Online Appendix

Parameters used in the Swedish forest sector model SweFor

The SweFor forest sector model

The aim of SweFor is to make it possible to analyze strategies for the Swedish forest sector and its impact on ecosystem services, and the activities associated with forest management, forest industry production, and supply to energy and semi-finished forest product markets. The time frame of an analysis is long-term and often extending over 100 years.

The model is of type intertemporal partial equilibrium model, where partial means that product prices other than those of timber and forest products are exogenous, equilibrium in that endogenous markets are cleared, and intertemporal because market equilibrium is simultaneously achieved across all periods. The objective of the model is to maximize net social surplus (NSS).

Abbreviations

m^3ub	m^3 solid volume (stem volume under bark above stump excluding top)
m^3sw	m^3 sawn wood
DHP	district heating plant

Terminology

SweFor builds on the following elements: plot, product, process, location, facility, and transport. Except for imports, raw material emanates from national forest inventory (NFI) *plots* and in quantities computed by a forest DSS (see section Forest DSS). A *product* is input to or output from a *process.* A process converts inputs to outputs. Every plot has a *location.* Processes are given locations. A location with a process represents a *facility*. *Transport* distances between plots and facilities and between facilities are known. Investments can only be bestowed on facilities that are named in the list of facilities.

Products

Products are associated with the following parameters (Table 1):

- Unit is used for keeping track of assortment conversions.
- Elasticities, for demand functions. All non-zero products are for delivery to forest products markets.
- Commodity type is used for knowing how to manage different products with regard to transports and markets.
- Products extracted on plots are associated with an extraction rate, i.e. the share of an assortment that goes for further processing in the facilities included in SweFor.

Table 1. Products, and their attribute values

Product	SweFor name	Unit	Ela-sticity	Commodity type[(a)]	Extrac-tion Rate
Pine saw timber	PinTim	m3fub	N/A	L	0.98
Pine pulpwood	PinPuw	m3fub	N/A	L	0.92
Spruce saw timber	SprTim	m3fub	N/A	L	0.98
Spruce pulpwood	SprPuw	m3fub	N/A	L	0.92
Deciduous wood	Decids	m3fub	N/A	L	0.88
Sawdust	Sawdst	m3fub	N/A	B	N/A
Chips	Chips_	m3fub	N/A	B	N/A
Residues above gr.	ResStm	tonTS	N/A	R	0.65
Sawn coniferous	Sawnwd	m3sw	-0.1225	E	N/A
Heat	Heat__	MWh	N/A	F	N/A
Pulp chem. process	PuChem	ton	-0.5	E	N/A
Pulp mech. process	PuMech	ton	-0.5	E	N/A
Dissolving pulp	PuDiss	ton	-1.93	E	N/A
Packaging	PaChem	ton	-0.3112	E	N/A
Other paper chem.	OtChem	ton	-0.4945	E	N/A
Other paper mech.	OtMech	ton	-0.4945	E	N/A
Newsprint	NwMech	ton	-0.5347	E	N/A

[(a)] L = Logs; B = Byproducts; R = Residues; E = Products for market; F = The demanded quantity should be met exactly and in proportion to initial capacity of each facility.

Elasticities for products Sawnwd, PaChem, OtChem, OtMech, and NwMech are derived from (Jonsson, Rinaldi and San-Miguel-Ayanz, 2015) as a weighted average of the elasticities of the most important markets, including the domestic, where elasticities for, respectively, coniferous sawn wood, packaging paper, printing & writing paper (for both OtChe and OtMech) and Newsprint were used. Elasticities for PuChem and PuMech are from (Mustapha, 2016) and PuDiss from (Schier *et al.*, 2021).

The extraction rate of all products marked L are derived from Paulsson (2022). Paulsson (2022) estimate that a total of 8% of felled trees are used for non-industrial use, mainly fire wood. This share is distributed in Table 1 on the different assortments in proportion to their market value and with attention to deciduous trees as the main source fire wood for private use. For residues (R), a range of studies have investigated the extraction rate of residues above ground. Ranta (2005) provide an estimate that reflects practical use.

Product imports

Maximum import volumes are set according to import statistics presented in (Fridh and Christiansen, 2015) by cross tabulating Table 5.4 and Table 15.2 for period 1 (see Table 2). The amount is thereafter reduced by 20% per 5-year period.

Table 2. Maximum import volumes per year in each 5-year period

	PinTim	PinPuw	SprTim	SprPuw	Decids
Period	**m3ub**	**m3ub**	**m3ub**	**m3ub**	**m3ub**
1	400,000	1,300,000	500,000	1,800,000	2,700,000
2	320,000	1,040,000	400,000	1,440,000	2,160,000
3	256,000	832,000	320,000	1,152,000	1,728,000
4	204,800	665,600	256,000	921,600	1,382,400
5	163,840	532,480	204,800	737,280	1,105,920
6	131,072	425,984	163,840	589,824	884,736
7	104,858	340,787	131,072	471,859	707,789
8	83,886	272,630	104,858	377,487	566,231
9	67,109	218,104	83,886	301,990	452,985
10	53,687	174,483	67,109	241,592	362,388
11	42,950	139,586	53,687	193,274	289,910
12	34,360	111,669	42,950	154,619	231,928
13	27,488	89,335	34,360	123,695	185,543
14	21,990	71,468	27,488	98,956	148,434
15	17,592	57,175	21,990	79,165	118,747
16	14,074	45,740	17,592	63,332	94,998
17	11,259	36,592	14,074	50,665	75,998
18	9,007	29,273	11,259	40,532	60,799
19	7,206	23,419	9,007	32,426	48,639
20	5,765	18,735	7,206	25,941	38,911
21	4,612	14,988	5,765	20,753	31,129

Product demand

The prices and volumes that, together with elasticity, determine demand are presented in Table 3, Table 4, and Table 5.

Table 3. Prices for marketed products in the BAU scenario (SEK per unit of product)

	Sawnwd	PuChem	PuMech	PuDiss	PaChem	OtChem	OtMech	NwMech
Period	m^3sw	t	t	t	t	t	t	t
1	2,152	5,672	4,522	7,544	7,987	8,979	6,195	5,204
2	2,083	6,045	4,884	7,544	7,778	8,170	5,930	4,496
3	2,013	6,417	5,245	7,544	7,568	7,361	5,665	3,789
4	1,999	6,435	5,260	7,544	7,571	7,391	5,682	3,791
5	1,984	6,452	5,274	7,544	7,573	7,420	5,699	3,794
6	2,009	6,350	5,190	7,544	7,604	7,425	5,713	3,822
7	2,034	6,248	5,107	7,544	7,635	7,429	5,726	3,850
8	2,068	6,271	5,126	7,544	7,697	7,433	5,770	3,864
9	2,102	6,293	5,144	7,544	7,758	7,437	5,815	3,878
10	2,135	6,376	5,212	7,544	7,828	7,466	5,860	3,859
11	2,168	6,458	5,279	7,544	7,898	7,495	5,905	3,840
12	2,182	6,444	5,267	7,544	7,884	7,417	5,898	3,820
13	2,196	6,430	5,256	7,544	7,870	7,339	5,890	3,799
14	2,197	6,332	5,175	7,544	7,790	7,233	5,836	3,754
15	2,198	6,234	5,095	7,544	7,711	7,128	5,782	3,709
16	2,175	6,235	5,096	7,544	7,733	7,128	5,782	3,710
17	2,152	6,236	5,097	7,544	7,756	7,129	5,783	3,710
18	2,152	6,236	5,097	7,544	7,756	7,129	5,783	3,710
19	2,152	6,236	5,097	7,544	7,756	7,129	5,783	3,710
20	2,152	6,236	5,097	7,544	7,756	7,129	5,783	3,710
21	2,152	6,236	5,097	7,544	7,756	7,129	5,783	3,710

Table 4. Quantity per year in units of products in the BAU scenario

	Heat__ [(a)]	Sawnwd	PuChem	PuMech	PuDiss
Period	MWh	m^3sw	t	t	t
1	27,000,000	18,628,757	3,404,588	530,250	336,337
2	27,000,000	18,926,066	3,419,384	530,250	367,970
3	27,000,000	19,223,376	3,434,181	530,250	402,578
4	24,000,000	19,784,190	3,473,971	530,250	440,441
5	25,000,000	20,345,004	3,513,760	530,250	481,866
6	24,000,000	20,868,631	3,530,343	507,176	527,186
7	25,000,000	21,392,257	3,546,926	484,102	576,768
8	23,000,000	21,522,292	3,569,343	477,912	631,014
9	23,000,000	21,652,326	3,591,761	471,722	690,362
10	23,000,000	21,652,326	3,618,555	471,722	755,292
11	23,000,000	21,652,326	3,645,349	471,722	826,328
12	23,000,000	21,652,326	3,672,280	482,983	904,046
13	23,000,000	21,652,326	3,699,211	494,243	989,073
14	23,000,000	21,652,326	3,725,168	436,560	1,082,097
15	23,000,000	21,652,326	3,751,124	378,877	1,183,870
16	23,000,000	21,652,326	3,785,468	365,245	1,295,214
17	23,000,000	21,652,326	3,819,813	351,613	1,417,031
18	23,000,000	21,652,326	3,819,813	351,613	1,550,305
19	23,000,000	21,652,326	3,819,813	351,613	1,696,114
20	23,000,000	21,652,326	3,819,813	351,613	1,855,636
21	23,000,000	21,652,326	3,819,813	351,613	2,030,162

[(a)] Distributed on DHPs in proportion to current capacity.

Table 5. Quantity per year in units of products in the BAU scenario (cont. from Table 4)

	PaChem	OtChem	OtMech	NwMech
Period	t	t	t	t
1	5,945,000	591,250	1,773,750	889,000
2	5,945,000	591,250	1,773,750	889,000
3	5,945,000	591,250	1,773,750	889,000
4	5,945,000	591,250	1,773,750	889,000
5	5,945,000	591,250	1,773,750	889,000
6	5,945,000	591,250	1,773,750	889,000
7	5,945,000	591,250	1,773,750	889,000
8	5,945,000	591,250	1,773,750	889,000
9	5,945,000	591,250	1,773,750	889,000
10	5,945,000	591,250	1,773,750	889,000
11	5,945,000	591,250	1,773,750	889,000
12	5,945,000	591,250	1,773,750	877,740
13	5,945,000	591,250	1,773,750	866,479
14	5,945,000	588,486	1,765,457	844,025
15	5,945,000	585,721	1,757,164	821,571
16	5,945,000	564,169	1,692,506	801,972
17	5,945,000	542,616	1,627,847	782,374
18	5,945,000	542,616	1,627,847	782,374
19	5,945,000	542,616	1,627,847	782,374
20	5,945,000	542,616	1,627,847	782,374
21	5,945,000	542,616	1,627,847	782,374

Processes

A process turns inputs into outputs with a fixed proportions production function with single input and single or multiple outputs. Table 6 describes the processes used in the current study. An output product from one process can be input to another process. Thus, several processes can be linked together in sequence according to the inputs and outputs of Table 7 (e.g. process PaChem uses PuChem as input, which comes from process PuChem. Process PuChem can in turn use outputs from processes Sawmpi, Sawmsp, and Sawmal. However, the link with output Chips will normally not constitute an integrated process since they normally do not share exactly the same location, i.e. geographical coordinates.

Table 6. Description of processes

Process	Description
Sawmpi	Sawn wood of pine
Sawmsp	Sawn wood of spruce
Sawmal	Sawn wood of both pine and spruce
Heatpl	Energy
PuChem	Chemical wood pulp, sulphate / sulphite, bleached
PuCTMP	Mechanical and semi-chemical wood pulp
PuDiss	Dissolving pulp
PaChem	Packaging
OtChem	Other papers based on chemical pulp
OtMech	Other papers based on mechanical pulp
NwMech	Newsprint

Table 7. Processes and their in- and outputs (product in bold designates the product determining the capacity of the process; for definition of products, see **Table 8**).

Process name	Product inputs	Product outputs
Sawmpi	PinTim	**Sawnwd**, Sawdst, Chips
Sawmsp	SprTim	Sawnwd, Sawdst, Chips
Sawmal	PinTim, SprTim	**Sawnwd**, Sawdst, Chips
Heatpl	PinPuw, SprPuw, Decids, Sawdst, Chips, ResStm	**Heat**
PuChem	PinTim, SprTim, PinPuw, SprPuw, Decids, Chips	**PuChem**
PuCTMP	SprTim, SprPuw	**PuMech**
PuDiss	PinTim, SprTim, PinPuw, SprPuw, Decids, Chips	**PuDiss**
PaChem	PuChem	**PaChem**
OtChem	PuChem	**OtChem**
OtMech	PuMech	**OtMech**
NwMech	PuMech	**NwMech**

The transformation in a process for an input to an output is determined by a combination of conversion factors. The conversion factors are found in Table 8.

Table 8. Conversion factors used to compile process input-output parameters

Name	Value	Source
Calorific value: MWh t^{-1}	4.90	(Christiansen, 2014) for forest fuel; to be compared with calorific value for wood 5.3 (*Typical calorific values of fuels*, 2022)

Wood density: t m^3ub^{-1}	0.46	Weighted density of pine, spruce, and birch (622 kg m^3ub^{-1}) adjusted for quota stem wood / forest fuel energy content
DHP efficiency	0.95	("Tillförd energi," 2021)
Sawdust: $m^3ub\ m^3ub^{-1}$	0.16	(Björklund and Persson, 2020); timber input through product output
Chips: $m^3ub\ m^3ub^{-1}$	0.26	(Björklund and Persson, 2020); timber input through product output
Sawn wood: $m^3sw\ m^3ub^{-1}$	0.51	(Björklund and Persson, 2020); timber input through product output
Chemical pulp: t m^3ub^{-1}	0.21	(Christiansen, 2014)
Dissolving pulp: t m^3ub^{-1}	0.21	(Christiansen, 2014)
Mechanical pulp: t m^3ub^{-1}	0.42	(Christiansen, 2014)
Ton packaging per ton chemical pulp	1.10	(Ek, Gellerstedt and Henriksson, 2009) refers to filler material
Ton other papers (chem) per ton chemical pulp	1.30	(Ek, Gellerstedt and Henriksson, 2009) refers to filler material
Ton other papers (mech) per mechanical pulp	1.30	(Ek, Gellerstedt and Henriksson, 2009) refers to filler material
Ton newspaper per ton mechanical pulp	1.10	(Ek, Gellerstedt and Henriksson, 2009) refers to filler material

Transports

Table 9. Parameters limiting transport options from plot to facilities or between facilities.

Product	Max trp (km)	Sawmpi	Sawmsp	Sawmal	PuChem	PuCTMP	PuMech	PuDiss	**Heatpl**
PinTim	300	2	0	2	2	0	0	2	0
PinPuw	300	0	0	0	2	0	0	2	2
SprTim	300	0	2	2	2	2	2	2	0
SprPuw	300	0	0	0	2	2	2	2	2
Decids	300	0	0	0	2	0	0	2	2
Sawdst	300	0	0	0	0	0	0	0	30
Chips_	300	0	0	0	2	0	0	2	30
ResStm	300	0	0	0	0	0	0	0	30

In Table 9, the basis for limiting transport distances ("Max trp") is the average transport distances observed for truck transports of around 90 to 100 km for timber and pulpwood and about 60 km for forest fuel (Asmoarp, Davidsson and Gustavsson, 2018). The rest of the table designates how many facilities can be reached for a product. It also limits the options for transport of certain products to certain processes. For instance, pine timber (PinTim) cannot go to a spruce sawmill (Sawmsp) or to the DHP (Heatpl).

Transport distances between NFI plots and locations and between locations are defined as Calibrated Route Finder (Krönt Vägval) (Svenson, 2017). This is a system for distance measurement which balances quantitative factors, such as distance, functional road class and road width, with qualitative factors, such as stress and traffic safety. It should, thus, reflect the actual route taken by trucks. The data is provided by the Skogforsk institute. Truck transport is the only means of transportation considered.

Locations and initial capacities of processes

The data on different processes, their locations and capacities stems from, regarding district heating, tables accessible at (Energiföretagen, 2021); coordinates were input manually. The bulk of data on sawmills and pulp and paper mills was provided by branch organization Skogsindustrierna. Data has occasionally been updated, primarily with closure of some pulp and paper mills. The different flavors of pulp and paper technologies are in some cases simplified to fit into the limited number of processes of SweFor.

Table 10 presents summary statistics of the processes. Sawmills, DHPs and pulp mills are processes that also represent different locations. Other processes are linked to these processes on the same location (paper making is generally treated as a fixture on top of the pulp process; a few pulp mills are not integrated and only produce market pulp). There are a total of 545 locations, however, to limit the size of the model, only the 70 DHPs with a capacity of at least 100 MWh y^{-1} representing an initial capacity of 25 TWh in total, corresponding to 80% of the total capacity, and only the 102 sawmills with a capacity of at least 100,000 m^3sw y^{-1} representing an initial capacity of 17.7 million m^3sw y^{-1} in total, corresponding to 94% of the total capacity, are included. All pulp mills are included.

Table 10. Summary statistics of the number and capacity of processes in 1000 units (processes in italics not used in this study)

Process	No.	Capacity
Sawmpi	12	2,723
Sawmsp	12	2,779
Sawmal	78	12,157
Heatpl	70	24,537
PuChem	26	11,585
PuCTMP	6	2,080
PuMech	0	0
PuDiss	8	460
PaChem	14	6,585
OtChem	4	810
OtMech	2	1,350
NwMech	1	245
PuBCCS	*6*	*0*
Summary		
DHPs	70	24,537
Sawmills	102	17,659
Pulp mills	40	14,125
Paper mills	21	8,990

Costs

Forest

The different cost items are presented in Table 11. The total cost for final felling, thinning, and forwarding of residues is assessed by applying the G15h costs in Table 11 to time consumption computed with models presented by Nurminen, Korpunen and Uusitalo (2006). Time consumption of forwarding of residues is from models presented by Brunberg and Eliasson (2013).

Table 11. Cost items of different forest management activities

Item	Unit	Cost	Unit cost source
Fertilization	SEK/ ha and kg	20	(Gödslingskalkyl, no date)
Stand establishment[a]	SEK/ha	9434 + 484*(SI-22)	(Skogsbrukets kostnader och intäkter 2020, no date)
Precommercial thinning[b]	SEK/ha	(1.625 + 0.000775*N)*600	(Skogsbrukets kostnader och intäkter 2020, no date); after Tabell 3
Harvester final felling	SEK/G15h	1350	(Skogsbrukets kostnader och intäkter 2020, no date)
Forwarder final felling	SEK/G15h	1070	(Skogsbrukets kostnader och intäkter 2020, no date)
Harvester thinning	SEK/G15h	1100	(Skogsbrukets kostnader och intäkter 2020, no date)
Forwarder thinning	SEK/G15h	900	(Skogsbrukets kostnader och intäkter 2020, no date)
Residue forwarding	SEK/G15h	1070	Same as forwarder final felling

[a] Cleaning, soil preparation and planting; SI = site index (H100 m)
[b] N = number of removed stems

The division of pulpwood and saw timber is computed according to the stand model in (Ollas, 1980) with top minimum diameters under bark set to 5 cm and 12 cm pulpwood and saw timber, respectively.

Processes

Table 10 gives the numbers for assessing the cost of operating the processes. They are all given per unit of the main output according to “Output factor for costs”. The cost of a process is determined by the investment cost to establish capacity, the fixed cost to maintain the capacity, and the variable cost (excluding feedstock) per output unit that is produced. “Depreciation period” signifies the life span of an investment. Different depreciation schemes can of course be used depending on the particular model formulation.

Table 12. Parameters for process cost assessment and execution (processes not attended to in this study in italics).

Process	Investment	Variable cost	Fixed cost	Depreciation period[(a)]	Output factor for costs
Sawmpi	828	309	303	20	Sawnwd
Sawmsp	828	309	303	20	Sawnwd
Sawmal	828	309	303	20	Sawnwd
Heatpl	1,285	168	0	20	Heat__
PuChem	16,763	834	650	20	PuChem
PuCTMP	14,731	2381	737	20	PuMech
PuDiss	16,763	1309	650	20	PuDiss
PaChem	4,751	544	250	20	PaChem
OtChem	4,751	544	250	20	OtChem
OtMech	3,069	180	153	20	OtMech
NwMech	3,069	180	153	20	NwMech

[(a)] With a geometric depreciation model, the period determines the depreciation factor such that the remaining capacity after this period is that same as for a linear depreciation model.

Cost figures are generally difficult to come by. The numbers in Table 12 represents a combination of various sources. Sawmill costs are based on (Lindholm, 2006), inflated with price index of 18%. Heatpl costs are based on (Energimarknadsinspektionen, 2011). PuChem and PuDiss use numbers of the 800,000 t capacity kraft mill presented by Onarheim et al. (2017) with 10 SEK EUR^{-1}. The same source is used for the additional costs associated with processes PaChem and OtChem (integrated board mill with capacity 700,000 ton). Mechanical and half-mechanical pulp and paper products are more complex due to lack of specific data for all processes. The starting point is investment cost of NwMech from Holmberg and Gustavsson (2007). The investment cost of PuCTMP is derived by multiplying with the quota between Newsprint and CTMP processes in (Mustapha, 2016). Fixed cost for PuCTMP and NwMech are then set to 5% of investment cost, the same assumption that is used by (Mustapha, 2016). Variable costs excluding electricity for PuCTMP and NwMech are set to the same values as for PuChem and PaChem, respectively. OtMech takes on the same values for all cost parameters as NwMech. Variable costs are in addition to the above, adjusted for net production/consumption of electricity according to Table 13 and priced at 650 SEK/MWh. A depreciation period of 20 years is set to all processes following (Anon, 2020). Onarheim et al. (2017) mentions 20-30 years as reasonable life spans.

Table 13. Conversion factors of electricity net production (+) or net consumption (-); source ("Så mycket el slukar bruken," 2014)

Process	MWh/ton
PuChem	0.04
PuCTMP	-2.34
PuDiss	-0.69
PaChem	-0.56
OtChem	-0.56

Transports

Transport cost as a function of distance and transported product is computed according to functions presented by Athanassiadis and Nordfjell (2017) for residues and for timber and pulpwood in (Eriksson, Athanassiadis and Öhman, 2013); see Table 14.

Table 14. Transport cost functions (m = terrain transport distance (m); k = road transport distance (km))

Unit	Product	Link	Function
SEK tonDM^{-1}	ResStm	Plot to Heatpl	(142. + 0.2*m) + 149.6 + (54. + 1.9*k)
SEK tonDM^{-1}	ResRot	Plot to Heatpl	(142. + 0.2*m) + 166.1 + (54. + 1.9*k)
SEK m^{3}sub^{-1}	PinTim PinPuw SprTim SprPuw Decids	Plot to Heatpl	TonTSperM3fub * (36. + 1.62*k) + 91.
SEK m^{3}sub^{-1}	PinTim PinPuw SprTim SprPuw Decids	Plot to other than Heatpl	TonTSperM3fub * (36. + 1.62*k)
SEK m^{3}sub^{-1}	Sawdst Chips_	Between processes	TonTSperM3fub * (36. + 1.62*k)

Product carbon parameters

The parameters associated the assessment of the carbon balance of products are found in Table 15:

- **C per Unit** is the amount of ton carbon per unit of the product. It is derived from the conversion factors described in Table 8 except for pulp which is from Rosendal, 2020.
- **DF product** is the displacement factor at the time of use (C/C) (Leskinen *et al.*, 2018).
- **DF finish** is the displacement factor at the end of life (C/C) (Leskinen *et al.*, 2018).
- **DF half-life** is the half-life of the product (y) (IPCC, 2014).
- **Initial** is the initial stock (tC). The initial stock refers to year 2020 and are the numbers used for Swedish LULUCF reporting. All paper and paper board is allocated to one product, PuChem, for simplicity; this does not affect results since all pulp and paper has the same half-life and end of life displacement factor.

Table 15. Displacement model parameters

Product	Unit	C per Unit	DF product	DF finish	DF half-life	Initial (tC)
Sawnwd	m3sw	0.230	1.3	0.4	35	115,512,122
Heat__	MWh	0.102	0.4	0	0	0
PuChem	ton	0.450	0.0	0.4	2	37,001,679
PuMech	ton	0.388	0.0	0.4	2	0
PuDiss	ton	0.450	2.8	0.4	2	0
PaChem	ton	0.409	1.0	0.4	2	0
OtChem	ton	0.346	0.0	0.4	2	0
OtMech	ton	0.298	0.0	0.4	2	0
NwMech	ton	0.353	0.0	0.4	2	0

References

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