Supporting information for:

Quantifying Energy and Greenhouse Gas Emissions Embodied in Global Primary Plastic Trade Network

Joseph Zappitelli[1], Elijah Smith[2], Kevin Padgett[3], Melissa M. Bilec[1], Callie W. Babbitt[4], and Vikas Khanna[1,3]*

[1] Department of Civil and Environmental Engineering, University of Pittsburgh, 3700 O'Hara Street, 742 Benedum Hall, Pittsburgh, Pennsylvania 15261, United States

[2] Department of Industrial Engineering, University of Pittsburgh, 3700 O'Hara Street, 1025 Benedum Hall, Pittsburgh, Pennsylvania 15261, United States

[3] Department of Chemical and Petroleum Engineering, University of Pittsburgh, 3700 O'Hara Street, 940 Benedum Hall, Pittsburgh, Pennsylvania 15261, United States

[4] Golisano Institute for Sustainability, Rochester Institute of Technology, 190 Lomb Memorial Drive, Rochester, New York 14623, United States

*Address correspondence to khannav@pitt.edu; telephone: +1-412-624-9603

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S1. Model Formation and Background Information

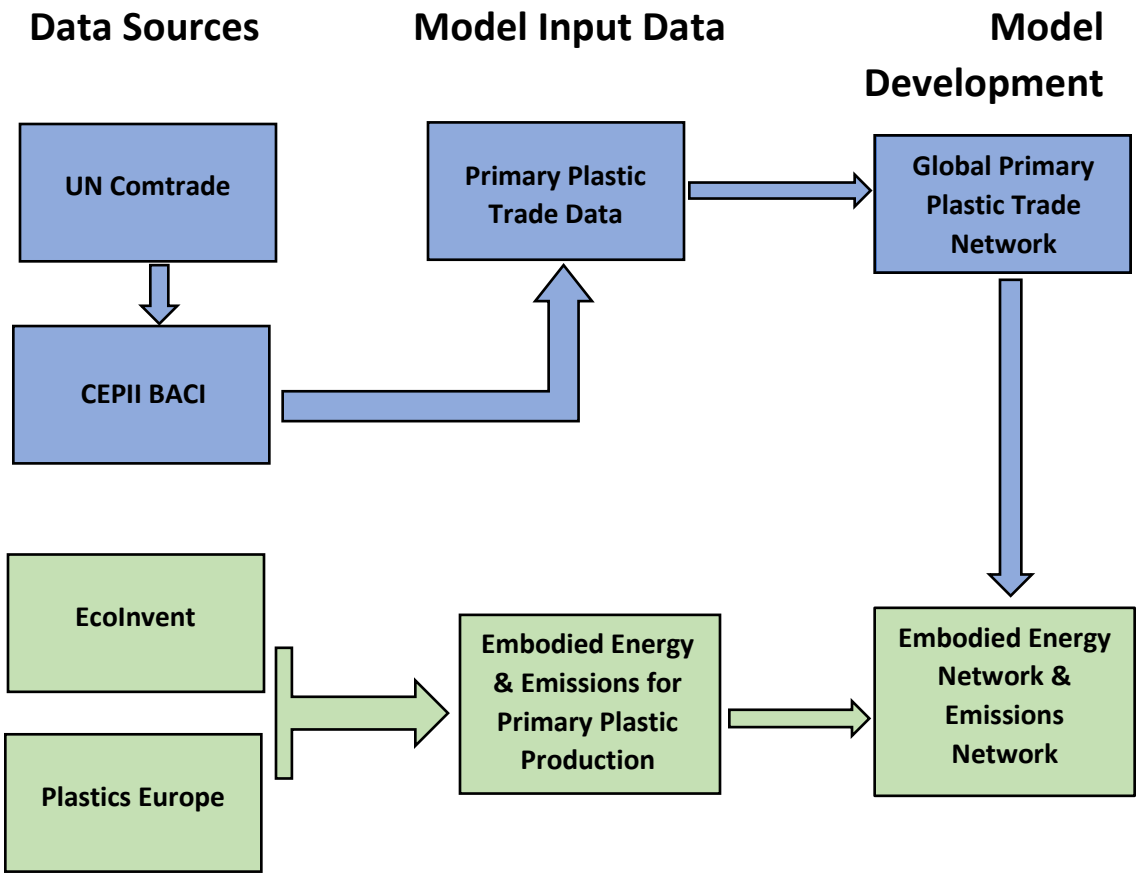

Figure S1. Visual representation of workflow from acquiring data to constructing network models of the global primary plastic trade network (GPPTN) and associated embodied flows.

Table S1. List of ISO 3-digit country name abbreviations

Country	Code	Country	Code
Afghanistan	AFG	Lesotho	LSO
Albania	ALB	Liberia	LBR
Algeria	DZA	Libya	LBY
American Samoa	ASM	Liechtenstein	LIE
Andorra	AND	Lithuania	LTU
Angola	AGO	Luxembourg	LUX
Anguilla	AIA	Macao	MAC
Antarctica	ATA	Madagascar	MDG
Antigua and Barbuda	ATG	Malawi	MWI
Argentina	ARG	Malaysia	MYS
Armenia	ARM	Maldives	MDV
Aruba	ABW	Mali	MLI
Australia	AUS	Malta	MLT
Austria	AUT	Marshall Islands (the)	MHL
Azerbaijan	AZE	Martinique	MTQ
Bahamas (the)	BHS	Mauritania	MRT
Bahrain	BHR	Mauritius	MUS
Bangladesh	BGD	Mayotte	MYT
Barbados	BRB	Mexico	MEX
Belarus	BLR	Micronesia (Federated States of)	FSM
Belgium	BEL	Moldova (the Republic of)	MDA
Belize	BLZ	Monaco	MCO
Benin	BEN	Mongolia	MNG
Bermuda	BMU	Montenegro	MNE
Bhutan	BTN	Montserrat	MSR
Bolivia (Plurinational State of)	BOL	Morocco	MAR
Bonaire, Sint Eustatius and Saba	BES	Mozambique	MOZ
Bosnia and Herzegovina	BIH	Myanmar	MMR
Botswana	BWA	Namibia	NAM
Bouvet Island	BVT	Nauru	NRU
Brazil	BRA	Nepal	NPL
British Indian Ocean Territory (the)	IOT	Netherlands (the)	NLD
Brunei Darussalam	BRN	New Caledonia	NCL
Bulgaria	BGR	New Zealand	NZL
Burkina Faso	BFA	Nicaragua	NIC
Burundi	BDI	Niger (the)	NER
Cabo Verde	CPV	Nigeria	NGA
Cambodia	KHM	Niue	NIU
Cameroon	CMR	Norfolk Island	NFK
Canada	CAN	Northern Mariana Islands (the)	MNP
Cayman Islands (the)	CYM	Norway	NOR

Central African Republic (the)	CAF	Oman	OMN
Chad	TCD	Pakistan	PAK
Chile	CHL	Palau	PLW
China	CHN	Palestine, State of	PSE
Christmas Island	CXR	Panama	PAN
Cocos (Keeling) Islands (the)	CCK	Papua New Guinea	PNG
Colombia	COL	Paraguay	PRY
Comoros (the)	COM	Peru	PER
Congo (the Democratic Republic of the)	COD	Philippines (the)	PHL
Congo (the)	COG	Pitcairn	PCN
Cook Islands (the)	COK	Poland	POL
Costa Rica	CRI	Portugal	PRT
Croatia	HRV	Puerto Rico	PRI
Cuba	CUB	Qatar	QAT
Curaçao	CUW	Republic of North Macedonia	MKD
Cyprus	CYP	Romania	ROU
Czechia	CZE	Russian Federation (the)	RUS
Côte d'Ivoire	CIV	Rwanda	RWA
Denmark	DNK	Réunion	REU
Djibouti	DJI	Saint Barthélemy	BLM
Dominica	DMA	Saint Helena, Ascension and Tristan da Cunha	SHN
Dominican Republic (the)	DOM	Saint Kitts and Nevis	KNA
Ecuador	ECU	Saint Lucia	LCA
Egypt	EGY	Saint Martin (French part)	MAF
El Salvador	SLV	Saint Pierre and Miquelon	SPM
Equatorial Guinea	GNQ	Saint Vincent and the Grenadines	VCT
Eritrea	ERI	Samoa	WSM
Estonia	EST	San Marino	SMR
Eswatini	SWZ	Sao Tome and Principe	STP
Ethiopia	ETH	Saudi Arabia	SAU
Falkland Islands (the) [Malvinas]	FLK	Senegal	SEN
Faroe Islands (the)	FRO	Serbia	SRB
Fiji	FJI	Seychelles	SYC
Finland	FIN	Sierra Leone	SLE
France	FRA	Singapore	SGP
French Guiana	GUF	Sint Maarten (Dutch part)	SXM
French Polynesia	PYF	Slovakia	SVK
French Southern Territories (the)	ATF	Slovenia	SVN
Gabon	GAB	Solomon Islands	SLB
Gambia (the)	GMB	Somalia	SOM
Georgia	GEO	South Africa	ZAF

Germany	DEU	South Georgia and the South Sandwich Islands	SGS
Ghana	GHA	South Sudan	SSD
Gibraltar	GIB	Spain	ESP
Greece	GRC	Sri Lanka	LKA
Greenland	GRL	Sudan (the)	SDN
Grenada	GRD	Suriname	SUR
Guadeloupe	GLP	Svalbard and Jan Mayen	SJM
Guam	GUM	Sweden	SWE
Guatemala	GTM	Switzerland	CHE
Guernsey	GGY	Syrian Arab Republic	SYR
Guinea	GIN	Taiwan (Province of China)	TWN
Guinea-Bissau	GNB	Tajikistan	TJK
Guyana	GUY	Tanzania, United Republic of	TZA
Haiti	HTI	Thailand	THA
Heard Island and McDonald Islands	HMD	Timor-Leste	TLS
Holy See (the)	VAT	Togo	TGO
Honduras	HND	Tokelau	TKL
Hong Kong	HKG	Tonga	TON
Hungary	HUN	Trinidad and Tobago	TTO
Iceland	ISL	Tunisia	TUN
India	IND	Turkey	TUR
Indonesia	IDN	Turkmenistan	TKM
Iran (Islamic Republic of)	IRN	Turks and Caicos Islands (the)	TCA
Iraq	IRQ	Tuvalu	TUV
Ireland	IRL	Uganda	UGA
Isle of Man	IMN	Ukraine	UKR
Israel	ISR	United Arab Emirates (the)	ARE
Italy	ITA	United Kingdom of Great Britain and Northern Ireland (the)	GBR
Jamaica	JAM	United States Minor Outlying Islands (the)	UMI
Japan	JPN	United States of America (the)	USA
Jersey	JEY	Uruguay	URY
Jordan	JOR	Uzbekistan	UZB
Kazakhstan	KAZ	Vanuatu	VUT
Kenya	KEN	Venezuela (Bolivarian Republic of)	VEN
Kiribati	KIR	Viet Nam	VNM
Korea (the Democratic People's Republic of)	PRK	Virgin Islands (British)	VGB
Korea (the Republic of)	KOR	Virgin Islands (U.S.)	VIR
Kuwait	KWT	Wallis and Futuna	WLF
Kyrgyzstan	KGZ	Western Sahara	ESH
Lao People's Democratic Republic (the)	LAO	Yemen	YEM

Latvia	LVA	Zambia	ZMB
Lebanon	LBN	Zimbabwe	ZWE
Lesotho	LSO		

Table S2. Commodity codes considered in the study, from UN Comtrade.[1]

Code	Description	Considered
390110	Ethylene polymers; in primary forms, polyethylene having a specific gravity of less than 0.94	LDPE
390120	Ethylene polymers; in primary forms, polyethylene having a specific gravity of 0.94 or more	HDPE
390190	Ethylene polymers; in primary forms, n.e.s. in heading no. 3901	Linear LDPE
390210	Propylene, other olefin polymers; polypropylene in primary forms	PP
390410	Vinyl chloride, other halogenated olefin polymers; polyvinyl chloride (not mixed with any other substances), in primary forms	PVC
390760	Polyethylene terephthalate; in primary forms	PET
390311	Styrene polymers; expansible polystyrene, in primary forms	Expandable PS
390319	Styrene polymers; (other than expansible polystyrene), in primary forms	General Purpose PS
390610	Acrylic polymers; polymethyl methacrylate, in primary forms	PMMA
390740	Polycarbonates; in primary forms	Polycarbonate
390810	Polyamides; polyamide-6, -11, -12, -6,6, -6,9, -6,10 or -6,12, in primary forms	Polyamide Fibers

S2. Primary Plastic Trade Data

The HS commodity code classification system[2] ranges from two-digit to six-digit codes, with increasing levels of specificity. The HS commodity code for plastics in general is 39 and there are further nested four-digit and six-digit codes within the plastics category. For this study we used the majority of six-digit commodity code data nested within the four-digit commodity code classes 3901-3911. The only exclusions were commodity codes that were for thermosets or bio-plastics, as the scope of this work is limited to thermoplastics, specifically: LDPE, HDPE, PP, PVC, PET, EPS, GGPS, PMMA, PC, PA, LLDPE.

The R programming environment[3] was used to perform all data analysis. After downloading the data, it was formatted to a square adjacency matrix with all 293 countries within their dataset along the rows and columns. Location (*i,j)* in the matrices represents a flow of product from node *i* to node *j*. Network coding tasks were completed in R, mainly with the support of the igraph package. The general work flow in R was to import and clean data to create a table with columns including importing country, exporting country and quantity of plastic resin exchanged.

S3. Life Cycle Data Acquisition

Table S3. Primary plastic resins and life cycle inventory (LCI) data

Material	Unit	Database	Cumulative Energy Demand[4] (MJ/unit)	GWP (kg CO_2 equivalent/unit)[5]
Polyethylene terephthalate	kg	Ecoinvent3[6]	73.9	3.18
Polyethylene, high density	kg	Ecoinvent3	72.7	2.09
Polyethylene, low density	kg	Ecoinvent3	71.9	2.27
Polyethylene, linear low density	kg	Ecoinvent3	71.7	2.01
Polypropylene	kg	Ecoinvent3	71.6	2.12
Polymethyl methacrylate	kg	Ecoinvent3	121	7.47
Polystyrene, expandable	kg	Ecoinvent3	86.7	3.64
Polystyrene, general purpose	kg	Ecoinvent3	85.5	3.76
Polyvinylchloride	kg	Ecoinvent3	50.1	3.64
Polycarbonate	kg	Ecoinvent3	93.2	8.24
Polyamide 6,6 (Nylon)	kg	Ecoinvent3	120	8.34

Table S4. Carbon percentages by mass for the plastic resins studied. These values were used to calculate embedded carbon.

Name	Molecule	Carbon Mass Percentage
LDPE	$(C_2H_4)_n$	85.628
HDPE	$(C_2H_4)_n$	85.628
PP	$(C_3H_6)_n$	85.628
PVC	$(C_2H_3Cl)_n$	38.438
PET	$(C_{10}H_8O_4)_n$	62.502
Ex PS	$(C_8H_8)_n$	92.257
G PS	$(C_8H_8)_n$	92.257
PMMA	$(C_5O_2H_8)_n$	59.985
PC	$(C_{16}H_{14}O_3)_n$	75.575
PA 6,6	$(C_{12}H_{22}N_2O_2)_n$	63.685
LLDPE	$(C_2H_4)_n$	85.628

S4. Network Analysis Methodology

Below is a list of network measures utilized in this analysis and brief description of each:

Degree The degree[7] of a node is a count of the number of edges connected to it. In a directed network, like the GPPTN, each link connecting two nodes has a direction that represents the origin and destination of traded goods. The in-degree of a node is the number of countries sending goods to a node, or importing relationships. Out-degree is the number of countries receiving goods from a node, or exporting relationships. Degree centrality is formulated for node *i* as follows:

$$DC(i) = \sum_{j=1}^{n} A_{ij} \quad \textbf{(1)}$$

Where *n* represents the number of nodes in the network, *A* represents the adjacency matrix of all node connections in the network. An entry A_{ij} in the adjacency matrix takes on a value of 1 if there is a connection between node *i* and node *j* and a value of 0 otherwise.

Strength The strength[8] of a node is similar in calculation to degree, but is a weighted sum of edge weights rather than a simple count of edges. In GPPTN, the weight of an edge is equivalent to the quantity of plastic traded between the two countries connected by the edge. A country's measure for in-strength is equivalent to total imports, out-strength is equivalent to total exports, and total strength is the sum of the two former quantities. Strength allows us to determine which countries are the dominant suppliers and consumers in the GPPTN and is computed for node *i as follows:*

$$SC(i) = \sum_{j=1}^{n} A_{ij} * w_{ij} \quad \textbf{(2)}$$

Where *n* represents the number of nodes in the networks, *A* represents the adjacency matrix, and w_{ij} represents the weight, or quantity of plastic traded, associated with the link between nodes *i* and *j*.

Betweenness Betweenness centrality[9] is a measure of the influence of a node, based on its position between two separate nodes. This measure looks to capture nodes serving "middlemen" roles in the network. These nodes may not have large quantities of flows, but their abundant and/or strategic trade partnerships are integral to fostering connectivity and trade flow within the network. Betweenness centrality for node *i* is computed as follows:

$$BC(i) = \sum_{j \neq k \neq i} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \quad \textbf{(3)}$$

Where σ_{jk} represents the number of shortest paths between nodes *j* and *k* and $\sigma_{jk}(i)$ represents the number of shortest paths between nodes *j* and *k* that pass through node *i.*

Eigenvector Eigenvector centrality[10] aims to measure the influence of a node, based on its connections to other influential nodes. An influential country has many trade partners, that in turn also have many additional trade partners themselves. This is evidence that the reference node is in a central position of a prominent clique within the network. Eigenvector centrality is calculated for the network with the following equation:

$$\boldsymbol{Ax = \lambda x} \tag{4}$$

Where *A* represents the adjacency matrix of all node connections within the network, *x* is a vector of centrality scores for all nodes, and λ is the largest eigenvalue that satisfies the equation. The resulting eigenvector is used to determine centrality ranks, with the largest values belonging to nodes with the top eigenvector centrality rankings.

Density A network's density is a comparison of the number of observed edges and the number of possible edges in a network. This value allows us to determine if the network is sparsely or heavily connected, which is important to understand the movement of goods in the network and to give context when interpreting the results of centrality measures. The following equation is used to calculate network density:

$$Density = \frac{E}{n(n-1)} \tag{5}$$

Where *E* represents the number of edges in the network and *n* represents the number of nodes in the network.

S5. Supplementary Network Analysis Results

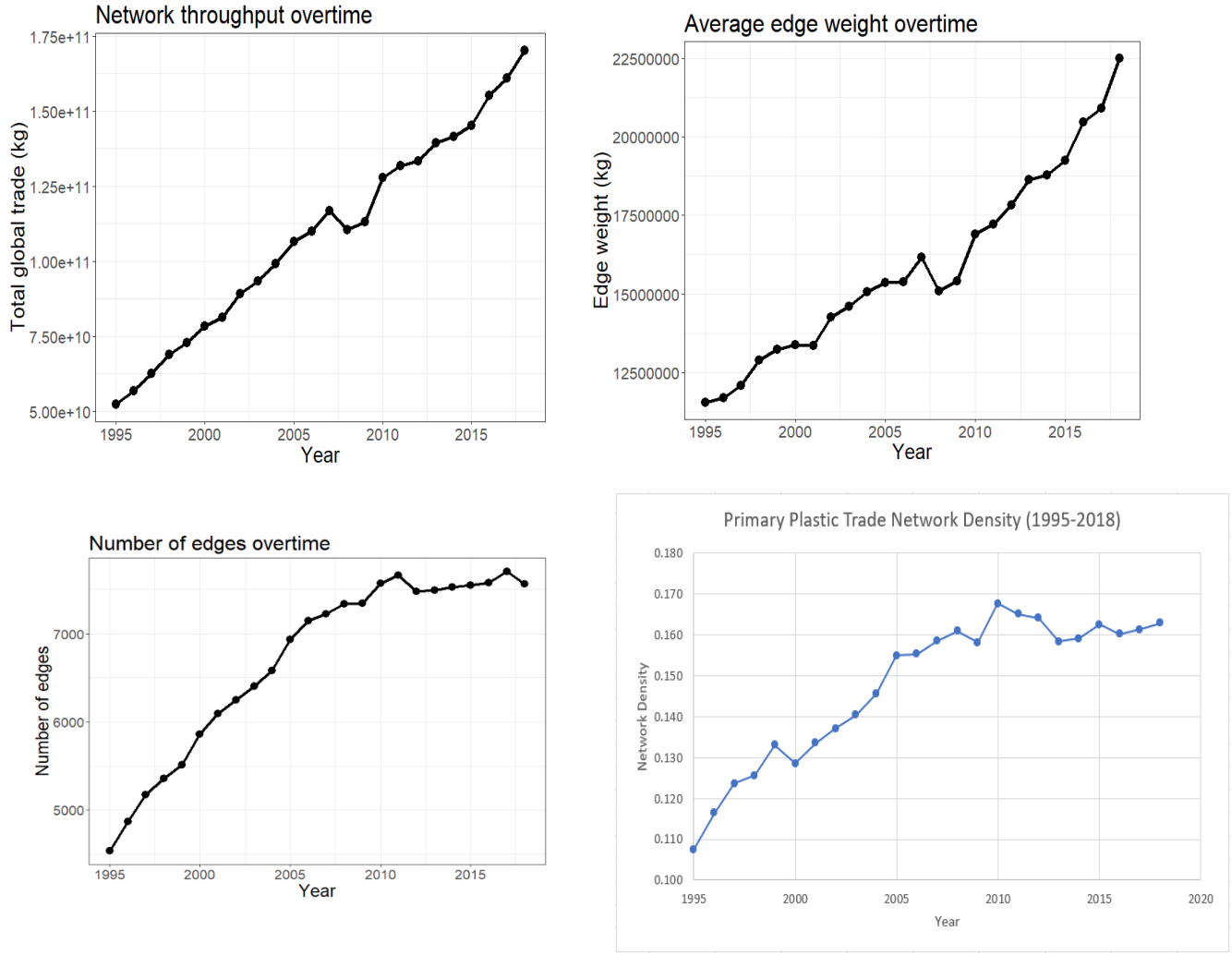

Figure S2. Network structural characteristic measures including count of nodes, edges, density, and throughput over time.

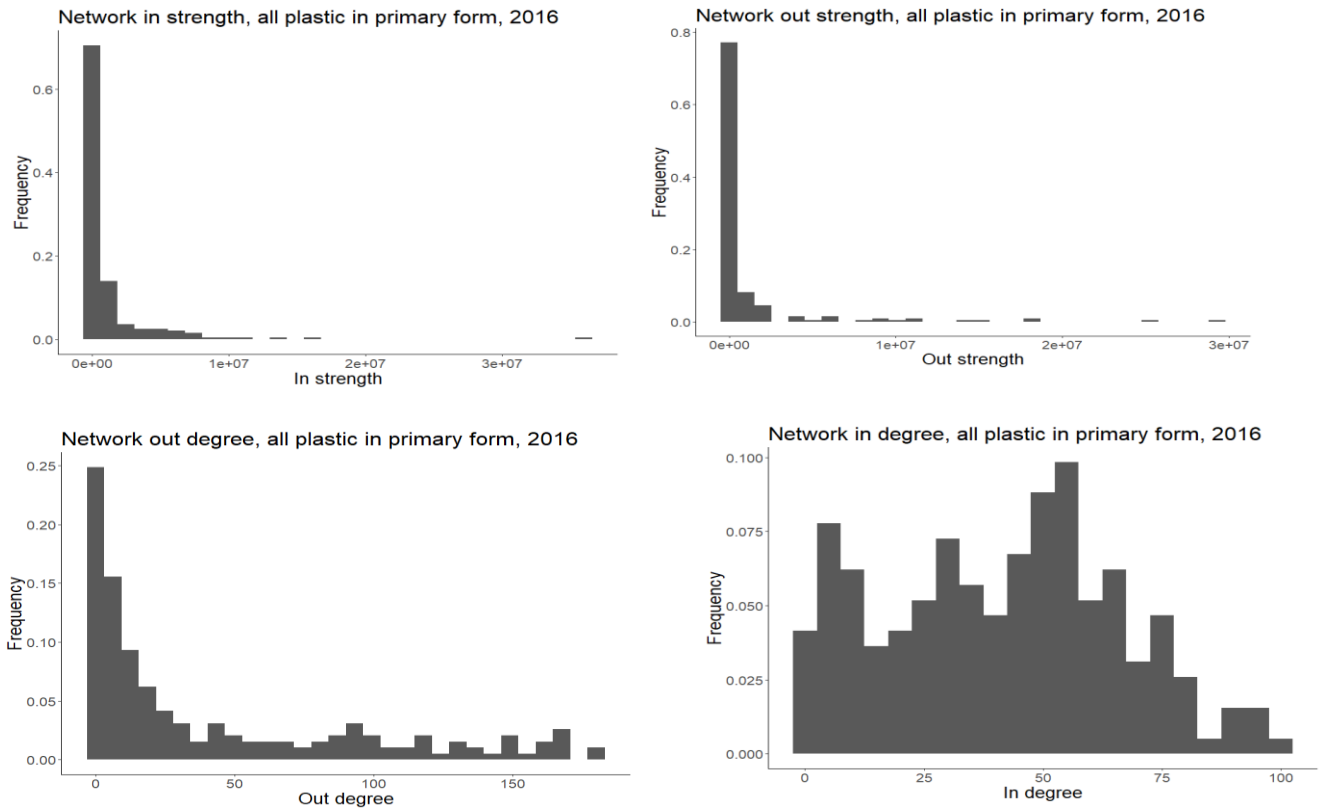

Figure S3. Histograms of in and out measures of degree (bottom) and strength (top) centrality.

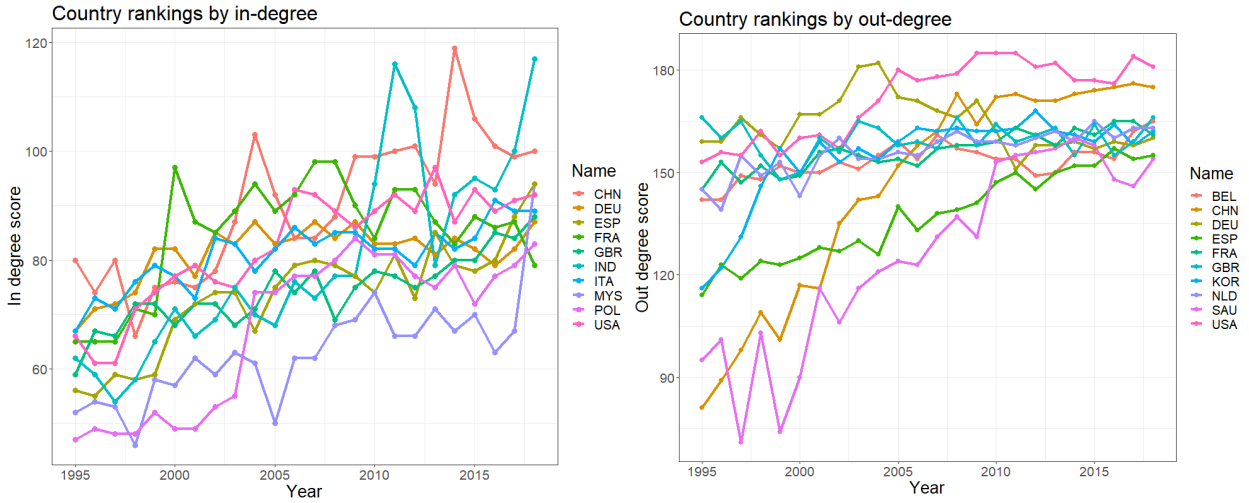

Figure S4. Degree centrality ranks over time.

Degree Overall, degree increases over time as more trade partnerships are formed in the GPPTN. Analyzing the out-degree data shows most countries do not significantly participate in the exporting of plastics in the GPPTN. The countries with highest score for this metric include

countries rich in fossil fuels or plastic resin production facilities, including USA, Saudi Arabia, Iran, Germany and Belgium-Luxembourg. On the other hand, almost all countries in the network participate in the importing of plastics in the GPPTN, and many of the nodes have over 50 edges. China has the greatest in-degree score by a large margin. To see a full list of top ranked countries by their degree centrality scores

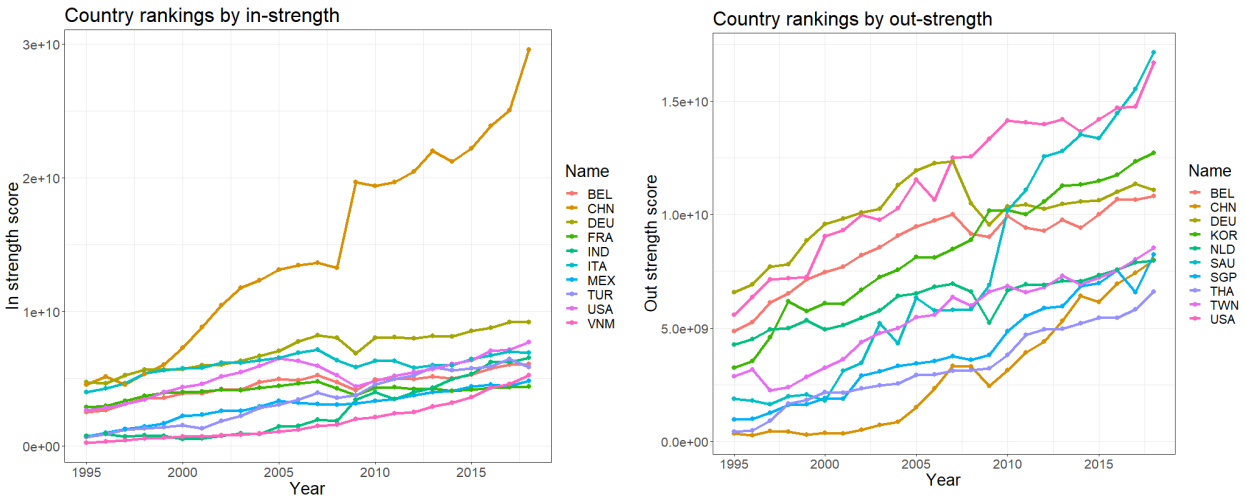

Figure S5. Strength centrality ranks over time.

Strength Analyzing the strength centrality measure over time shows similar results to degree. Strength scores increased over time as the quantity of plastic resins traded increased over time. When looking at the out-strength, or exports, of countries in the network, it is apparent that the majority of the network does not significantly participate in the exporting of plastics. Similar countries score high in strength ranking as the countries that scored high in degree ranking. The in-strength analysis provides similar results, leading to the conclusion that the majority of trade in the network is completed by a handful of key nodes.

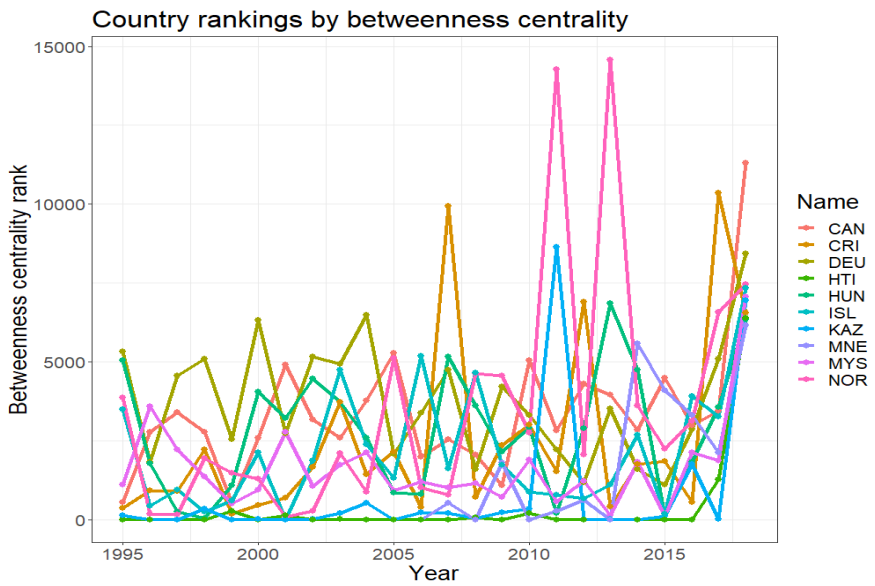

Figure S6. Betweenness centrality ranks over time.

Betweenness Over the time period of the study, the countries that ranked high in betweenness score tend to switch from year to year. A high score for this measure indicates a country is playing a middleman role in the network, meaning the country imports a substantial amount just to export a substantial amount as well to other countries. Scandinavian countries like Denmark, Norway and Iceland had high scores for betweenness centrality. Hong Kong was another territory that scored high in this score, which can be explained by intermediary trade that travels through Hong Kong ports to China, the network's largest importer of plastic resins.

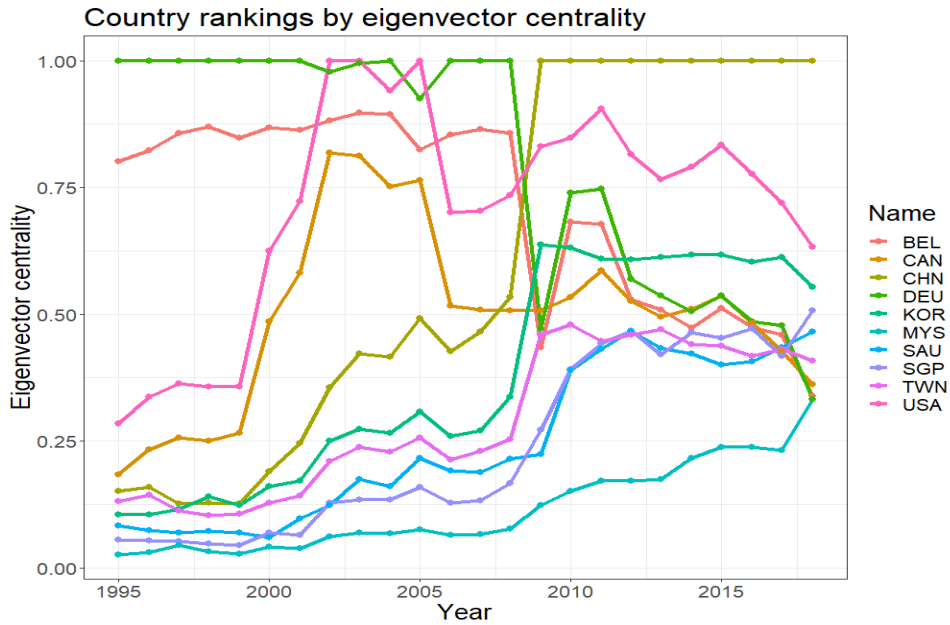

Figure S7. Eigenvector centrality ranks over time.

Eigenvector To measure a country's influence in a network, eigenvector centrality is utilized. We measured eigenvector centrality on a scale from 0 to 100, with the most influential country given a 100. The rest of the countries were ranked between 0 and 100 based on their influence compared to the top node. If we compare the key actors identified by the backbone algorithm and eigenvector centrality ranking, there is a large overlap. USA, China and South Korea have dominated the GPPTN since the early to mid-2000's, with Malaysia, Singapore and Saudi Arabia consistently trending upwards to become key nodes in the network. There is also a strong correlation (correlation coefficient of 0.86 and 0.81 respectively) between eigenvector centrality and both out and in strength. This suggests that countries who wish to trade large amounts of plastic resin must form partnerships with the most influential nodes in the network, who are responsible for the majority of the large trade flows.

Table S4: Additional assortativity coefficients, measuring the propensity of nodes to trade with one another based on having a similar score for various node centrality measures.

Centrality measure	Total Degree	In-degree	Out-degree	Total Strength	In-strength	Out-strength
Assortativity coefficient	-0.333	-0.268	-0.288	-0.144	-0.093	-0.121

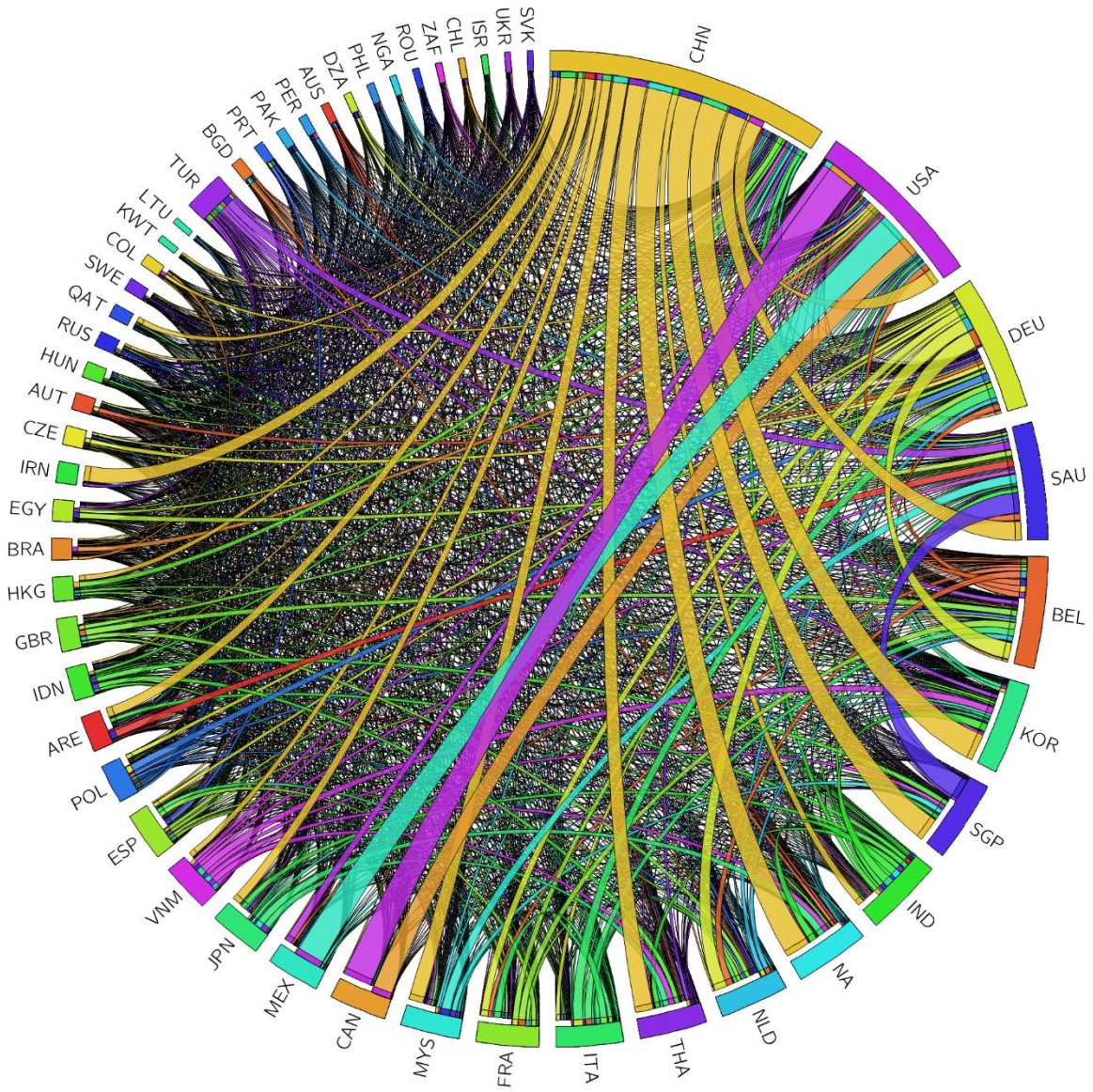

Figure S8: Circos figure depicting embodied GHGs in the GPPTN for 2018.

S6. Statistical Distribution Testing

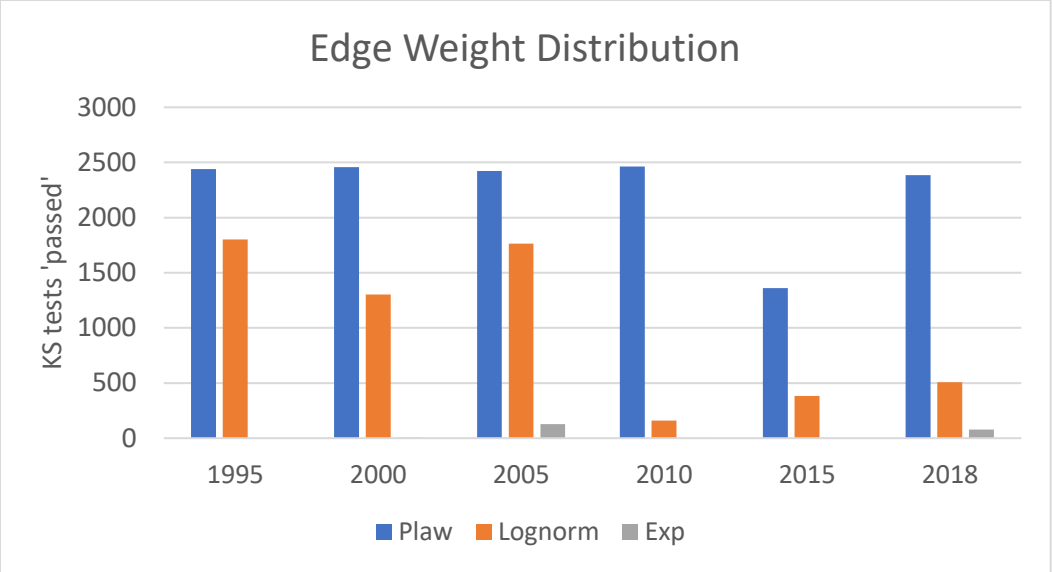

Figure S9: Edge weight distribution KS-testing results.

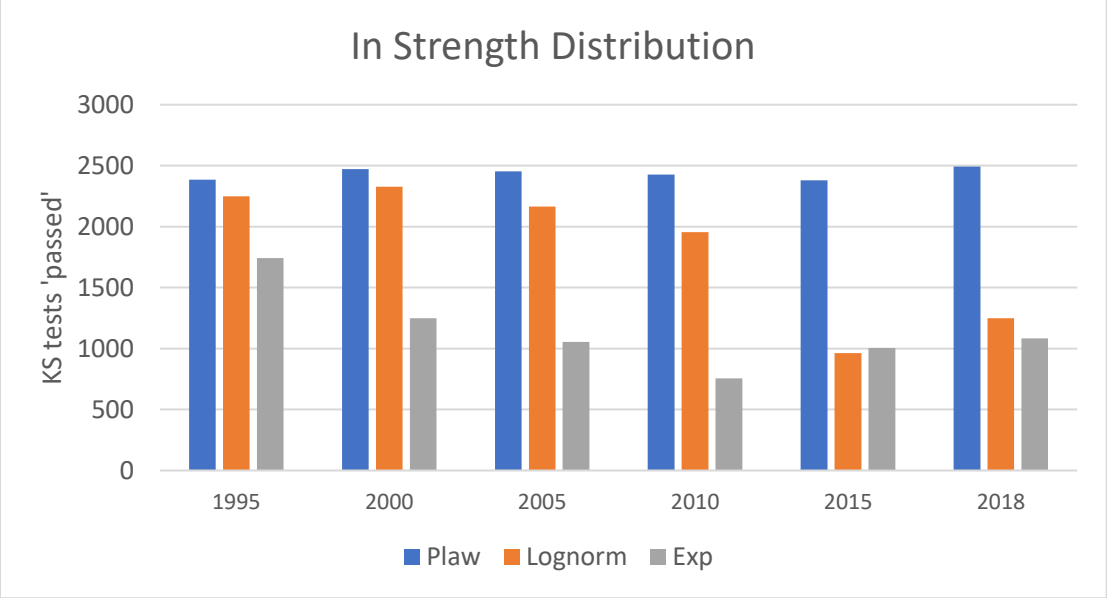

Figure S10: In-strength distribution KS-testing results.

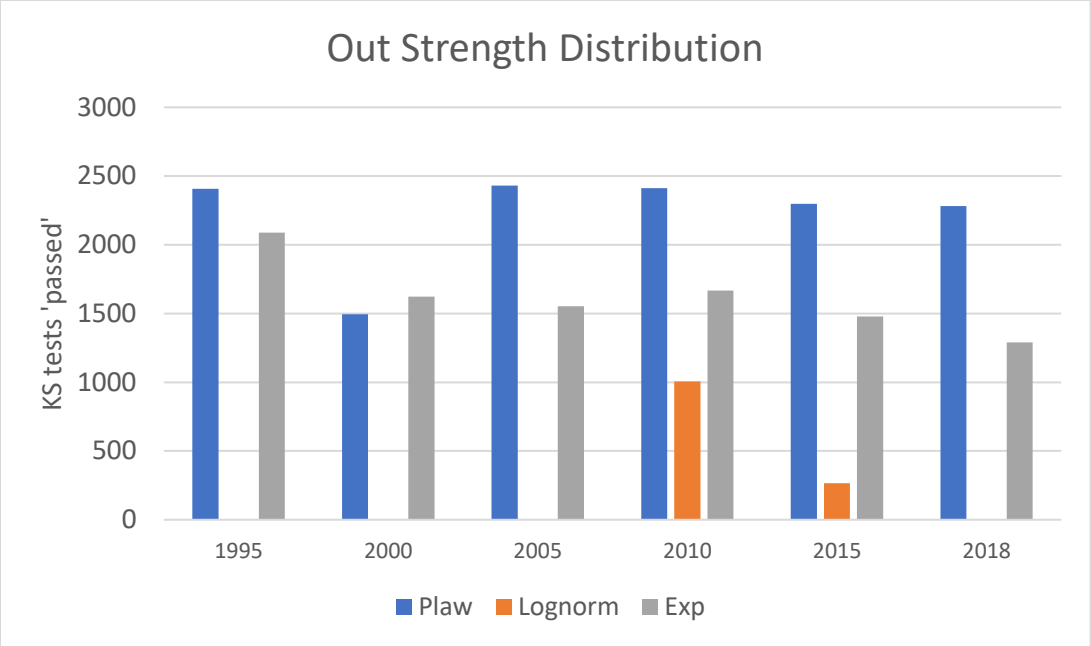

Figure S11: Out-strength distribution KS-testing results.

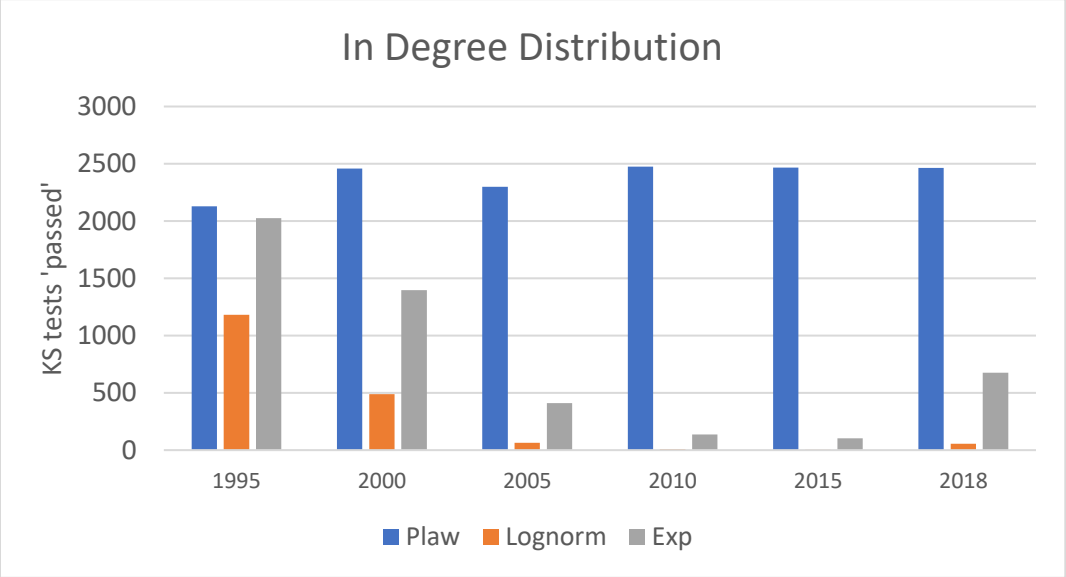

Figure S12: In-degree distribution KS-testing results.

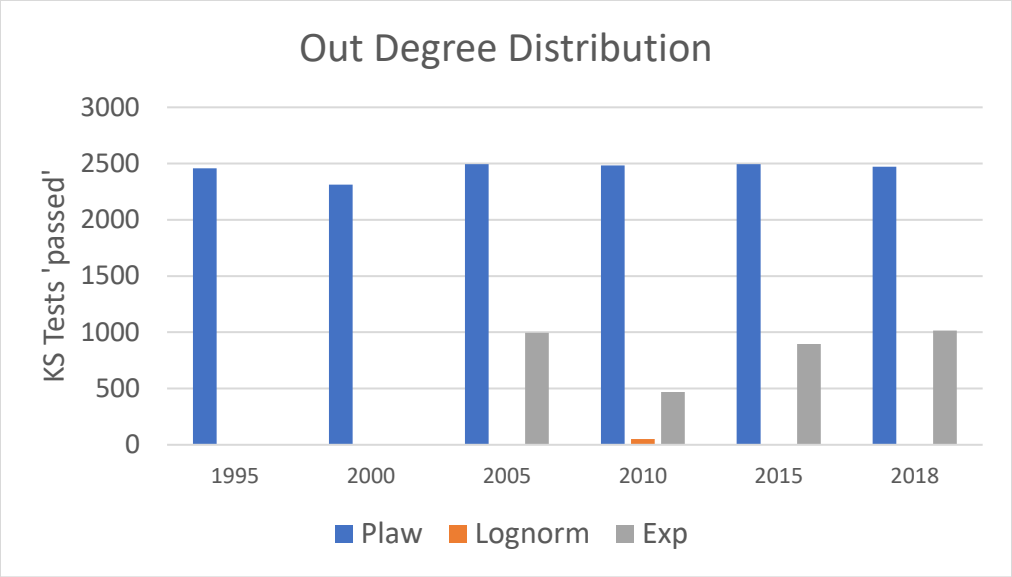

Figure S13: Out-degree distribution KS-testing results.

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