Supporting Information: Designing Industrial Networks using Ecological Food Web Metrics

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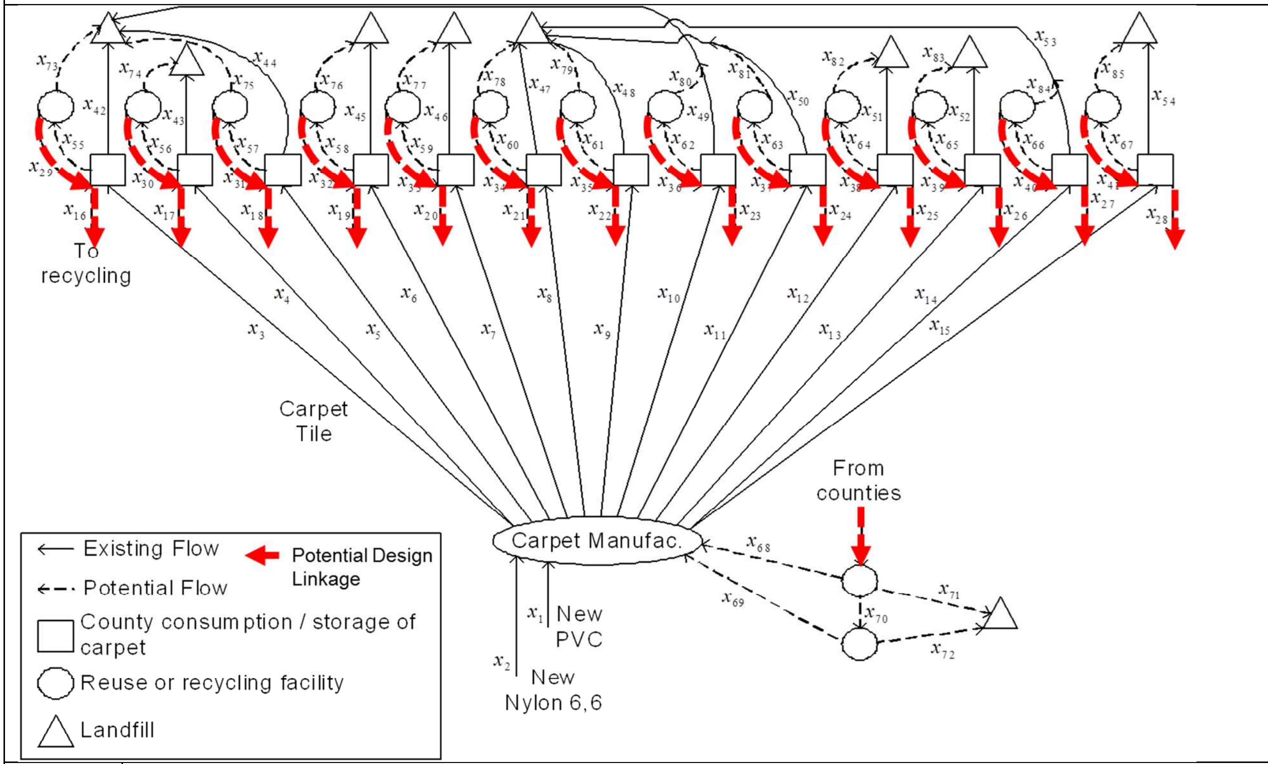
TABLE S1: CARPET RECYCLING NETWORK MODEL

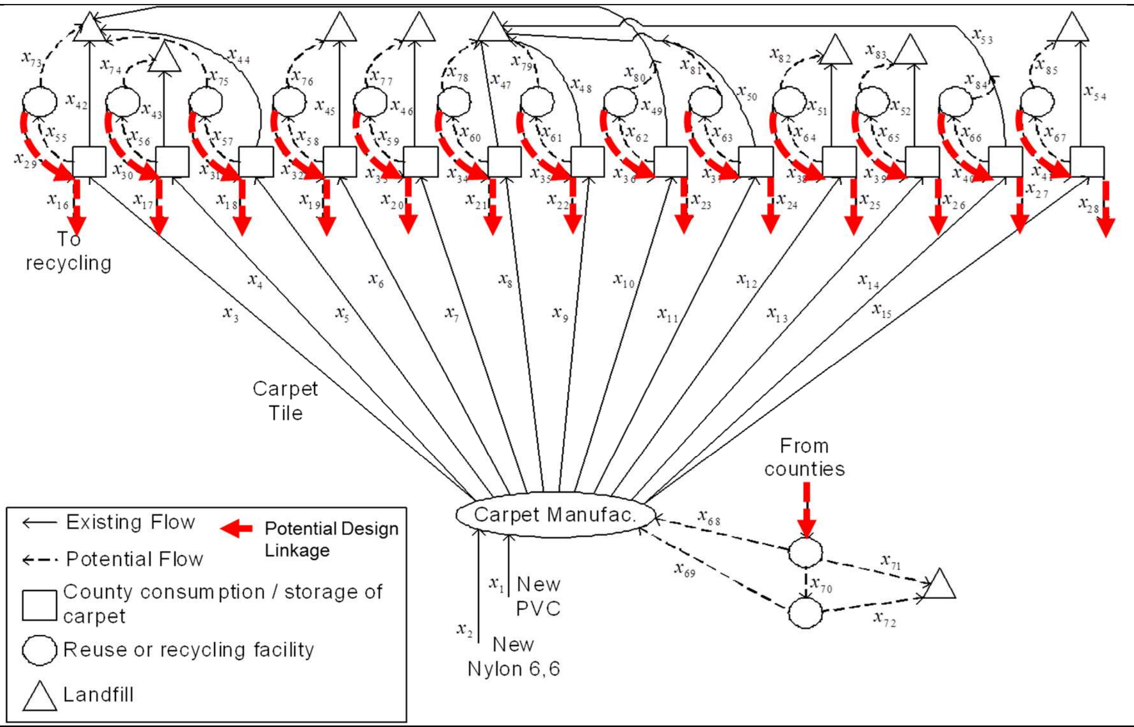


Given		
Parameters		
Costs:		
	c_{pvc} = 0.2758	PVC backing (PVC and filler) cost [$/kg]
	c_n=3.55	Nylon 6,6 cost [$/kg]
	c_{tip}=0.03	Landfill tipping fee [$/kg]
	c_d=0.61	EIA diesel fuel price estimate for Summer 2009 [$/L]
	c_e=.0559	Retail electricity price [$/kWh]
	c_{Lt}=16.6	Hourly truck driver wage in 2008 [$/hr]
	c_{Lru}=10.41	Reuse cleaning labor [$/hr]
	c_{Lbale}=11.8	Baling labor [$/hr]
	c_{Ls}=13.21	Shredding labor [$/hr]
	c_{Lg}=13.21	Grinding labor [$/hr]
	c_{Lms}=14.98	Material separation labor [$/hr]
	c_{Lp}=13.78	PVC pellet creation labor [$/hr]
	c_{Lncy}=13.5	Nylon cyclonic air separator labor [$/hr]
	c_{Lnb}=13.5	Nylon bunker melt labor [$/hr]
	c_{Lns}=13.5	Nylon spinneret [$/hr]
	c_{Lnc}=13.5	Nylon cooling [$/hr]
	c_{Lnd}=13.5	Nylon drawing [$/hr]

	c_{Lnw}=13.5	Nylon winding [$/hr]
	Emissions:	
	e_{pvc}=[2015, 10.27, 0.0007, 12.12, 8.43, 0.001, 4.03, 0.002, 3E-05, 1.4, 1.47, 10.43]	g emission/kg PVC produced [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]
	e_n=[6681, 42.09, 0.74, 21.6, 17.85, 2E-06, 6.27, 0.08, 4E-06, 3.89, 2.11, 0]	g emission/kg Nylon 6,6 produced [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]
	$e_{cleaner}$=[7.28E-03, 0, 0, 4.78E-05, 8.94E-06, 0, 0, 0, 7.78E-11, 0, 0, 0]	g emission/kg deep cleaning solution produced [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]
	e_{v3}=[487.446; 0.0032; 0.0030; 0.0061; 3.06; 0; 11.87; 0; 0; 1.00; 0.08; 0]	g emission/km [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]
	e_{v8A}=[882.502; 0.0032; 0.0030; 0.011; 6.52; 0; 25.26; 0; 0; 2.12; 0.16; 0]	“
	e_e=[629.58; 0; 0; 4.13; 0.77; 0; 0; 0; 6.73E-06; 0; 0; 0]	g emission/kWh generated; only CO_2, SO_2, NO_x and Hg provided [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]
	Unit Efficiencies:	
	f_{pvc}=0.7	Total material efficiency for PVC recycling (output PVC backing mass/input backing mass)
	f_n=0.7	Total material efficiency for Nylon 6,6 recycling (output nylon face mass/input nylon face mass)
	R_n=0.2	Fraction of carpet tile face mass sent to nylon recycling
	f_{17}=0.9	Total material efficiency for carpet reuse (output reusable carpet tile mass/input reusable carpet tile mass)
	f_{18}=0.9	“
	f_{19}=0.9	“
	f_{20}=0.9	“
	f_{21}=0.9	“
	f_{22}=0.9	“
	f_{23}=0.9	“
	f_{24}=0.9	“
	f_{25}=0.9	“
	f_{26}=0.9	“
	f_{27}=0.9	“
	f_{28}=0.9	“
	f_{29}=0.9	“
	Recycling Process Data:	

	$e_{ruclean}$=1.16E-5	Electricity consumed while cleaning reusable carpet tiles [kWh/kg]
	e_{bale}=.002	Electricity consumed to bale recyclable carpet tiles [kWh/kg]
	e_{s}=.056	Electricity consumed to shred recyclable carpet tiles [kWh/kg]
	e_{g}=.055	Electricity consumed to grind recyclable carpet tiles [kWh/kg]
	e_{ms}=.178	Electricity consumed to separate ground carpet tile materials [kWh/kg]
	e_{p}=.01	Electricity consumed during PVC pellet creation [kWh/kg]
	e_{ncy}=.0082	Electricity consumed to cyclonically separate nylon [kWh/kg]
	e_{nb}=.819	Electricity consumed by a bunker melter [kWh/kg]
	e_{ns}=.506	Electricity consumed by nylon spinnerets [kWh/kg]
	e_{nc}=.232	Electricity consumed to cool nylon [kWh/kg]
	e_{nd}=.317	Electricity consumed to draw nylon [kWh/kg]
	e_{nw}=.257	Electricity consumed to wind drawn nylon [kWh/kg]
	T_{ru}=1.16E-5	Throughflow for cleaning reusable carpet tiles [kg/hr]
	T_{bale}=.002	Throughflow for baling recyclable carpet tiles [kg/hr]
	T_{s}=.056	Throughflow for shredding recyclable carpet tiles [kg/hr]
	T_{g}=.055	Throughflow for grinding recyclable carpet tiles [kg/hr]
	T_{ms}=.178	Throughflow for separating ground carpet tile materials [kg/hr]
	T_{p}=.01	Throughflow for PVC pellet creation [kg/hr]
	T_{ncy}=.0082	Throughflow for cyclonic nylon separation [kg/hr]
	T_{nb}=.819	Throughflow for bunker melter [kg/hr]
	T_{ns}=.506	Throughflow for nylon spinnerets [kg/hr]
	T_{nc}=.232	Throughflow for cooling nylon [kg/hr]
	T_{nd}=.317	Throughflow for nylon draw [kg/hr]
	T_{nw}=.317	Throughflow for nylon winding [kg/hr]
	Transportation Data:	
	s_{avg}=93.115	Average truck speed in km/hr (55 mph)
	l_{v3}=1814	Load capacity of a HDDV3 truck [kg/truck]
	l_{v8A}=12247	Load capacity of a HDDV8A truck [kg/truck]
	η_{v3}=.425	Fuel efficiency of a HDDV3 truck [km/L]
	η_{v8A}= η_{v3}	Fuel efficiency of a HDDV8A truck [km/L]

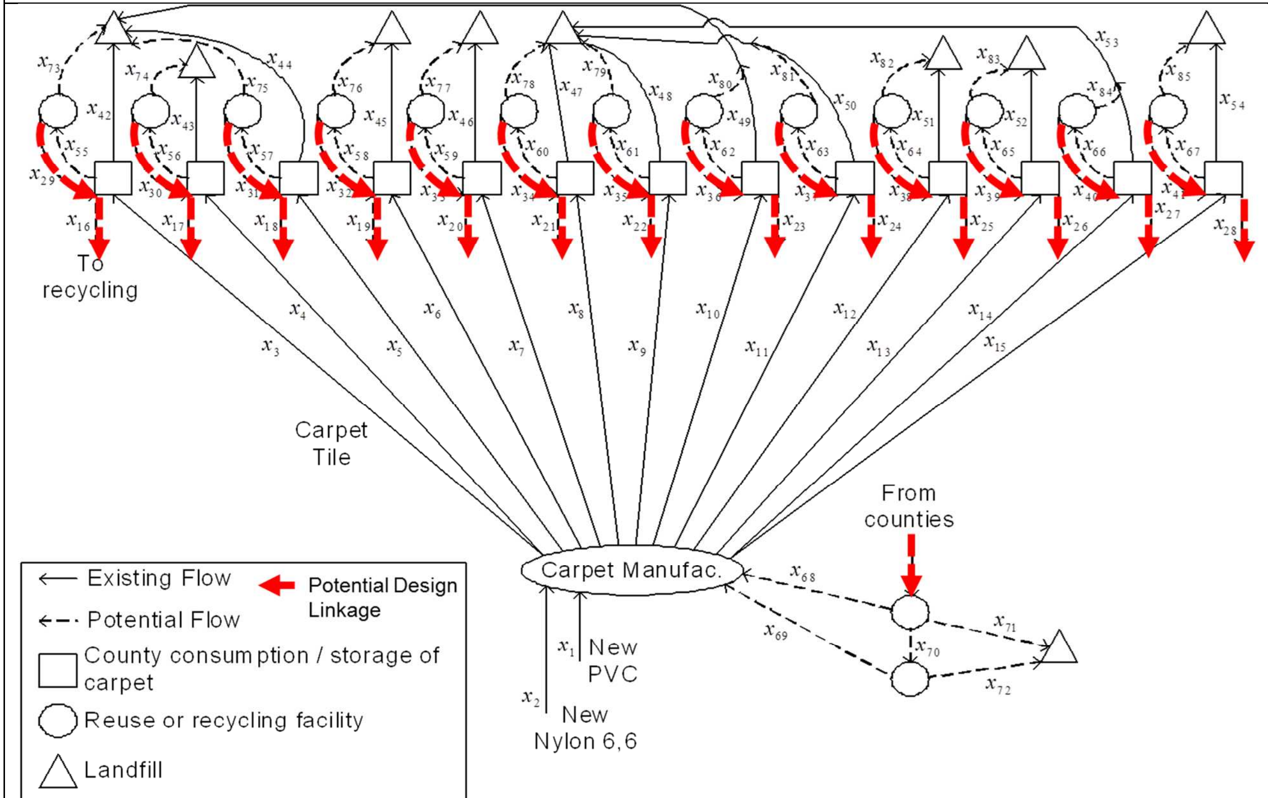
Table S1: The basic model structure for the carpet recycling network used to test the objective functions outlined in Tables S2 and S3.

TABLE S2: TRADITIONAL OBJECTIVE FUNCTION		
		
Find:		
	x_i for i=16,17…41	Amount of used carpeting sent to recycling (i=16-28) and reuse (i=29-41) centers
Goal Target Values for Traditional Objective Function:		Values are taken from the best possible scenario for the model multiplied by a goal scaling value of 0.8. Emissions are measured in grams and cost in US dollars.
	$G_{CO2} = 6.67x10^9$	Carbon Dioxide **CO_2** emissions (g/year)
	$G_{CH4} = 3.17x10^7$	Methane **CH_4** emissions (g/year)
	$G_{N2O} = 3.02x10^5$	Nitrous Oxide **N_2O** emissions (g/year)
	$G_{SO2} = 3.06x10^7$	Sulfur Dioxide **SO_2** emissions (g/year)
	$G_{NOx} = 2.25x10^7$	Mono-Nitrogen Oxides **NOx** emissions (g/year)
	$G_{Pb} = 1.43x10^3$	Lead **Pb** emissions (g/year)
	$G_{CO} = 1.75x10^7$	Carbon Monoxide **CO** emissions (g/year)
	$G_{VOCs} = 3.50x10^4$	Volatile Organic Compounds **VOCs** emissions (g/year)
	$G_{Hg} = 52$	Mercury **Hg** emissions (g/year)
	$G_{HC} = 4.35x10^6$	Hydrocarbon **HC** emissions (g/year)
	$G_{PM} = 3.02x10^6$	Particulate Matter **PM** emissions (g/year)

	$G_{Sox} = 1.50x10^7$	Sulfur Oxides **SOx** emissions (g/year)
	$G_{cost} = 5.90x10^6$	Total network cost (US dollars/year)
Traditional Objective Function:	Minimize total cost and emissions	
	$d_{min} = 1 - \frac{value}{goal\ target\ value}$	Difference between the value of each variable and its goal value
	$w = \frac{1}{13}$	Weighting factor for the 13 components (12 emissions and total cost) of the traditional objective function
	$d_{emissions} = w\left(1 - \frac{e_{CO2}}{G_{CO2}}\right) + w\left(1 - \frac{e_{CH4}}{G_{CH4}}\right) + w\left(1 - \frac{e_{N2O}}{G_{N2O}}\right) + w\left(1 - \frac{e_{SO2}}{G_{SO2}}\right) + w\left(1 - \frac{e_{NOx}}{G_{NOx}}\right) + w\left(1 - \frac{e_{Pb}}{G_{Pb}}\right) + w\left(1 - \frac{e_{CO}}{G_{CO}}\right) + w\left(1 - \frac{e_{VOCs}}{G_{VOCs}}\right) + w\left(1 - \frac{e_{Hg}}{G_{Hg}}\right) + w\left(1 - \frac{e_{HC}}{G_{HC}}\right) + w\left(1 - \frac{e_{PM}}{G_{PM}}\right) + w\left(1 - \frac{e_{SOx}}{G_{SOx}}\right)$	
	$d_{cost} = w\left(1 - \frac{C}{G_{cost}}\right)$	
	$Z_{trad} = d_{cost} + d_{emissions}$	Minimize objective function

Table S2: Emission values used in calculating the traditional objective function, and the final form of the traditional objective function.

TABLE S3: BIO-INSPIRED OBJECTIVE FUNCTION



Input-Output Matrices and Vectors :		
	$\boldsymbol{P} = f(\boldsymbol{x})$	I-O Production matrix with nonzero elements determined by the structure of carpet flow network
	$\boldsymbol{p}_{rsum} = \sum_{j=2}^{30} p_{ij}$	Column vector containing the sum of the elements of selected rows in matrix **P**
	$\boldsymbol{Q} = [q_{ij}]\ where\ q_{ij} = \begin{cases} \frac{p_{ij}}{\sum_{j=1}^{n} p_{ij}}\ for \sum_{j=1}^{n} p_{ij} > 0 \\ 0 \qquad for \sum_{j=1}^{n} p_{ij} \le 0 \end{cases}$	Instantaneous Fractional Flow matrix
	$\boldsymbol{N} = (\boldsymbol{I} - \boldsymbol{Q})^{-1}$	Transitive Closure matrix
	$\boldsymbol{c}_{re} = \left[\frac{n_{kk} - 1}{n_{kk}}\right]\ for\ k = 2,3 \dots 30$	Column vector of return cycling efficiencies for network nodes
	$m_{tstc} = \boldsymbol{c_{re}}^{\boldsymbol{T}} \boldsymbol{p_{rsum}}$	Cyclic throughflow
	Adjacency and Community Matrices :	
	$\boldsymbol{A_{adj}} = f(\boldsymbol{f})$	Structural adjacency matrix with binary elements determined by network connections
	$\boldsymbol{C} = \boldsymbol{A_{adj}}^{\boldsymbol{T}}$	Community matrix
	Nodes and Trophic Links :	

	$s = f(\boldsymbol{C}) = f(\boldsymbol{A_{adj}})$	Number of nodes in a community matrix; usually equal to the size of the community matrix
	$L = \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}$	Number of links connected nodes in the adjacency or community matrix
	Structural Metrics :	
	$L_D = {}^{L}/_{S}$	Link density
	$P_{special} = {}^{n_{s-pred}}/_{n_{predator}}$	Specialized predator ratio
	$P_r = {}^{n_{prey}}/_{n_{predator}}$	Prey to predator ratio
	$G = {}^{L}/_{n_{predator}}$	Generalization
	$V = {}^{L}/_{n_{prey}}$	Vulnerability
	$\lambda_{max} = max. real\ eigenvalue\ \boldsymbol{A_{adj}}$	Cyclicity
	Input-Output Metrics :	
	$m_{in} = x_1 + x_2$	Carpet material inflow
	$m_{tst} = \sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}$	Total system throughflow
	$MPL = \frac{m_{tst}}{m_{in}}$	Mean Path Length
	$FCI = \frac{m_{tstc}}{m_{tst}}$	Finn Cycling Index
Find:		
	x_i for *i*=16,17…41	Amount of used carpeting sent to recycling (i=16-28) and reuse (i=29-41) centers
Satisfy:		
	$\sum_{i=16}^{28} x_i \leq 1{,}189{,}300$	PVC recycling facility capacity constraint
	$x_{i+28} \leq 0.1r_i\ , for\ i = 1{,}2 \dots 13$	Reuse facility capacity constraint
	$x_i \geq 0\ , for\ i = 1{,}2 \dots 85$	Positive flow constraint
Goal Target Values for Bio-Inspired Objective Function:		Values are the average value of 50 food webs from the literature.
	$G_{P_{special}} = 0.10$	Specialized Predator Ratio
	$G_{P_r} = 1.09$	Prey to Predator Ratio
	$G_{L_D} = 5.04$	Linkage density

	$G_G = 6.18$	Generalization
	$G_V = 5.34$	Vulnerability
	$G_{\lambda_{max}} = 4.24$	Cyclicity
	$G_{MPL} = 5.7$	Mean Path Length
	$G_{FCI} = 0.295$	Finn Cycling Index
Bio-Inspired Objective Function:	Minimize total difference between metrics and their goal values	
	$1 \geq n \geq 8$	n: the number of metrics included in the objective function
	$w = \frac{1}{n}$	Weighting factor for the 8 food web metrics (6 structural metrics and 2 flow based metrics) of the bio-inspired objective function
	Minimize:	
	$p_{special}, p_r$	Metrics to reduce to reach goal values
	$d_{min} = 1 - \frac{metric\ value}{metric\ goal\ target\ value}$	Difference between the value of each variable and its goal value
	$d_{min} = w\left(1 - \frac{P_{special}}{G_{P_{special}}}\right) + w\left(1 - \frac{P_r}{G_{P_r}}\right)$	
	Maximize:	
	$L_D\ , G,\ V,\ \lambda_{max}, MPL, FCI$	Metrics to increase to reach goal values
	$d_{max} = 1 - \frac{metricgoal\ target\ value}{metric\ value}$	Difference between the value of each variable and its goal value
	$d_{max} = w\left(1 - \frac{G_{L_D}}{L_D}\right) + w\left(1 - \frac{G_G}{G}\right) + w\left(1 - \frac{G_V}{V}\right) + w\left(1 - \frac{G_{\lambda_{max}}}{\lambda_{max}}\right) + w\left(1 - \frac{G_{MPL}}{MPL}\right) + w\left(1 - \frac{G_{FCI}}{FCI}\right)$	
	$Z_{bio} = d_{min} + d_{max}$	Minimize objective function

Table S3: Formulas and goal values used in calculating the metrics of the bio-inspired objective function, as well as its final form.