sustainability

Supplementary Materials

1. Analytical Framework of the MCDA Assessment

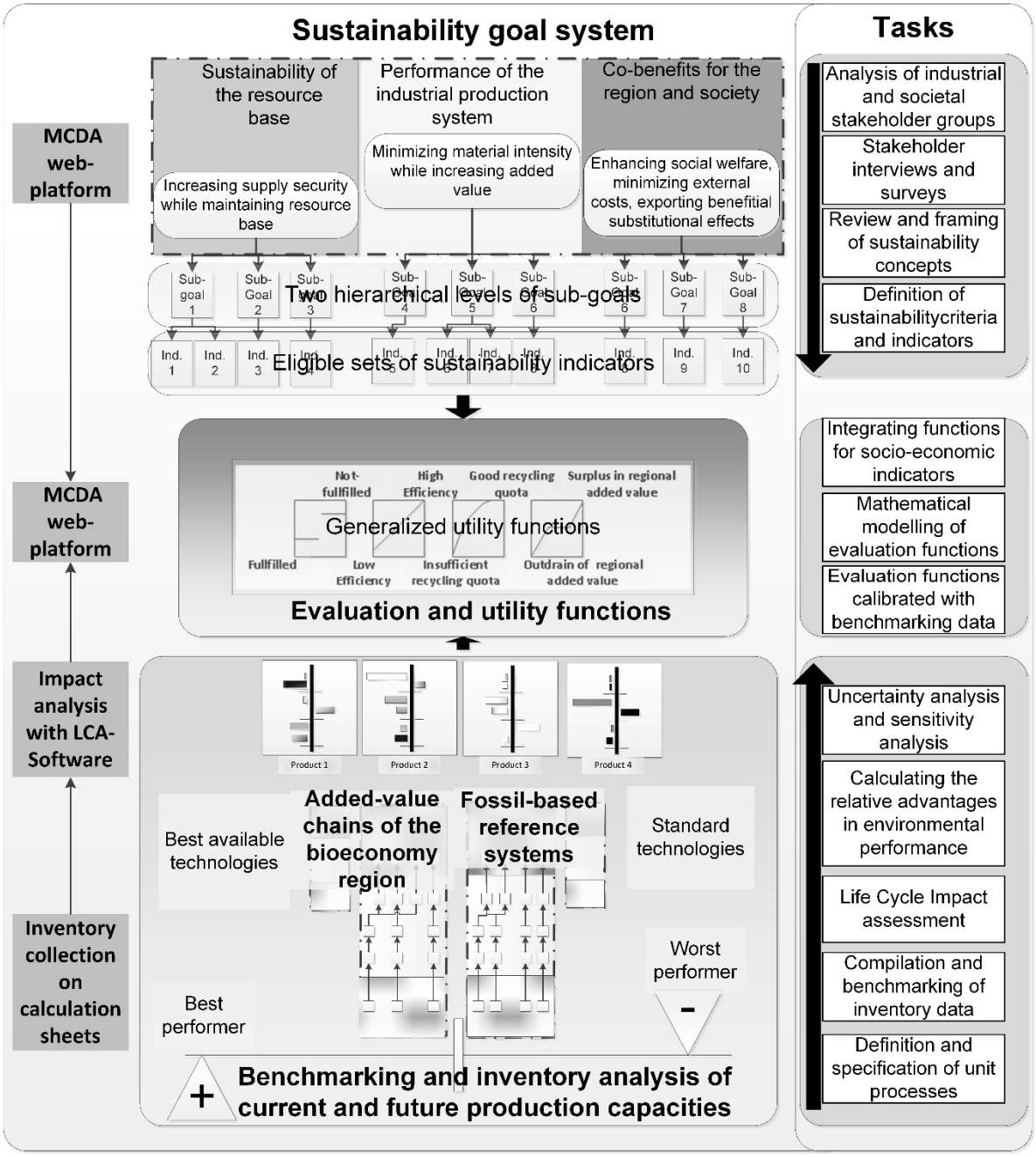

Figure S 1: Analytical and conceptual framework of the MCDA tool "SUMINISTRO"

10 **Table S 1: Material and sectoral specifications of the assessed product basket**

Product category	Product	statistic categories used for sectoral benchmarks in the sLCA	share of beech-wood resource in the final product
Wood panel boards	wood fiber insulation board	WZ 02.10, WZ 49.20, WZ 49.41 WZ 16.21	10 bis 15 %
Engineered wood products	Cross-laminated timber	WZ 02.10, WZ 49.20, WZ 49.41 WZ 16.21	55%
Engineered wood products	Moulded ply wood	WZ 02.10, WZ 49.20, WZ 49.41 WZ 16.21	35%
Engineered wood products	Laminated veneer lumber	WZ 02.10, WZ 49.20, WZ 49.41 WZ 16.10 WZ 16.21	100%
Platform chemicals	Ethylene (PET, PE)	WZ 02.10, WZ 49.20, WZ 49.41 WZ 20.14, WZ 20.16, WZ 22.22, WZ 22.23, WZ 46.901	100% cellulose-based
Platform chemicals	Lignin (premium quality)	WZ 02.10, WZ 49.20, WZ 49.41 WZ 20.52	100% lignin-based
Platform chemicals	Polylactic Acid polymers	WZ 02.10, WZ 49.20, WZ 49.41 WZ 20.14, WZ 20.16, WZ 22.22, WZ 22.23, WZ 46.901	100% cellulose-based
Composite materials	Natural fiber reinforced composite with substitution of Polyol with Lignin in PU-foam	WZ 02.10, WZ 49.20, WZ 49.41 WZ 20.52 WZ 16.21	Share of flax, hemp and kenaf, acrylic resin and PU-foam
Composite materials	Phenolic resin -based boards reinforced with beech wood fibers	WZ 02.10, WZ 49.20, WZ 49.41 WZ 20.52 WZ 16.22 WZ 20.52	20% Lignin as susbstitute in the phenolic resin matrix und 45% of beech wood -based fibers in the resin matrix

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2. Material flows within the wood-based industrial network

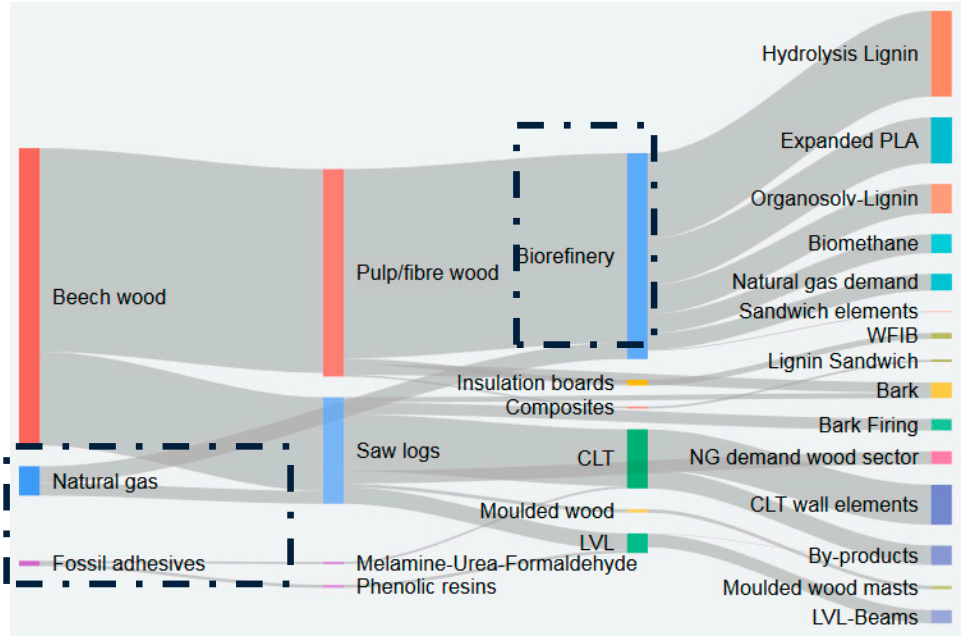


Figure S 2: Sankey Chart representing the material flows for Scenario 1

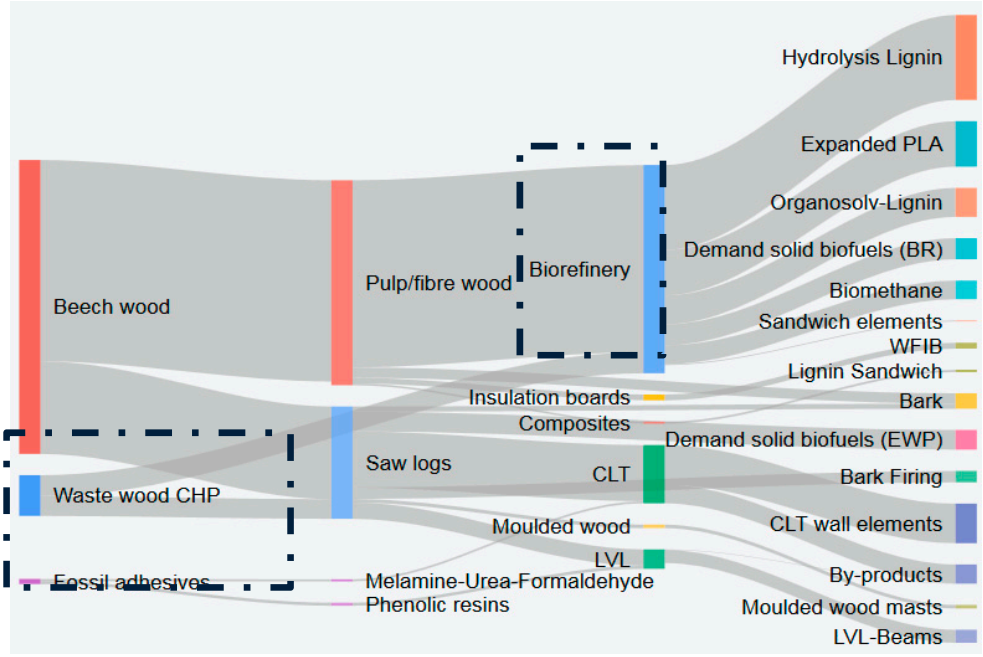


Figure S 3: Sankey Chart representing the material flows for Scenario 2

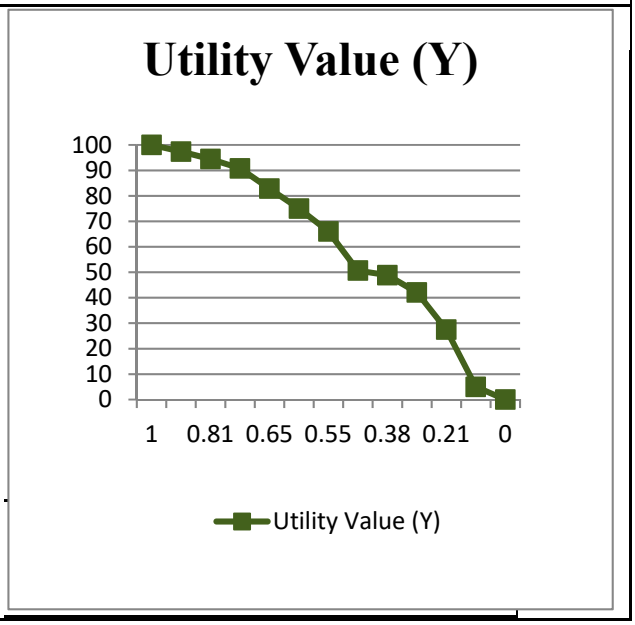
3. Methodology: Exemplary utility functions

Table S 2: Qualitative scale for Indicator RB 1 "Maximizing or Guaranteeing high standards of raw material provision"

Indicator	**RB 1**	**Sustainability standards of raw material provision**
Maximize / Minimize		Maximize
Aggregation level		Bioeconomy network
Share of feedstocks certified with respect to sust. forest management		
Level	Value	Product groups
0 % of raw materials are certified	0	
Below 10 % of raw materials are certified	1	
Below 20 % of raw materials are certified	2	
Below 30 % of raw materials are certified	3	
Below 40 % of raw materials are certified	4	
Below 50 % of raw materials are certified	5	
Below 60 % of raw materials are certified	6	Biorefinery products
Below 70 % of raw materials are certified	7	
Below 80 % of raw materials are certified	8	
Below 90 % of raw materials are certified	9	LVL, CLT, WFIB
Up to 100% of raw materials are certified	10	

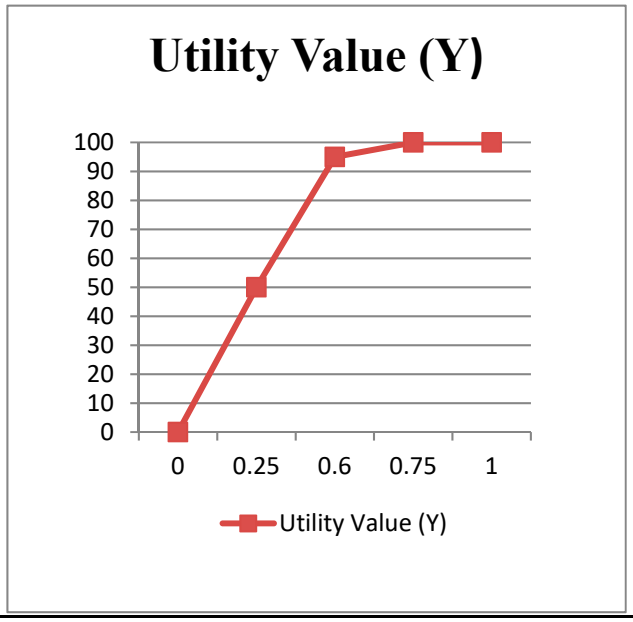
Table S 3: Utility function for Indicator RB 4 "Increase of energy self-sufficiency"

Indicator	**RB 4**	**Increase of energy self-sufficiency**
Aggregation level		Bioeconomy network
Coverage degree of energy self-sufficiency [$MWh_{self\text{-}supplied}/MWh_{total\ demand}$]		**Graph of the utility function**
Evaluation (X)	Utility Value (Y)	
1	100	
0.88	97.38	
0.81	94.45	
0.73	90.78	
0.65	82.84	
0.6	75	
0.55	66.02	
0.5	50.66	
0.38	48.86	
0.31	42.09	
0.21	27.45	
0.15	5	
0	0	



25 **Table S 4: Utility function for Indicator RP 4 "Cascading factor"**

Indicator	**RP 4**	**Cascading factor**
Aggregation level		Bioeconomy network
Share of secondary raw materials in input raw materials [$w_{secondary\ raw\ material}/w_{total\ input}$]		**Graph of the utility function**
Evaluation (X)	Utility Value (Y)	
0	0	
0.25	50	
0.6	95	
0.75	100	
1	100	

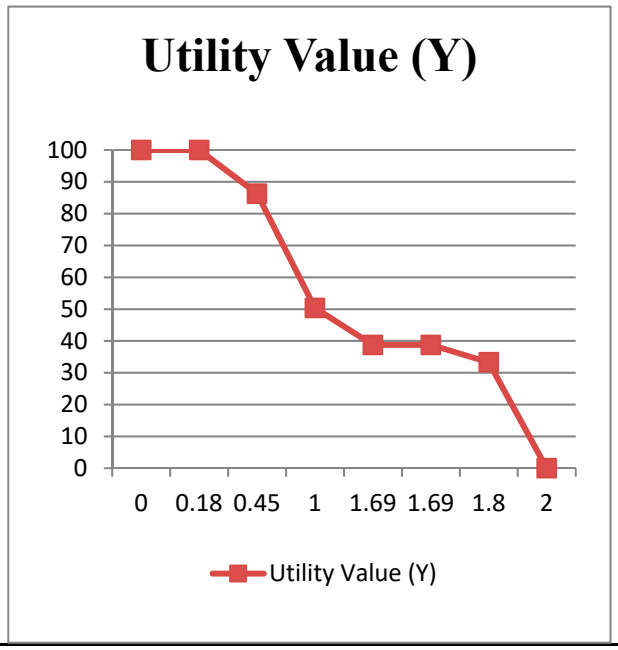


26 **Table S 5: Qualitative scale for Indicator RP 5 "Reduction of cumulative energy consumption"**

Indicator	**RP 5**	**Reduction of cumulative energy consumption**
Maximize / Minimize		Maximize
Aggregation level		Bioeconomy network
Cumulative Energy demand of the assessed product basket against the average cumulative energy consumption of reference basket		
Level		Value
50 % below average		10
40% below average		9
30 % below average		8
20% below average		7
10% below average		6
Value is indifferent from the average of reference products		5
10% above average		4
20 % above average		3
30% above average		2
40 % above average		1
More than 50 % above average		0

27 **Table S 6: Utility function for Indicator RP 7 "Reduction of GHG emissions"**

Indicator	**RP7**	**Reduction of GHG emissions**
Aggregation level		Bioeconomy network
GHG -Emissions [t $CO_{2\text{-equiv}}$/t]		**Graph of the utility function**
Evaluation (X)	Utility Value (Y)	
0	100	
0.18	100	
0.45	86.28	
1	50.33	
1.69	38.76	
1.69	38.76	
1.8	33.3	
2	0	



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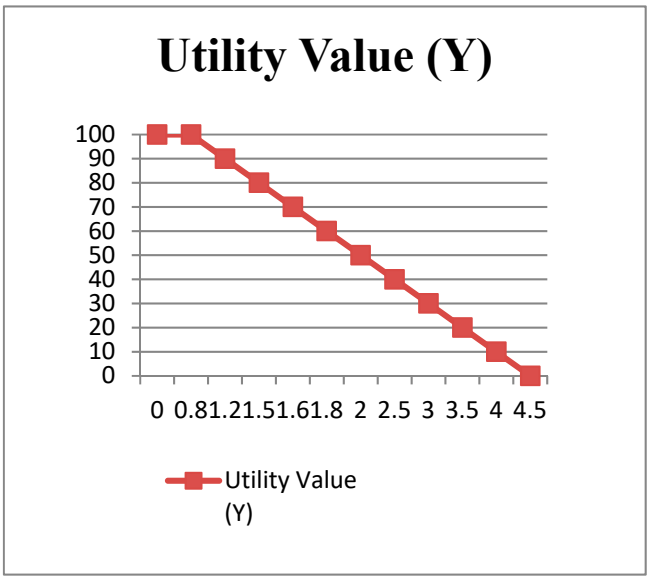
29 **Table S 7: Utility function for Indicator RP 8 "Minimization of water use"**

Indicator	**RP8**	**Minimization of water use**
Aggregation level		Bioeconomy network
Consumption of groundwater and surface water (total system) 1000 m^3/t		**Graph of the utility function**
Evaluation (X)	Utility Value (Y)	
0	100	
0.8	100	
1.2	90	
1.5	80	
1.6	70	
1.8	60	
2	50	
2.5	40	
3	30	
3.5	20	
4	10	
4.5	0	



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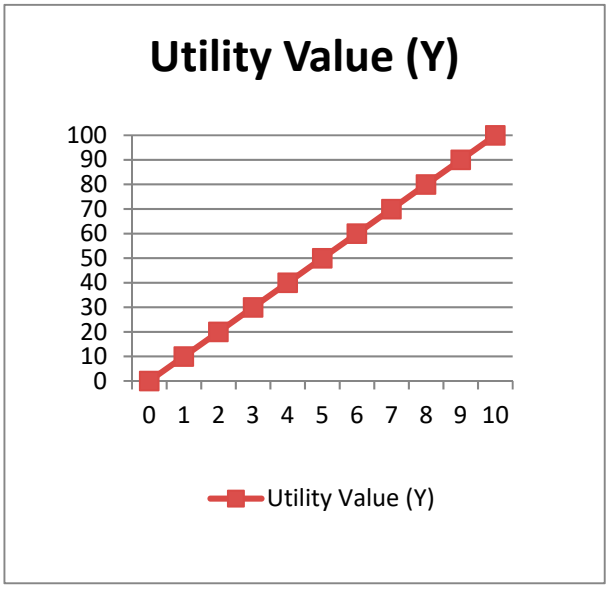
31 **Table S 8: Utility function for Indicator RB 8 "Adequate remuneration"**

Indicator	**RB 8**	**Adequate remuneration**
Maximize / Minimize		Maximize
Aggregation level		Bioeconomy network
Payment compared against payments according to collective wage		

Evaluation (X)	Utility Value (Y)
0	0
1	10
2	20
3	30
4	40
5	50
6	60
7	70
8	80
9	90
10	100



Remark: Calibration has to be done applying the RESPONSA-Framework of A. Siebert

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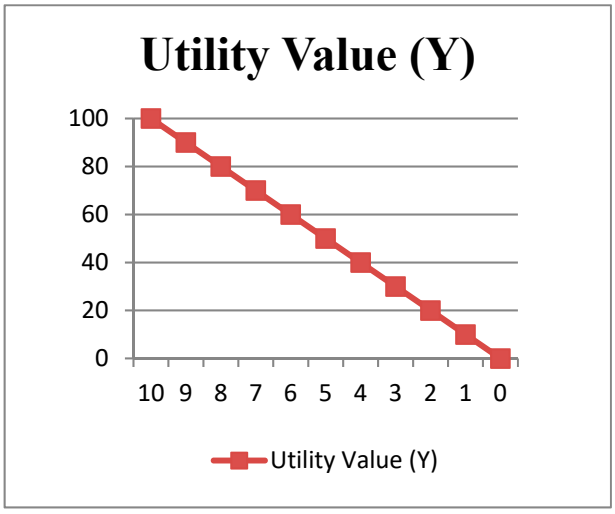
33 **Table S 9: Utility function for Indicator RB 9.1 "Minimizing the accident numbers"**

Indicator	**RB 9.1**	**Minimizing the accident numbers**
Maximize / Minimize		Minimize
Aggregation level		Bioeconomy network
Number of occupational accidents per 1000 employees		

Evaluation (X)	Utility Value (Y)
10	100
9	90
8	80
7	70
6	60
5	50
4	40
3	30
2	20
1	10
0	0



Remark: Calibration has to be done applying the RESPONSA-Framework of A. Siebert

Table S 10: Utility function for Indicator RB 9.2 "Minimizing the accident numbers"

Indicator	**RB 9.2**	**Minimizing the number of fatal accidents**
Maximize / Minimize		Minimize
Aggregation level		Bioeconomy network
Number of fatal occupational accidents per year		
Evaluation (X)	Utility Value (Y)	
10	100	
9	90	
8	80	
7	70	
6	60	
5	50	
4	40	
3	30	
2	20	
1	10	
0	0	
Remark: Calibration has to be done applying the RESPONSA-Framework of A. Siebert		

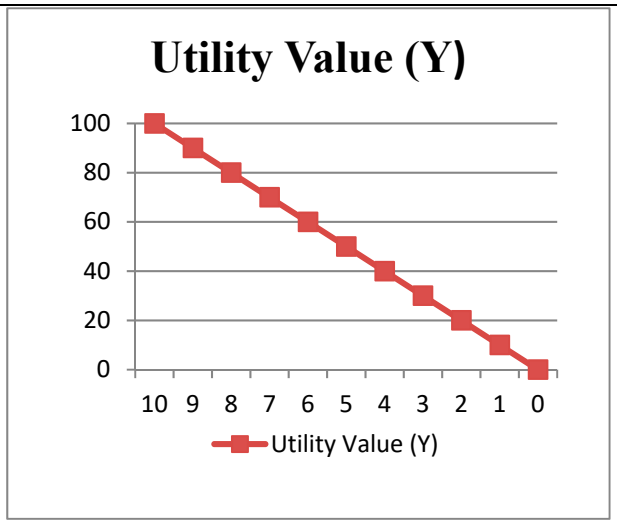
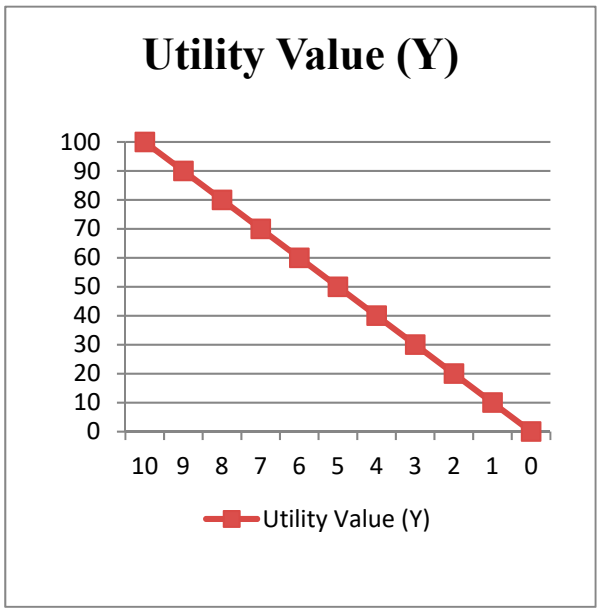


Table S 11: Utility function for Indicator RB 11 "Prevention of occupational diseases"

Indicator	**RB 11**	**Prevention of occupational diseases**
Maximize / Minimize		Minimize
Aggregation level		Bioeconomy network
Are effective organizational for the prevention of occupational diseases implemented		
Evaluation (X)	Utility Value (Y)	
10	100	
9	90	
8	80	
7	70	
6	60	
5	50	
4	40	
3	30	
2	20	
1	10	
0	0	



5. Results

Table S 12: Overview of the indicator benchmarking and the weighted average of the calibrated indicators for scenario 1 as non-normalized absolute figures

ID	Description of the Indicator	Unit	Max.-Min. values as benchmarks for the regional product basket		Weighted average
			Max.	Min.	
RP 1	Minimising the consumption of fresh water (ground water and surface water)	m^3/t	1383.151	738.99	**986.2**
RP 2	Increasing the resource efficiency of biomass conversion	w/w	90.701	59.78	**78.8**
RP 3	Reduction of waste from fossil-based auxiliaries	w/w	0.065	0.02	**0.046**
RP 4	Cascading factor	w/w	1.332	1.00	**1.2**
RP 5	Reduction of cumulative energy consumption	MJ/t	58.180	23.49	**38.5**
RP 6	Maximizing land use efficiency (forest biomass, agroforestry and agrarian biomass)	t saw logs/ ha, t fiber/ ha, t sugar / ha , t pulp/ha , t/ ha*t/t Sucrose	14.129	4.90	**8.7**
RP 7	Reduction of GHG emissions	t CO2-eqv./t	1.248	0.87	**1.035**
RP 8	Increase in material efficiency	e.g. U-Value, Tensile modulus	1.632	0.77	**1.1**
RP 9	Employment of highly qualified employees	% of total workforce	5.394	3.24	**4.0**
RP 10	Employment of marginally employed persons	% of total workforce	7.192	2.80	**6.2**
RP 11	Employment in research and development	% of total workforce	7.369	5.60	**6.3**
RB 1	Maximizing or Guaranteeing high standards of raw material provision	w/w [t Input certified and regic	99.884	37.22	**74.0**
RB 2.1	Maximizing the recycled content at the end of its life		15.215	5.13	**9.8**
RB 2.2	Qualitative factor for multi-stage cascading (Extrusion cycles and moulding bevaiour)		0.842	0.76	**0.8**
RB 4	Maximizing the coverage degree of energy self-sufficiency	% [MWh Selfsupply/MWh total demand of process energy]	80.791	30.55	**43.1**
RB 5	Maximizing the share of renewable energy	%	65.923	38.46	**43.8**
RB 6	Minimizing the proportion of imported fossil resources	%	78.093	45.45	**61.7**
RB 7	Development of the share of protected landscape and converted forest land over time in 10 years	ha initial/ha status	n.a.	n.a.	**n.a.**
RB 8	Adequate remuneration"	Score from A. Siebert	7.571	4.64	**7.0**
RB 9.1	Minimizing the accident numbers	Score from A. Siebert	7.991	5.99	**7.0**
RB 9.2	Minimizing the accident numbers	Score from A. Siebert	7.991	1.00	**7.0**
RB 11	Prevention of occupational diseases	Score from A. Siebert	6.807	4.00	**5.4**
RB 12	Minimizing the cases of illness	Score from A. Siebert	6.492	5.61	**5.9**
RB 13	Minimizing the cases of illness	Score from A. Siebert	6.892	4.13	**6.4**
RB 13	Employess per 100 t abd.-dry of product-output	MA/ 100 t atro	0.120	0.01	**0.0351**
RB 14	Creation of training places	Score from A. Siebert	7.991	5.48	**7.0**
RB 15	Maximizing employee participation in the company	Score from A. Siebert	0.000	0.00	**0.0**
EB 1	Maximizing municipal tax revenues	€/a für Clusterregion	n.a.	n.a.	**n.a.**
EB 2	Strengthening underdeveloped rural regions		n.a.	n.a.	**n.a.**
EB 3	Maximizing financial participation in the company	Score from A. Siebert	4.889	1.20	**4.8**
EB 4	Maximizing financial participation in the company	Score from A. Siebert	n.a.	n.a.	**n.a.**
EB 5	Improvement of working conditions	Score from A. Siebert	8.890	4.72	**6.2**
EB 6	Improvement of working conditions	Score from A. Siebert	6.250	2.72	**5.7**
EB 7	No use of PBT substances		99.884	99.88	**99.9**
WS 1	Added-value creation	Distance from the best performer and €/t	307.838	55.08	**233.4**
WS 2	Competitive production costs	€/t	483.638	736.40	**558.1**
WS 3	Potential for capacity expansion in the competition regime (input capacities)	Kilotons	2315000.000	482500.00	**632662.8**

Table S 13: Sources used in indicator benchmarking

ID	Description of the ndicator	Unit	Sources
RP 1	Minimising the consumption of fresh water (ground water and surface water)	m^3/t	Questionaires in the Leading-Edge Cluster, GaBi databases, ReCiPe Evaluation
RP 2	Increasing the resource efficiency of biomass conversion	w/w	Iffland 2015, Budzinski & Nitzsche 2016, 2017
RP 3	Reduction of waste from fossil-based auxiliaries	w/w	
RP 4	Cascading factor	w/w	Own classification of wood-based products according to waste wood categoreis, content of additives and common recycling pathways and infrastructuresin
RP 5	Reduction of cumulative energy consumption	MJ/t	Project meeting and questionaires in the Leading-Edge Cluster, GaBi databases, Benchmarking studies as Richter 2007 and EPD results from IBU and others
	Minimierung des Dampfbedarf in Bioraffinerie-Prozessen	t Dampf/ t	Budzinski & Nitzsche 2016, 2017
RP 6	Maximizing land use efficiency (forest biomass, agroforestry and agrarian	t/ ha*t/t Sucorose	Project questionaires, EcoInvent Inventories, Land use projects
RP 7	Reduction of GHG emissions	t CO2-eqv./t	Project meeting and questionaires in the Leading-Edge Cluster, GaBi databases, Benchmarking studies as Richter 2007 and EPD results from IBU and others
RP 8	Increase in material efficiency	e.g. U-Value, Tensile modulus	S. Franke Holzbautag Biel 2013, V. Thole Weichholztagung WKI/HNE 2014, Pollmeier 2015, Homatherm
RP 9	Employment of highly qualified employees	% of total workforce	Siebert et. al 2018
RP 10	Employment of marginally employed persons	% of total workforce	Siebert et. al 2018
RP 11	Employment in research and development	% of total workforce	Siebert et. al 2018
RB 1	Maximizing or Guaranteeing high standards of raw material provision	w/w [t Input certified and regionally mobilzed / t total feedstock input]	Publicly available informations on certification shares of utilized forest resources on the homepages of companies, available informations from naturplus e.V. certififications, interviews with FSC and PEFC
RB 2.1	Maximizing the recycled content at the end of its life	Share of waste wood categories AI and AII	Project workshops, meetings and internal emails, own classification of impregnated woodm products acc
RB 2.2	Qualitative factor for multi-stage cascading (Extrusion cycles and moulding bevaiour)		
RB 4	Maximizing the coverage degree of energy self-sufficiency	% [MWh Selfsupply/MWh total demand]	Questionaires in the Leading-Edge Cluster, GaBi databases, CML Evaluation
RB 5	Maximizing the share of renewable energy	%	Fraunhofer ISE, https://www.energy-charts.de, Nettoerzeugung von Kraftwerken zur öffentlichen Stromversorgung, Datenquelle: 50 Hertz, Amprion, Tennet, TransnetBW, Destatis, EEX letztes Update: 21 Jan 2018 02:23
RB 6	Minimizing the proportion of imported fossil resources	%	
RB 7		ha initial/ha status	
RB 8	Adequate remuneration"	Score from A. Siebert	Siebert et. al 2018, Zapf, I., 2015., Kohaut et al. 2013
RB 9.1	Minimizing the accident numbers	Score from A. Siebert	Siebert et. al 2018,baua Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2014.
RB 9.2	Minimizing the accident numbers	Score from A. Siebert	Siebert et. al 2018,baua Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2014.
RB 11	Prevention of occupational diseases	Score from A. Siebert	Siebert et. al 2018,Bechmann et al. 2013 IAB-Forschungsbericht 14.
RB 12	Minimizing the cases of illness	Score from A. Siebert	Siebert et. al 2018,baua Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2014.
RB 13	Minimizing the cases of illness	Score from A. Siebert	Siebert et. al 2018, Knieps et al. 2014
RB 13	Employess per 100 t abd.-dry of product-output	MA/ 100 t atro	Siebert et. al 2018, Steffens & Bombosch 2008, Pollmeier 2014
RB 14	Creation of training places	Score from A. Siebert	Siebert et. al 2018,
RB 15	Maximizing employee participation in the company	Score from A. Siebert	Siebert et. al 2018, Statistik der Bundesagentur für Arbeit, 2015, 2016
EB 1	Maximizing municipal tax revenues	€/a für Clusterregion	
EB 2	Strengthening underdeveloped rural regions		
EB 3	Maximizing financial participation in the company	Score from A. Siebert	Siebert et. al 2018
EB 4	Maximizing financial participation in the company	Score from A. Siebert	Siebert et. al 2018
EB 5	Improvement of working conditions	Score from A. Siebert	Siebert et. al 2018
EB 6	Improvement of working conditions	Score from A. Siebert	Siebert et. al 2018
EB 7	No use of PBT substances		
WS 1	Added-value creation	€	Wenderdel ETH 2015, UBA 3009, UBA 2012, Fachhochschule Bern 2015 , Mikado Pollmeier 2015
WS 2	Competitive production costs	€/t	Wenderdel ETH 2015, UBA 3009, UBA 2012, Fachhochschule Bern 2015
WS 3	Potential for capacity expansion in the competition regime	Kilotons	Budzinski & Nitzsche 2016, Hildebrandt 2017, IEA 2013 , FAO/UNECE 2014, 2015, Nova Institute 2014

45 **Table S 14: Normalized results for scenarios 1,2, and 3 as presented in the radar plot in the results section**

		Scenario 1: Getting in shape: LCF-Biorefinery starts its operation, capacities for composites and engineered wood products are installed	Scenario 2: Thermal Cascades: Waste-Wood-based heat substitutes natural gas, increase of renewable electricity share and PLA production	Scenario 3: Fully bio-based: Resin supply is fully bio-based and PLA secondary raw materials recycling established
Max_Energy self-suffiency	Maximising the energy self-suffiency in heat supply [% of kWh/kWhtotal]	57	75	100
Max_renewable electricity	Maximising share of renewable Electricity [% of kWh/kWhtotal]	40	65	100
Min_import fossil ressources	Minimising the fractions of imported fossil ressources	40	65	100
Adequate remuneration	Fair and equal payment	70	70	70
Min_accidents	Minimising the number of accidents compared to refernce companies	59	62	65.0
Min_fatal accidents	Minimising of fatal accidents	59	59	59
Min_occup. diseases	Minimising occupational diseases	64	64	64
Min_illness	Minimising illness leaves	64	64	64
Create training positions	Creation of training positions	60	65	70
Max_financial partizipation	Increasing finacial partizipation of employess	50	50	50
Max_financial partizipation	Increasing financial partizipation of employess	40	40	40
Min_marginal employment	Shares in marginal employment compared to reference companies	61	61	61
Reduce waste	Reduction of aviodable production wastes	40	35	25

Max_Profit	Profitmargin per Ton of Product	65	70	80
Max_Secondary raw materials	Cascading factor at End of Product service Life	10	25	35
Max_land-use efficiency		50	50	50
Max_qualified employment	Shares in highly qualified employment compared to reference companies	39	40.95	42.9975
Refer_R&D positions	Shares in R&D positions compared to reference companies	49	52	55
Max_conversion efficiency	Increasing the efficiency in conversion of biomass resources	48.6	55	65
Min_cumulative carbon footprint	Cumulative Carbon Footprint at factory gate	73.2	85	100
Max_waste wood recycling	Waste wood: Increase of of recycling at the End of the product service life	54	65	75
Assurance_sustainable biomass	Sustainability assurance in biomass provisioning	56.6	75	100
Min_CED	Minimising the cumultaive energy demand	58.6	65	72
Max_ GHG mitigation potential	Potential mitigation of GHG emissions	40	80	100