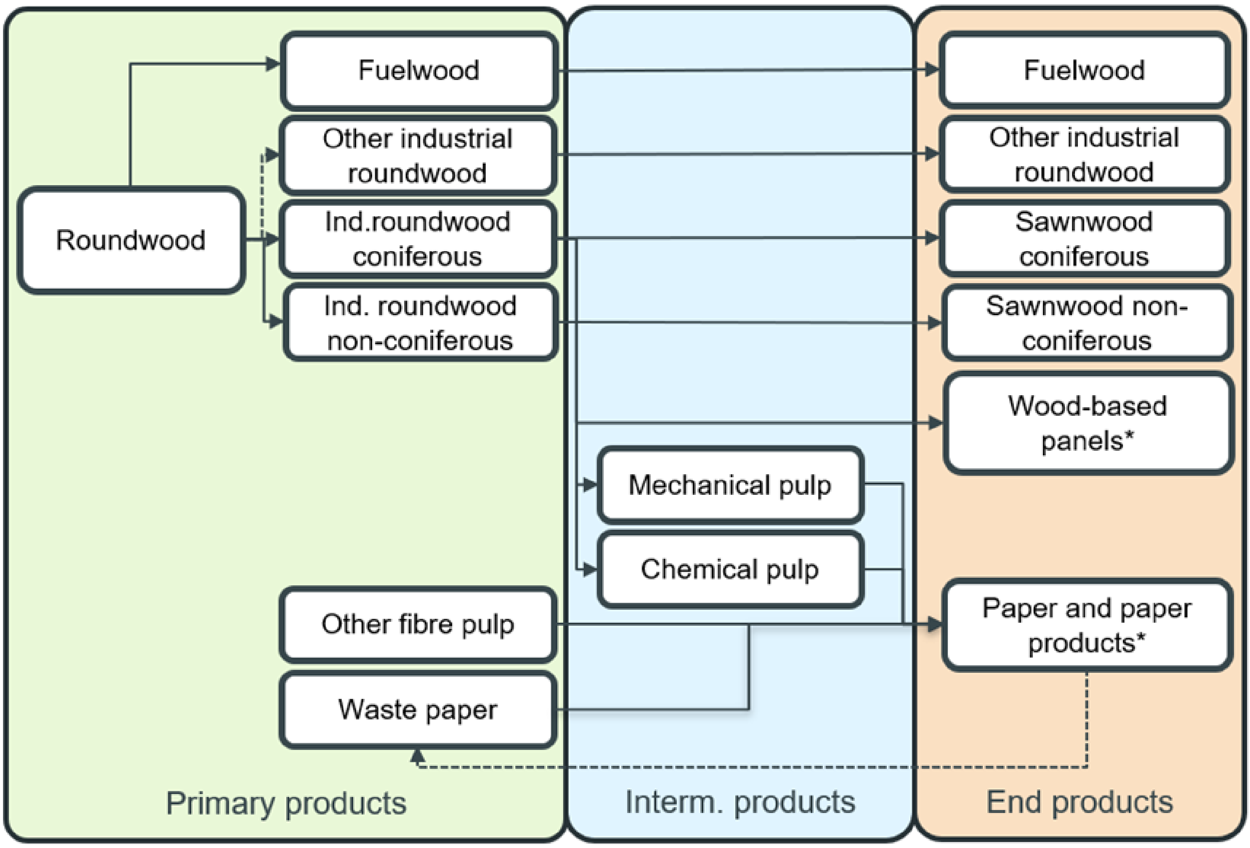
The supply of roundwood depends on wood prices and stock volume, which in turn is determined by the growth dynamics of forest stock, the change in forest area, and harvest volumes.

In TiMBA, each country imports from and to the world market. Trade occurs when the price of a product in a particular country exceeds the foreign price plus transport costs, or vice versa, is lower than the world price. Simultaneously, there is a need for trade due to the scarcity of goods in one country. This dynamic consequently incentivizes international trade as countries attempt to balance their production and consumption through imports and exports. The difference in production costs and prices between countries further reinforces the need for such trade interactions to optimize resource allocation and market equilibrium.

The base year for the scenario simulations with the current version of TiMBA is 2020. Model simulations are embedded in an overarching workflow comprising several consecutive software components (see section 3.8). Input data for TiMBA are calibrated prior to model runs: Besides the main application TiMBA, this workflow comprises supportive packages to load, smooth, and calibrate model input data to generate input files tailored to specific research questions automatically. The primary purpose of the model calibration is to correct cross-sectoral data inconsistencies in country records on production and trade along the value-adding chain. After smoothing input data for outliers, a solver-based goal programming routine is employed to compute those production quantities, input-output coefficients, and costs that minimize the sum of the weighted deviational variables from observed to calibrated production in the base year. The calibration procedure is described in Buongiorno and Zhu (2014) and altered according to Schier et al. (2018). Scenario simulations with TiMBA are guided by specific parameters and assumptions shaping model simulations (see section 2.7). The model input file containing calibrated market data, parameters, and other exogenous assumptions is provided together with the model.

The model output comprises information about production, consumption, trade quantities, and prices, as well as forest development and technology.

Figure 1: Material flow and product structure in TiMBA



Source: own illustration

Note Figure 1: The amounts of coniferous and non-coniferous other industrial roundwood are calculated out of the total amount of industrial roundwood and summed up as total other industrial roundwood for model simulation. Fuelwood is not further processed before being sold as the end product. Wood residues used as input in the wood-based panel and pulp sectors are not explicitly modeled in TiMBA but are implicitly considered by input-output coefficients. All produts except for sawnwood can be produced of a mix of raw materials. Thus, wood-based panels could be made from a single input or a mixture of coniferous and non-coniferous roundwood, while paper products could be made from a single input or a mixture of pulps and waste paper. Other fiber pulp and waste paper are inputs to the paper sector.

2 Model formulation and specifications

The following section describes the model concept in detail. It is based on the formal description of the GFPM (Buongiorno et al. 2003; Buongiorno 2015).

TiMBA computes periodic production, import, exports, consumption, and prices for the forest-based sector, considering available forest resource endowment and cost, technology, and trade constraints. For each period, the recursive market model is composed of a static and a dynamic phase.

TiMBA calculates a global equilibrium across products and countries in the static phase in a given year. The optimization problem is solved for each year by maximizing the economic welfare, defined as the sum of the producer and consumer economic surplus.

In the dynamic phase, changes in the equilibrium conditions (shifts in parameters determining the model outcome such as growing GDP, population or cost) are updated from one period to the next.

The optimization problem (equation 1) is maximized using the CVXPY package (Steven Diamond and Stephen Boyd 2016; Agrawal et al. 2018) and the OSQP solver (Stellato et al. 2020):

$$\begin{aligned}\max_Z = \sum_i \sum_k \int_0^{D_{i,k}} P_{i,k}\left(D_{i,k}\right) dD_{i,k} - \sum_i \sum_k \int_0^{S_{i,k}} P_{i,k}\left(S_{i,k}\right) dS_{i,k} \\ - \sum_i \sum_k \int_0^{Y_{i,k}} m_{i,k}\left(Y_{i,k}\right) dY_{i,k} - \sum_i \sum_j \sum_k c_{i,j,k}\, T_{i,j,k}\end{aligned} \tag{1}$$

with P as price, D as demand, S as supply, Y as manufacturing, m as manufacturing costs, T as trade, c as transportation costs and the indices i as the domestic country, j as trade partner country and k as commodity.

The maximization is subject to the following optimization constraint that balances all material flows along the represented supply chain for each country while accounting for trade:

$$S_{i,k} + Y_{i,k} + \sum_j I_{j,k} = D_{i,k} + \sum_n a_{i,k,n}\, Y_{i,n} + \sum_j X_{j,k} \tag{2}$$

Equation 2 forms for the country (i) and commodity (k) the specific material balance which imposes that the domestic supply of raw materials ($S_{i,k}$) plus the imports ($I_{j,k}$) and the manufactured quantity ($Y_{i,k}$) must be equal to the domestic demand ($D_{i,k}$) of final products plus the input to manufacture other products ($Y_{i,n}$) plus the exports ($X_{j,k}$). $a_{i,k,n}$ depicts the amount of input of product k to produce one unit of product n. The dual values of the material balance (shadow prices) are used as product prices in TiMBA. The model is delivered with different material balance options, allowing the user to control the mathematical form of the constraint that is integrated into the optimization. The chosen form will influence the computation time of the solver and might impact the resulting shadow prices (see section 3.4).

2.1 Demand

The demand for wood-based products in TiMBA is correlated to the income (y) and wood prices. The inverted demand function (equation 3) defines the quantity of demand for end products where D^* is the current demand of product k in country i at last period's price, $P_{i,k,t-1}$ is the last period's price and δ is the price elasticity of demand.

$$P_{i,k}\left(D_{i,k}\right) = P_{i,k,t-1}\left(\frac{D_{i,k}}{D^*_{i,k}}\right)^{1/\delta_{i,k}} \tag{3}$$

The demand can be shifted exogenously over the simulation periods (equation 4) to mirror socioeconomic changes using g_y as the growth rate of income, g_D as the exogenous growth rate of demand, α as exogenous parameters to shift the influence of the growth rates and t as the time index.

$$D^*_{i,k} = D_{i,k,t-1}\left(1 + \alpha_y g_y + \alpha_{D,t-1} g_{D,t-1} + \alpha_0\right) \tag{4}$$

2.2 Supply

The supply of roundwood depends on wood prices and forest development, which is determined by the growth dynamics of the forest stock, the change in forest area, and harvested volumes. The inverted supply function defines the quantity of supply for raw products (equation 5) where S^* is the current supply of product k in the country i at the last period's price and λ is the supply price elasticity. Further details on the connection between the supply and the forest stock and area dynamics are provided in the chapter 2.5.

$$P_{i,k}\left(S_{i,k}\right) = P_{i,k,t-1}\left(\frac{S_{i,k}}{S^*_{i,k}}\right)^{1/\lambda_{i,k}} \tag{5}$$

To reflect socioeconomic and environmental changes, the supply function can be shifted exogenously over the simulation periods according to equation 6. In the following equation, g_y represents the income growth rate, and g_I depicts the growth rate of forest inventory. β_y is the supply elasticity of income and β_I is supply elasticity relative to the inventory. In TiMBA, the supply elasticity of income is product-specific, differentiating between raw materials sourced from the forest and raw materials for paper and paper product production.

$$S^*_{i,k} = S_{i,k,t-1}\left(1 + \beta_y g_y + \beta_I g_I\right) \tag{6}$$

Forest area development and, thus, timber supply is coupled with GDP per capita developments based on the concept of the environmental Kuznets curve (Panayotou 1993). The section 2.5 provides further details.

2.3 Manufacturing

Manufacturing of intermediate and end products is determined using country- and product-specific input-output coefficients and manufacturing unit costs. The product- and country-specific manufacturing costs are calculated based on the manufactured quantity according to equation 7 where $m_{i,k}$ are the manufacturing cost, m^* the current manufacturing cost at the last period's manufactured quantity, and ζ is the elasticity of manufacturing cost concerning the manufactured quantity.

$$m_{i,k}\left(Y_{i,k}\right) = m^*_{i,k,t-1}\left(\frac{Y_{i,k}}{Y_{i,k,t-1}}\right)^{\zeta_{i,k}} \tag{7}$$

The manufacturing costs of each product represent all costs of inputs not explicitly modeled in TiMBA (labor, energy, capital, additional materials), excluding costs of raw materials in a given year and country. For net exporting countries, raw material costs are computed by multiplying the domestic prices of input products by the input-output coefficients. For net importing countries, raw material costs are computed by multiplying the world market price of input products by the input-output coefficients.

The input-output coefficient of each product in a specific year and country states the amount of input necessary to produce one unit of output. A goal programming procedure is applied to obtain the input-output coefficients and manufacturing costs for the base period. Their calculation depends on production and trade data from FAOSTAT (2022) and exogenous bounds on minimum and maximum input per output and cost (Buongiorno 2015).

Manufacturing costs and input-output coefficients can be exogenously shifted over the calculated periods to reflect technological development. While input-output coefficients are updated in TiMBA, manufacturing costs are developed based on an exogenous growth rate g_m following equation 8.

$$m_{i,k}^{*} = m_{i,k,t-1}(1 + g_m) \tag{8}$$

2.4 Trade

In TiMBA, all countries import from and export to a virtual buffer region called zy. Since all countries trade via the region zy, bilateral trade fluxes are not represented in the basic model version. The trade in TiMBA depends on the transportation costs ($c_{i,j,k}$), the world price, and trade inertia bounds. Equation 9 represents the country and product-specific unit cost of transportation ($c_{i,j,k}$) where c^* is the current transportation cost at the last period's traded quantity and τ the elasticity of transport cost with respect to traded quantity.

$$c_{i,j,k}(T_{i,j,k}) = c_{i,j,k,t-1}^{*}\left(\frac{T_{i,j,k}}{T_{i,j,k,t-1}}\right)^{\tau_{i,j,k}} \tag{9}$$

In the base period, $c_{i,j,k}$ is determined by equation 10 where $f_{i,j,k}$ represents the freight cost per unit of transported product k between country i and j. $t_j k^X$ and $t_j k^I$ depict the export and import ad-valorem tax rates, respectively. $P_{i,k,t-1}$ is the world price of the previous period. In TiMBA, the net importing countries carry the transportation costs plus the world price. The price for net exporting countries is the world price.

$$c_{i,j,k} = f_{i,j,k} + t_j k^X P_{ik,t-1} + t_j k^I f_{i,j,k} + P_{ik,t-1} \tag{10}$$

Further, trade in TiMBA is constrained by trade inertia bounds which depict an exogenous development range based on the traded quantity of the previous period (equation 11) where ${T_{i,j,k}}^L$ and ${T_{i,j,k}}^U$ are the lower and upper bounds, respectively. For the first period, trade inertia bounds are close to zero to comply with trade quantities from the calibration. To avoid infeasibility, trade inertia bounds are introduced as a flexible constraint in the optimization. In this way, TiMBA can trespass the trade inertia bounds when necessary to find an optimal solution. However, trespasses are sanctioned in the objective function (Z) by multiplying the difference by the lower or upper bound with the world prices (equation 11 - 13).

$$T_{i,j,k}^{L} \leq T_{i,j,k} \leq T_{i,j,k}^{U} \tag{11}$$

$$\Delta T_i jk = \left(T_{i,j,k}^{L} - x\right) + \left(x - T_{i,j,k}^{U}\right) \tag{12}$$

$$Z - \Delta T_{i,j,k} W P_k \tag{13}$$

In TiMBA, the world prices are the dual values (shadow prices) of the material balance for the region zy, which equilibrate all imports ($T_{i,j,k}$) and exports ($T_{j,i,k}$) globally by supplying the deficits ($S_{zy,k}$) or absorbing the surpluses ($D_{zy,k}$) in production according to equation 14:

$$\sum T_{i,j,k} + S_{zy,k} - \sum T_{j,i,k} - D_{zy,k} = 0 \tag{14}$$

Freight costs and ad-valorem tax rates for imports and exports can be exogenously changed over the simulation periods to mirror changes in socioeconomic circumstances (e.g., changes in trade agreements) using the following equation 15:

$$c_{i,j,k}^{*} = c_{i,j,k,t-1}\left(1 + g_f + g_t^{i} + g_i^{x}\right) \tag{15}$$

where g_f is the growth rate of freight costs, g_t^i is the growth rate of import taxes and g_t^x is the growth rate of export taxes.

2.5 Forest

The development of forest area is simulated exogenously using the environmental Kuznets curve (EKC) approach (Kuznets 1955; Grossmann and Krueger 1991). This concept describes an inverted U-shaped relationship between income development and deforestation. Initially, as GDP per capita rises, deforestation increases until it reaches a turning point. Beyond this point, further increases in GDP per capita result in a decreasing rate of deforestation (Panayotou 1993). Forest stock growth is linked to the area's development (equation 16).

$$g_I = \left(1 + \gamma_0 \left(\frac{I_{t-1}}{A_{t-1}}\right)^{\sigma} + (\alpha_0 + \alpha_1 y')e^{\alpha_2 y'}\right) \tag{16}$$

with I as forest inventory, A as forest area, σ as elasticity of inventory per unit area, y' as per capita income and γ and α as exogenous parameters to shift the growth rates.

Forest stock evolves according to the growth-drain equation 17 following Buongiorno (2015):

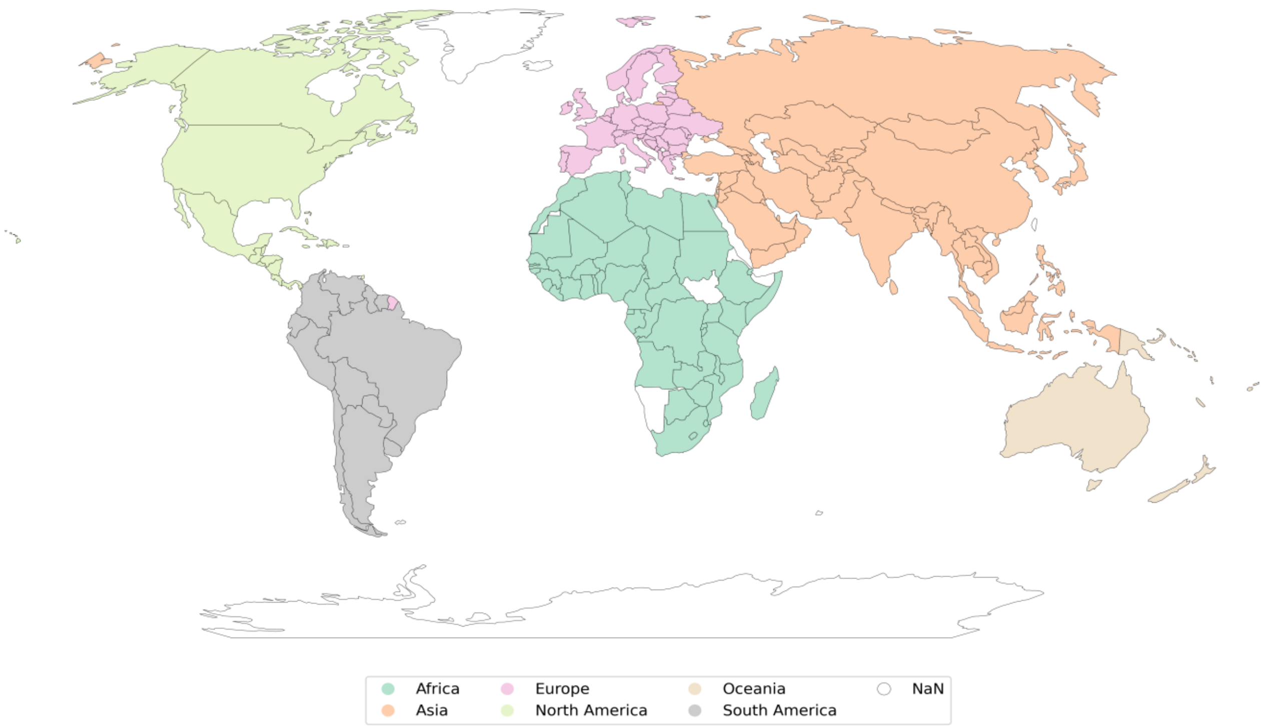
$$I_t = (I_{\mathrm{t}-1} + (g_a + g_u + g_u^*)I_{\mathrm{t}-1}) - pS_{\mathrm{t}-1} \tag{17}$$

Where g_a is the annual rate of change of forest area, g_u is the periodic rate of forest growth, g_u^* is the adjustment rate of forest growth and $pS_{\mathrm{t}-1}$ is harvest of previous period.

2.6 Countries and Products

For each of the 180 countries considered in the model (Figure 2), TiMBA includes three main sectors along the forest-based value chain: Forestry, the wood-processing industries, and the consumers of forest-based products. Forestry provides the forest resources to supply fuelwood and coniferous, non-coniferous, and other industrial roundwood. Wood-processing industries then transform coniferous and non-coniferous industrial roundwood into intermediate and end products, either used as input for, e.g., paper production or demanded by consumers.

Figure 2: Countries included in TiMBA



Source: own illustration, continental aggregation according to Table A 2

Beyond three types of roundwood, the product structure of TiMBA further distinguishes coniferous and non-coniferous sawnwood, plywood and veneer sheets, particle board including OSB, fiberboard, newsprint, printing and writing paper and other paper and paperboard as end products, as well as mechanical and chemical wood pulp (including semi-chemical wood pulp) as intermediate and other fiber pulps and waste paper as additional raw materials. TiMBA simulates the production, import, export, consumption, and prices for these products annually and in each country. As shown in Table 2, not every product is subject to supply, trade, manufacturing, or consumer demand.

Table 2: Items simulated with TiMBA

Item	Item Code	Unit	S	M	D	T	P	G
Fuelwood	80	1,000 m^3	x		x	x	x	
Industrial Roundwood C	81	1,000 m^3	x			x	x	
Industrial Roundwood NC	78	1,000 m^3	x			x	x	
Oth Industrial Roundwood	82	1,000 m^3	x		x		x	
Sawnwood C	83	1,000 m^3		x	x	x	x	
Sawnwood NC	79	1,000 m^3		x	x	x	x	
Plywood and Veneer	84	1,000 m^3		x	x	x	x	
Particle Board, incl. OSB	85	1,000 m^3		x	x	x	x	
Fibre Board	86	1,000 m^3		x	x	x	x	
Mechanical Pulp	87	1,000 t		x		x	x	
Semi chem. and Chem. Pulp	88	1,000 t		x		x	x	
Other Fibre Pulp	89	1,000 t	x	x		x	x	
Waste Paper	90	1,000 t	x			x	x	
Newsprint	91	1,000 t		x	x	x	x	
Print. and Writing Paper	92	1,000 t		x	x	x	x	
Other Paper and Paperb.	93	1,000 t		x	x	x	x	
Forest Area	-	1,000 ha						x
Forest Stock	-	million m^3						x

Source: own representation based on Buongiorno et al. (2003) and Buongiorno (2015), product definitions according to the FAOSTAT (UNECE 2024) and FRA (FAO 2018) reports

Note: S = Supply; M = Manufacturing, D = Demand, T = Trade, P = Price, G = Growth

2.7 Overview on Input Data and Parameter

TiMBA uses input data and model parameters from various sources. Input data for TiMBA are subject to a goal-programming-based calibration procedure that tackles data inconsistencies and determines initial input-output coefficients and manufacturing costs along the forest-based value chain. The model calibration for TiMBA follows the procedure formally described in Buongiorno (2015) and modified by Schier et al. (2018). Currently, the calibration procedure is not included in the TiMBA package. The calibrated data are provided in the form of an Excel sheet as input for simulations together with the model under https://github.com/TI-Forest-Sector-Modelling/TiMBA.

The input data for calibrating the model are obtained from three global databases: The FAOSTAT Database on Forestry Production and Trade (FAOSTAT 2022), the FAO Global Forest Resources Assessment (FAO 2022) and the World Bank Development Indicators (World Bank 2022).

Data on country-specific production and trade volumes of raw, intermediate, and end products are taken from FAOSTAT (FAOSTAT 2022). Product consumption for the base year is then calculated as production + imports – exports. Further, data on country-specific export values are used to compute the unit product prices in the base year as the total export volume divided by the total export quantity stated in constant US $ of 2018 using the GDP deflator[1] from the World Development Indicators database. Unit prices differ for net-importer and net-

[1] NY.GDP.DEFL.ZS

exporter countries. The unit price of net-importers of a given commodity is the export unit price plus commodity-specific freight costs, and tariffs. Tariffs are derived from WTO Integrated Database (IDB) (WTO 2024) notifications as the average of ad valorem duties for the last current year available of the respective reporter country and product on HS-code level 4 to 6. Freight costs are calculated as freight factor times export unit value. Freight factors are taken from the Forest Sector Model (Buongiorno et al. 2003; Buongiorno 2021) (see Table 1). Data extraction as well as country and product specific calculation of tariffs is provided by Schier et al. (2025).

Data on GDP[2] and population[3] for the base year are derived from the World Development database (World Bank 2022).

Data on national Forest Area are taken from the FRA (FAO 2022). However, data records on Growing Stock on Total Forest Area (Forest Stock) in the FRA are incomplete and thus, were complemented by the authors. A description of data and their generation is provided by Schier et al. (2025).

Wood product consumption is tied to the product price and income (GDP). Elasticities of demand represent these relations. Roundwood production is driven by the prices of raw materials as well as the forest stock density of a country and is represented by respective elasticities. It is assumed that roundwood supply equals roundwood removals from the forest (considering approx. 20 % harvest losses). Supply of wastepaper and other fiber pulp depends on product prices and national income (GDP). All elasticities are summarized in Table 3.

Table 3: Demand and supply elasticities

	Demand elasticity		Supply elasticity		
Commodity	price	income	price	income	forest stock
Fibre Board	-0.4629†	1.0661†			
Fuelwood	-0.1458†	0.5680†			
Newsprint	-0.1208†	0.2371†			
Other Paper and Paperb.	-0.1695†	0.2283†			
Print. and Writing Paper	-0.5188†	0.3626†			
Particle Board, incl. OSB	-0.4923†	0.7502†			
Plywood and Veneer	-0.3534†	0.5960†			
Sawnwood C	-0.3001†	0.4409†			
Sawnwood NC	-0.1221†	0.2162†			
Fuelwood			1.0311‡	-	1.1000¤
Industrial Roundwood C			1.0738†	-	1.1000¤
Industrial Roundwood NC			1.0440†	-	1.1000¤
Oth. Industrial Roudwood	-0.1243¤	-0.0321¤	1.3100¤		1.1000¤
Waste Paper			1.0000¤	0.1710ǂ	-
Other Fibre Pulp			1.0000¤	0.1400¤	-

Source: this is a summarizing table compiled by the authors: † Elasticities are taken from Morland et al. (2018), ‡ adapted based on Morland et al. (2018), ¤ taken from Buongiorno (2021), ǂ taken from Berglund and Söderholm (2003).

Manufacturing of intermediate and end products is determined using country and product-specific input-output coefficients and manufacturing costs. Each product's manufacturing cost represents all inputs not explicitly modeled in TiMBA (e.g., labor, energy, capital, additional materials), excluding the cost of raw materials in a given year and country. The input-output coefficient of each product in a year and country states the amount of input

2 "GDP (current US$)": NY.GDP.MKTP.CD

3 "Population, total": SP.POP.TOTL

needed to produce one output unit. These parameters are determined for each country and product during the model calibration (see above) and depend on production and trade data from FAOSTAT (2022) and fixed bounds, determining the minimum and maximum amount of input per unit of output and manufacturing cost.

Forest stock growth without harvest is negatively correlated to forest density as described by the elasticity of -0.45 (Buongiorno 2015). Via an environmental Kuznets curve, the rate of forest area change is linked to the GDP per capita. The effects of GDP per capita and squared GDP per capita on the forest area annual growth rates are taken from Buongiorno (2015), who estimated the coefficients to be 0.0014 and 0.0898 (see equation 16), respectively. The ratio of wood drain from the forest to harvest is set to be 1.2, meaning that 20 % of the above-ground biomass is left on site after harvesting as logging residues, while 80 % is supplied as roundwood (under bark).

Because of the lack of data, some of the parameters had to be set based on experts' knowledge while accounting for the model's dynamic behavior.

2.8 Exogenous Parameter Development

Currently, TiMBA simulates forests and wood product market developments until 2050. Beyond the endogenous equilibrium process, exogenous shifts of certain parameters reflect the development pathway from year to year. Demand is subject to annual changes following the projected GDP growth and endogenous price developments, so new prices and income levels shift the demand for wood-based products via elasticities. Forest area development and, thus, stock volume and timber supply are coupled to GDP per capita developments based on the concept of the environmental Kuznets curve (Panayotou 1993). Thus, wood supply is subject to endogenous price development and forest stock growth and shifts according to the respective elasticities at an annual interval.

Data on GDP and population growth are taken from the "Middle of the road" scenario (SSP2) described in "The Shared Socioeconomic Pathways" as provided by the IIASA database (Keywan Riahi et al. 2017). The SSP2 scenario describes a world of modest population growth where social, economic, and technological trends continue similarly to historical patterns. Parameters driving forest growth other than GDP per capita are held constant. The authors estimated the future development of input-output coefficients and manufacturing costs in a subsequent study based on historical data. Trade is constrained by constant trade inertia bounds as defined in Buongiorno et al. (2003) and lastly applied in Buongiorno (2021).

3 Computer Software

3.1 General description and software installation

TiMBA is an open-source, ready-to-use model for the global forest sector written in Python, complying with modern programming standards (PEP8). The model is hosted and distributed using GitHub[4]. The versioning is managed using Zenodo[5]. TiMBA relies exclusively on open-access and free-of-charge packages, which allow users to conduct analyses without higher software costs. In that way, TiMBA tries to encourage transparent and community-based forest sector analyses.

The model uses the CVXPY environment (Steven Diamond and Stephen Boyd 2016; Agrawal et al. 2018) and the OSQP solver (Stellato et al. 2020). The model has a modular structure that allows the adaptation of the model to the targeted research question by turning off or on independent functionalities. Further, this structure enables users to extend the model framework with new features by adding new modules while securing the functionality of other model components.

In TiMBA, demand, supply, import, export, manufacture, and exogenous developments are handled as domains with separate specifications. All domains are aligned on a uniform length equal to the cartesian product of covered commodities and countries to allow for vector calculations. As a recursive PE model, TiMBA has a static and a dynamic phase for each period. In the static phase, functions for each domain described above are linearized based on input data for the base period. For all other periods, the linearization is based on optimization results, and parameter shifts. In the dynamic phase, key parameters of the model are exogenously shifted to reflect scenario assumptions on socioeconomic, environmental, and technological changes between two periods. The section 2 provides details on parameter shifts in each domain. The linearized domain functions are vectorized and bundled in the quadratic objective function. The economic equilibrium in a given period is calculated by using the quadratic solver OSQP (Stellato et al. 2020) embedded in the environment CVXPY (Steven Diamond and Stephen Boyd 2016; Agrawal et al. 2018). The CVXPY environment offers a large range of settings and other quadratic solvers. However, only the model results calculated with default solver settings delivered with TiMBA were exhaustively tested. All changes in the solver environment or settings might impact the results. Optimization constraints are formulated as vectors based on indexes and passed over to the solver OSQP as a list.

3.2 Installing TiMBA

To download and install TiMBA on your local device, following steps are required:

Clone the repository: Begin by cloning the repository to your local machine using the following command:

git clone https://github.com/TI-Forest-Sector-Modelling/TiMBA.git

Switch to the TiMBA directory, navigate into the TiMBA project folder on your local machine:

cd TiMBA

It is recommended to set up a virtual environment for TiMBA to manage package dependencies. The package is tested with all Python versions up to 3.12.6 for Windows and Ubuntu OS using GitHub Actions. We cannot guarantee the full functionality of the package with another Python version. Select the correct Python interpreter. Show installed versions:

[4] https://github.com/TI-Forest-Sector-Modelling/TiMBA

[5] https://zenodo.org/records/14765500

py -0

If you have installed multiple versions of Python, activate the correct version using the py-Launcher.

py -3.12.6 -m venv venv

If you are using only a single version of Python on your computer:

python -m venv venv

Activate the virtual environment. Enable the virtual environment to isolate TiMBA dependencies.

venv\Scripts\activate

Install TiMBA in the editable mode:

pip install -e .

If the following error occurs: "ERROR: File"setup.py" or "setup.cfg" not found." you might need to update the pip version you use with:

python.exe -m pip install –upgrade pip

3.3 Check installation

To check if the installation was successful, the following command can be run from the terminal:

run_timba –help

The help provides you with information about the basic model settings, which can be changed to adapt model runs to your needs (see section 3.4 for further details).

Test if TiMBA is running by executing the model only for the first period:

run_timba -MP=1

The TiMBA model has a test suite to ensure its functionality while allowing for continuous integration and development of new features. Run the test suite to check the functionality of the package and validate the produced results with those provided by the authors using the coverage report:

coverage run

To reduce the test suite's running time, only the first period will be computed and compared. The test suite results will not be saved. The computed and provided validation results are compared with a relative tolerance of 5 %.

The coverage report of the TiMBA model can be accessed using:

coverage report

3.4 Model settings

Users can interact with TiMBA in multiple ways. When running TiMBA from a terminal (e.g., CMD), the integrated CLI allows users to change basic model parameters and turn on or off specific modules. More advanced settings can be accessed in *default_parameter.py*. Changes in settings made via the CLI will overwrite parameters in *default_parameters.py*.

Multiple settings are integrated into TiMBA to allow users to interact with the model and adapt the modeling parameters to their research interests. The following chapter provides a brief overview of the model settings.

Basic model settings include:

- The flag *default_year* controls the base year of simulation [default: 2020]: The integer defines the year in which the simulation starts. If the user-defined base year does not correspond to the base year in the entries in scenario_input.xlsx, TiMBA automatically corrects user-defined settings.
- The flag *default_max_period* controls the maximum number of periods for the simulation [default: 10]: The maximum number of periods determines how many periods TiMBA will calculate. The end year might vary depending on the structure of scenario_input.xlsx. With the default settings and input data, TiMBA calculates until 2050.
- The flag *default_calc_product_price* controls how product prices in TiMBA are obtained [default: shadow_PP]: The model has two options. While prices obtained using both methods can be identical, differences for specific countries and products are common.
  - If *shadow_PP* is selected, shadow prices (dual values) directly obtained from the optimization are used as product prices. This is the default option in the model.
  - If calculated_PP is selected, product prices are calculated based on optimized quantities using price elasticities.
- The flag *default_calc_world_price* controls how world market prices in TiMBA are obtained [default: shadow_WP]: The model comes with three options, which can lead to significant differences in the projections. Only the option shadow_WP has been validated extensively.
  - If shadow_WP is selected, world market prices are directly obtained from the optimization (dual values). This is the default option in the model.
  - If constant_WP is selected, world market prices are held constant on the level of the base year.
  - If average_WP is selected, world market prices are calculated as the weighted average of product prices in all countries.
- The flag *default_MB* controls the form of the material balance, which is handed over to the solver [default: C_specific_MB]: The model comes with three options, which impact the total number of optimization constraints and, thereby, the model's runtime. The optimization results can vary depending on the selected material balance option. Only the default option has been validated extensively.
  - If C_specific_MB is selected, the material balance is formulated as a commodity-specific optimization constraint applied to all countries. In this case, the number of optimization constraints related to the material balance equals the number of modeled commodities.
  - If RC_specific_MB is selected, the material balance is formulated as a commodity-specific and country-specific optimization constraint. In this case, the number of optimization constraints related to the material balance equals the number of modeled commodities times the number of countries.
  - If RCG_specific_MB is selected, the material balance is formulated as a country-specific optimization constraint for different commodity groups (raw, intermediate, and final products, fuelwood, and other industrial roundwood). In this case, the number of optimization constraints related to the material balance equals the number of commodity groups times the number of countries.
- The flag *global_material_balance* activates the global material balance, balancing all wood flows globally using the buffer region zy [default: False].
- The flag *serialization_flag* controls if serialized input pkl files are used instead of provided input xlsx files [default: False]. This flag allows to accelerate the data processing steps, which process and save the input xlsx files into the data containers. If new input xlsx files are used, we recommend deactivating the flag to pass over changed inputs to TiMBA. New input xlsx files will automatically be serialized after the processing. After

the serialized files update, the serialization flag activation is recommended to speed up sensitivity analyses with unchanged input files.

- The flag *dynamization_activated* controls if key parameters of TiMBA are dynamized according to defined shifts in the sheet ExogChange in scenario_input.xlsx to reflect socioeconomic, environmental, and technological changes (see section 2.8 for details) [default: True].
- The flag *constants* controls if the slope and intercept of linearized domain functions and product prices are constant over the simulation timeframe. The list of boolean allows controlling the variability of all three components separately where the following position corresponds to the following element: [constant prices, constant slopes, constant intercepts]. We recommend using the default: [False, False, False], which has been validated exhaustively. Changed combinations can have a significant impact on the model results or even lead to unfeasibility of optimization.
- The flag *capped_prices* controls if product prices obtained from the optimization or calculated are capped to avoid price outliers [default: False].
- The flag *cleaned_opt_quantity* controls if optimized quantities are cleaned using upper and lower bounds aligned with exogenous entries to avoid quantity outliners [default: False].
- The flag *verbose_optimization_logger* controls if information outputs related to the optimization steps are printed in the console and logged [default: True].
- The flag *verbose_calculation_logger* controls if information outputs related to all modeling steps apart from the optimization is printed in the console and logged [default: False].
- The flag *read_additional_information_file* controls if the additional input files from the folder 02_Additional_Information is processed. The additional information holds important data for additional modules [default: True].
- The flag *test_timba_results* controls if produced model results are tested against a set of validation data (ground truth results) [default: True]. This flag is relevant for the test suite of TiMBA which allows us to exhaustively check the model's functionality after code changes. The test suite is automatically triggered when a working branch is pulled into the main branch on GitHub. Moreover, the test suite can be launched manually by the user using the command detailed in 3.3. With changed input data, this test will fail if the new results deviate from the ground truth results by more than 5 %. Users should consider changing input data for the unit test when changing the input data or deactivating the flag.
- The flag *default_transportation_impexp_factor* controls a factor for Transportation Import/Export [default: 1].

As described, TiMBA is delivered with a set of default settings, which were tested and validated. For standard usage, we recommend to use default parameters. Changes in default parameters might be necessary for more advanced usage and model development.

3.5 Settings as parameters

The CLI allows you to access basic model settings and their default values (see 3.4). Check if the CLI command is registered and available on your computer by executing either:

run_timba –help

Default settings can be changed in the following way:

run_timba -MP=5 -PP="calculated_PP" -WP="shadow_WP"

For the example above, TiMBA will simulate 5 periods (-MP) using calculated prices as product prices (-PP) and shadow prices as world market prices (-WP).

3.6 Advanced settings

In addition to the settings accessible via the CLI or *default_parameters.py*, users can control advanced settings through changes in *Defines.py*. Advance settings include:

Solver settings (detailed descriptions can be accessed in the CVXPY documentation[6]):

- The variable *MAX_ITERATION* defines the maximal amount of iteration for the solver to solve the optimization problem [default: 500,000].
- The variable *REL_ACCURACY* defines the relative accuracy of the solver when solving the optimization problem while accounting for the optimization constraints [default: 0.00025].
- The variable *ABS_ACCURACY* defines the absolute accuracy of the solver when solving the optimization problem while accounting for the optimization constraints [default: 0.00001].

By modifying the solver settings, the user can change the optimization's runtime, giving the solver more or less flexibility. Modifications in the solver settings are likely to impact the model results and should, therefore, be followed by a result validation.

Optimization settings:

- The variable *TRADE_INERTIA_DEVIATION* defines relative deviations allowed from set trade inertia bounds for all countries, giving additional trade flexibility [default: 0.005].
- The variable *TRADE_INERTIA_DEVIATION_ZY* defines relative deviations allowed from set trade inertia bounds for the buffer region zy, which gives additional flexibility to absorb global export surpluses and compensate for global import deficits [default: 0.001].
- The variable *TRADE_BOUND_DEVIATION_PENALTY* defines the penalty applied in the optimization for deviations from trade inertia bounds, which gives additional flexibility to the solver [default: 99,999,999].
- The variable *TRADE_PREV_DEVIATION_PENALTY* defines the penalty applied in the optimization for deviations from traded quantities in the previous period, which gives additional flexibility to the solver [default: 0]
- The variable *PRICE_DEVIATION_THRESHOLD* defines the relative threshold for allowed price changes compared to prices from the previous period [default: 0.5]. The threshold is activated when the flag capped_prices is turned on.

All optimization settings related to trade allow the solver additional flexibility regarding the trade. The settings can be changed to 0 to deactivate the flexibility mechanism. Default settings are calibrated to the most accurate trade and world market prices.

Disclaimer: The model was validated for a selection of settings. Some setting combinations might not be coherent, leading to unfeasibility problems, simulation errors, or unreliable results. Without any further specification, TiMBA will use default settings. Users can adapt the input file (scenario_input.xlsx) to conduct more complex scenario-based analyses. Changes in the sheet "ExogChange" allow the user to shift exogenously model parameters to reflect socioeconomic, environmental, and technological changes. Some parameter developments may not be coherent or compatible with the model's theoretical framework, resulting in unfeasible problems or unreliable results. In case of problems, users should double-check the consistency of changes made in the input files.

6 https://www.cvxpy.org/

3.7 Data handling and processing

All input data required to run TiMBA in its basic version are provided in the project (scenario_input.xlsx). All input data are processed and stored in multiple data containers, serialized, and saved in the folder 03_Serialization. By activating the flag serialization_flag, processing steps will be skipped, and a serialized data container will be used instead. TiMBA allows users to provide multiple input files to the model by adding them to the corresponding folder. TiMBA will automatically loop over all provided files. Input data are structured in the following way:

```
.
`- data
  `-- input
    `-- 01_Input_Files
      |-- scenario_input.xlsx # contains all input data for the model.
    `-- 02_Additional_Information
      |-- additional_information.xlsx # contains additional information on commodities and
                                        countries
      |-- worldprice.xlsx # contains exogenous world prices
    `-- 03_Serialization
      |-- AddInfoContent.pkl # contains serialized information about the last additional input
                               data which is processed by the model
      |-- WorldDataContent.pkl # contains serialized information about the last input data which
                                 is processed by the model
      |-- WorldPriceContent.pkl # contains serialized information about the last world
                                  price data which is processed by the model
```

The package will generate a result directory called `output`, which is located inside the data folder. The final directory after one run, it will look something like this:

```
.
`- data
  `-- output
      |-- ....log # contains the logged process of the simulation
      |-- DataContainer_....pkl # contains all output information in a Python dictionary as pkl
                                  file
      |-- results....csv # contains main results as csv file
      |-- worldprices....csv # contains world price results as csv file
      |-- forest....csv # contains forest area and stock results as csv file
      |-- manufacture....csv # contains results for manufacturing as csv
      |-- results_aggregated....csv # contains aggregated results on continent level as csv file
```

Important output information:

No output file will ever be overwritten by the application itself. New results files will be generated in the format results_D<yyyymmdd>T<hh-mm-ss>.csv and saved to the output folder. The log file will not be overwritten as well; no new file will be created on additional runs. Log information gets appended to the existing log file. Removing the log file before executing the model will not result in errors.

TiMBA relies on packages such as pandas and numpy to handle and process data. While running TiMBA, all data is stored separately in each domain's data container (see exemplary structure overview), where it is saved in pandas data frames. This allows access to all data at any point of processing. The original data from the input files are stored as data. The data of all domains are harmonized to a uniform length to facilitate the handling of the optimization (called data_aligned). data_aligned always only holds the data of the current period.

In preparation for the optimization, data of all relevant domains are vectorized in one separate data container OptimizationHelpers. The optimization results are stored in the respective domains and merged in OptimizationResults, which holds all additional information used by the solver.

```
.
`- self # Python class TiMBA
  `-- Data # Overarching data container
      |-- Demand # contains data related to demand
          |-- data  # contains original data from scenario_input.xlsx
          |-- data_aligned # contains harmonized data of the current period
```

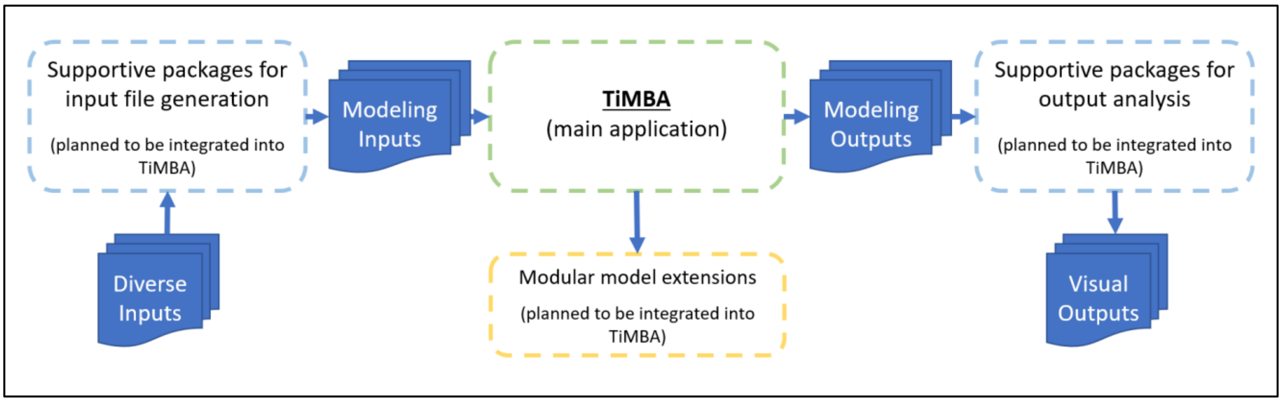
```
        |-- data_periods # contains harmonized data with optimization results of all
                           calculated periods so far
        |-- domain  # domain name
        |-- file path # path of the input file
    |-- ExogChangeDemand # contains data related to exogenous shifts for demand
        |-- data  # contains original data from the input files
        |-- data_aligned # contains harmonized data
    ...
    |-- Other domains
    ...
    |-- OptimizationHelpers  # contains vectorized data
        |--data # contains vectorized data of the current period
        |--data_periods # contains all vectorized data of all calculated periods so far
```

3.8 TiMBA workflow and development roadmap

TiMBA simulations are embedded in an overarching workflow, allowing for conducting global scenario-based analyses semi-automatedly (Figure 3). Besides the main application TiMBA, this workflow comprises supportive packages to calibrate data from multiple sources and automatically generate input files tailored to specific research questions. Users can dynamically explore and analyze the optimization results. The supportive packages are planned to be published in future extensions of TiMBA.

Further, different plugin extensions of TiMBA are currently being prepared at the Thünen Institute of Forestry. They will expand the model's capacities or refine aspects of the basic model version. Collaborative efforts with external experts to advance TiMBA's basic version or develop new plugin extensions will be fostered. A continuous upgrade of TiMBA to newer Python and package versions is planned but will depend on available time capacities within the TiMBA team.

Figure 3: Software workflow of TiMBA, including supportive packages and extensions



Source: own illustration

3.9 Software requirements

TiMBA was developed and tested using a Windows operating system (Windows 10 Enterprise) with 32 GB RAM and all Python versions up to 3.12.6. The compatibility with other operating systems (e.g., Ubuntu) is continuously tested via GitHub Actions. Operating systems with lower computational capacities might encounter problems when running TiMBA.

All necessary packages to run TiMBA are automatically installed when downloading the project from GitHub and activating the virtual environment. Step-by-step instructions about the installation procedure are provided in the README.md. All packages integrated into TiMBA, including the solver, are open-access and free of charge.

3.10 Validation

TiMBA underwent an extensive validation process to ensure the model's quality and functionality. More information about the validation process and results will be published in a forthcoming paper.

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Annex

Annex Table 1: Freight cost of shipping one product unit from the origin to the destination country

Commodity	Freight Factors
Industrial Roundwood NC	0.18
Sawnwood NC	0.11
Fuelwood	0.21
Industrial Round C	0.18
Oth Industrial Roundwood	-
Sawnwood C	0.11
Plywood and Veneer	0.04
Particle Board incl. OSB	0.04
Fiber Board	0.04
Mechanical Pulp	0.08
Semi chem. and Chem. Pulp	0.08
Other Fibre Pulp	0.08
Waste Paper	0.20
Newsprint	0.05
Print. and Writing Paper	0.06
Other Paper and Paperb.	0.06

Source: Buongiorno (2021)

Annex Table 2: List of 180 countries included in TiMBA

Continents	ISO3 Country codes																
Africa	AGO	BDI	BEN	BFA	BWA	CAF	CIV	CMR	COD	COG	CPV	DJI	DZA	EGY	ETH	GAB	GHA
	GIN	GMB	GNB	GNQ	KEN	LBR	LBY	LSO	MAR	MDG	MLI	MOZ	MRT	MUS	MWI	NER	NGA
	REU	RWA	SDN	SEN	SLE	SOM	STP	SWZ	TCD	TGO	TUN	TZA	UGA	ZAF	ZMB	ZWE	
Asia	AFG	ARE	ARM	AZE	BGD	BHR	BRN	BTN	CHN	CYP	GEO	IDN	IND	IRN	IRQ	ISR	JOR
	JPN	KAZ	KGZ	KHM	KOR	KWT	LAO	LBN	LKA	MDV	MMR	MNG	MYS	NPL	OMN	PAK	PHL
	PRK	QAT	RUS	SAU	SGP	SYR	THA	TJK	TKM	TLS	TUR	UZB	VNM	YEM			
Europe	ALB	AUT	BEL	BGR	BIH	BLR	CHE	CZE	DEU	DNK	ESP	EST	FIN	FRA	GBR	GRC	HRV
	HUN	IRL	ITA	LTU	LUX	LVA	MDA	MKD	MNE	NLD	NOR	POL	PRT	ROU	SRB	SVK	SVN
	SWE	UKR															
North and Central America	ANT	BHS	BLZ	BRB	CAN	CRI	CUB	DMA	DOM	GTM	HND	HTI	JAM	LCA	MEX	MTQ	NIC
	PAN	SLV	TTO	USA	VCT												
Oceania	AUS	COK	FJI	NCL	NZL	PNG	PYF	SLB	TON	VUT	WSM						
South America	ARG	BOL	BRA	CHL	COL	ECU	GUF	GUY	PER	PRY	SUR	URY	VEN				

Source: own representation, country names according to ISO3-Codes and grouped according to TiMBA continental aggregates

Annex Table 3: List of input parameters for TiMBA for each model domain

Supply	Forest	Transportation	Demand	Manufacturing
price	gdp_per_capita_base_period	freight_cost	price	net_manufacturing_cost
quantity	forest_stock	import_ad_valorem_tax_rate	quantity	quantity
elasticity_price	growth_rate_forest_stock	export_ad_valorem_tax_rate	elasticity_price	elasticity_price
elasticity_gdp	elasticity_growth_rate_forest_stock	quantity	elasticity_gdp	
elasticity_stock	forest_area	elasticity_trade_exporter	elasticity_expectations	
elasticity_area	forest_area_growth_rate	elasticity_trade_importer	lower_bound	
elasticity_fourth	linear_gdp_forest_area_growth_rate	trade_inertia_bounds	upper_bound	
elasticity_fifth	exponential_gdp_forest_area_growth_rate	price		
elasticity_sixth	fraction_fuelwood	elasticity_price		
elasticity_respect_previous_p	ratio_inventory_drain			
lower_bound	max_ratio_inventory_drain			
upper_bound	CO2_growing_stock			
last_period_quantity	price_CO2			
	alpha			
	gamma			
	periodic_growth_rate_of_forest_area			
	forest_growth_without_harvest			
	supply_from_forest			

Source: own representation

Annex Table 4: List of input parameters exogenously

Supply	Forest	change_freight_cost	Demand	Manufacturing
elasticity_price	growth_rate_stock	change_import_tax_rate	elasticity_price	growth_rate_net_manufact ure_cost
growth_rate_value	growth_rate_area	change_export_tax_rate	growth_rate_value	change_input_output
growth_rate_gdp	growth_rate_gdp	exogenous_growth_rate_exp ort_trade_shift	growth_rate_gdp	
elasticity_gdp	adjustment_endogenous_growth_rate_stock	elasticity_trade_exporter_shif t	growth_demand_expect ed	
growth_rate_fourth_shif t	elasticity_growth_rate_stock_on_area	exogenous_growth_rate_imp ort_trade_shift	growth_lower_bound	
growth_rate_fifth_shift	growth_rate_linear_GDP_forest_area_growth_rat e	elasticity_trade_importer_shif t	elasticity_gdp	
growth_rate_sixth_shift	growth_rate_squared_GDP_forest_area_growth_r ate	trade_inertia_bounds		
growth_rate_upper_bou nd	fraction_fuelwood			
	ratio_inventory_drain			
	max_ratio_inventory_drain			

Source: own representation, input parameters are shifted over the simulation horizon to reflect socio-economic, political, and environmental dynamics

Bibliografische Information:
Die Deutsche Nationalbibliothek verzeichnet diese Publikationen in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet unter www.dnb.de abrufbar.

Bibliographic information:
The Deutsche Nationalbibliothek (German National Library) lists this publication in the German National Bibliographie; detailed bibliographic data is available on the Internet at www.dnb.de

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Zitationsvorschlag – *Suggested source citation:*
TI-FSM - Thünen Institute Forest Sector Modelling (2025) TiMBA - Timber market Model for policy-Based Analysis : documentation of model structure, data, and parameters. Braunschweig: Johann Heinrich von Thünen-Institut, 35 p, Thünen Working Paper 263, DOI:10.3220/253-2025-16

THÜNEN

Thünen Working Paper 263

Herausgeber/Redaktionsanschrift – *Editor/address*
Johann Heinrich von Thünen-Institut
Bundesallee 50
38116 Braunschweig
Germany

thuenen-working-paper@thuenen.de
www.thuenen.de

DOI:10.3220/253-2025-16
urn: urn:nbn:de:gbv:253-2025-000054-4