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Lessons from Living Systems for the Development of Sustainable Industrial Resource Networks

可持续工业资源网络之发展生存系统带来的启示

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Abstract - **From de Mestral's hook-and-loop fasteners to the industrial symbiosis in Kalundborg, Denmark, organisms and ecosystems have provided inspiration for multiple novel inventions. Bio-inspiration at the industrial system scale can reduce energetic and material environmental burdens as documented in the case of Kalundborg's symbiosis. Practical successes with symbioses suggest the value of ecological guidance, but a systematic means of designing ecological inspiration into an industrial resource network requires further development. Additionally, a theoretical basis for the observed environmental efficiencies needs additional elucidation. This work further develops a systematic means of using bio-inspiration in resource network design, and it explores a potential thermodynamic foundation for energetic and material efficiencies noted in industrial resource networks.**

Using an established correlation between a measure of ecological structure and 1st Law Efficiency, this work explores a theoretical basis in classical thermodynamics for observed environmental efficiencies in symbioses. Increasingly complex variations of Rankine and Brayton power cycles are analyzed in the traditional sense to determine theoretical 1st Law efficiencies. Then, they are analyzed as ecosystems using ecosystem metrics. Power cycles with increasingly ecological values for linkage density (L_d), an ecosystem network metric, are seen to possess generally higher thermodynamic efficiencies.

Moving from analysis to design, this work reports upon ongoing efforts to use ecological metrics as a guide for designing more energetically efficient, sustainable industrial resource networks. Design of a carpet tile production, reuse, and recycling network serves as an example. Using ecological metrics with target values obtained from the study of ecosystems, the structure of a modeled carpet tile network is adjusted to become more quantitatively ecological. More ecological network configurations, as measured in terms of linkage density (L_d), generate lower environmental impacts. The influence of other ecological metrics is also explored.

Keywords - **symbiosis, eco-industrial park, bio-inspiration, holistic biomimicry, biomimetic, energy.**

I. INTRODUCTION

From de Mestral's hook-and-loop fasteners (i.e. Velcro) to Kalundborg, Denmark's symbiosis (an aggregation of production facilities that use wastes as inputs), organisms and ecosystems have provided inspiration for multiple novel inventions [1]. Bio-inspiration at the industrial system scale can reduce energetic and material environmental burdens as documented in the case of Kalundborg's symbiosis [2, 3]. These industrial symbioses, also known as eco-industrial parks (EIP), contain co-located facilities that use waste material and energy from some facilities as production inputs for others, thus improving material and energy efficiency. Practical successes with symbioses suggest the value of ecological guidance for enhancing environmental sustainability, but a systematic means of designing ecological inspiration into EIPs and larger industrial resource networks requires further development. Moreover, a theoretical basis for the observed environmental efficiencies needs additional elucidation. This work advances the systematic use of bio-inspiration in the design of industrial resource networks and provides continuing evidence of a theoretical foundation for the observed benefits of bio-inspiration in these networks [4].

A foundation for systematically guiding industrial resource network design using bio-inspiration exists, but it requires further development. Biomimetic principles for guiding designs toward more environmentally sustainable outcomes were drawn from a study of biological and ecological literature [5]. Made operational using a set of ecological metrics, one of these principles was applied to the design of a modeled carpet tile industrial resource network that includes manufacturing, distribution, reuse and recycling activities [5-7]. Making the network's structure and resource flow patterns more ecological, as measured by the suite of employed metrics, decreased the network's environmental impact. Two main areas of development remain. First, presence in ecological literature and ability to adapt findings to engineering contexts served as the primary selection criteria for ecological metrics used in industrial network design. Further screening of metrics found in ecological literature may help identify the most important ones. Second, reasons for the success of these metrics rooted in something more than the biological sciences were not apparent in the carpet tile study. The holistic approach of applying an ecological pattern may bring the observed environmental benefits for any number of reasons that further investigation can identify.

The laws of thermodynamics bind all systems, including both ecological and engineering systems. The use of thermodynamic cycles, a well-studied and understood class of networks, may explain some of the trends in values observed using the suites of measures in the carpet tile study. In fact, prior work identified a relationship between one of the ecological metrics used in the carpet tile study and the 1st Law of Thermodynamics [4]. Specifically, the study reveals a positive correlation between the ecological structural metric cyclicity and thermal efficiency when one calculates the structural metric for thermodynamic Rankine and Brayton power cycles [4]. However, this initial study only examines the relationship between one of the seven structural metrics in the original carpet tile study [6]. A similar correlation might exist for other ecological metrics. The presence of such correlations would strengthen arguments for a connection between environmental performance improvements through ecological mimicry and thermodynamic efficiency.

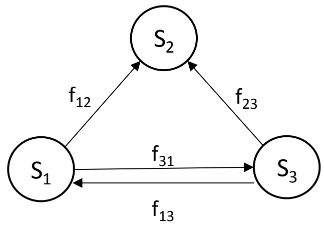
Testing for a correlation between the full suite of previously used structural ecological metrics and thermal efficiency advances both objectives of this work. It develops the use of bio-inspiration in resource network design by evaluating the individual metrics and by testing the thermal efficiency correlation as a general method of screening ecological metrics. Additionally, it probes at the root cause of previously observed environmental performance improvements by using a test that can link said performance to well established thermodynamic laws.

II. Method of Evaluating System Structure

To accomplish these ends, this work uses the ecological structural metrics presented by Reap [6] and used by Layton and coauthors to analyze eco-industrial parks [8]. The method of applying these metrics is the one employed by Layton, Reap and coauthors [4, 7]. This larger suite of ecological structural metrics is applied to the original set of thermodynamic cycles [4].

2.1. Ecological Structural Metrics

To quantify food web (FW) characteristics, ecologists traditionally use structural metrics based on the number of species (S) in a food web as well as the directional material and energy linkages (f_{ij}) that join them [9-12]. One should note that S may represent aggregations of species known as trophic species that share the same sets of predators and prey [13]. This allows one to represent FWs as simple two dimensional arrays **[F]** of size S x S where linkage direction is entered as traveling from row to column (See Fig. 1).



(i)

$$[F] = \begin{bmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{bmatrix}$$

(ii)

$$[F] = \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

(iii)

Fig. 1, Progression for representing a food web (FW) as a two dimensional array; (i) FW diagram; (ii) generic 2D array; (iii) 2D array for the given diagram

One uses values from and properties of this array to calculate ecological structural metrics. The sum of the directional connections in **[F]** yields a value for the number of linkages (L).

$$L = \sum_{i=1}^{m} \sum_{j=1}^{n} f_{ij} \quad (1)$$

Linkage Density (L_d) is the ratio of directional material and energy connections, links (L), in a FW to the number of species connected by the web.

$$L_d = {}^{L}\!/_{S} \quad (2)$$

Connectance (C_{con}) is the number of links in a FW divided by the number of possible links between species in the web.

$$C = {}^{L}\!/_{S^2} \quad (3)$$

Forbidding consumption within a species (cannibalism), one calculates a modified version of connectance (C_{nc}) with a smaller number of possible links.

$$C_{nc} = \frac{L}{S(S-1)} \quad (4)$$

The link structure in the food web array allows one to identify prey and predator species needed to calculate additional structural metrics. The number of prey species (n_{prey}) equals the number of nonzero rows in **[F]**.

$$f_{row}(i) = \begin{cases} 1 \; for \; \sum_{j=1}^{n} f_{ij} > 0 \\ 0 \; for \; \sum_{j=1}^{n} f_{ij} = 0 \end{cases} \quad (5)$$

$$n_{prey} = \sum_{i=1}^{m} f_{row}(i) \quad (6)$$

The number of predators ($n_{predator}$) equals the number of nonzero columns in **[F]**.

$$f_{col}(j) = \begin{cases} 1 \; for \; \sum_{i=1}^{m} f_{ij} > 0 \\ 0 \; for \; \sum_{i=1}^{m} f_{ij} = 0 \end{cases} \quad (7)$$

$$n_{predator} = \sum_{j=1}^{n} f_{col}(j) \quad (8)$$

One identifies specialized predators ($n_{s\text{-}pred}$), the number of predators consuming only one species in a web, by counting the number of columns in **[F]** with only one link.

$$f_{scol}(j) = \begin{cases} 1 \; for \; \sum_{i=1}^{m} f_{ij} = 1 \\ 0 \; for \; \sum_{i=1}^{m} f_{ij} \neq 1 \end{cases} \quad (9)$$

$$n_{s-pred} = \sum_{j=1}^{n} f_{scol}(j) \quad (10)$$

Prey-to-predator ratio (P_r) is the ratio of the number of species consumed by another species to the number of species which consume species.

$$P_r = {}^{n_{prey}}/_{n_{predator}} \quad (11)$$

Specialized predator ratio ($P_{special}$) is the ratio of the number of species that consume only one other species to the total number of species which consume other species.

$$P_{special} = {}^{n_{s-pred}}/_{n_{predator}} \quad (12)$$

Generalization (G) is the average number of prey eaten per predator in **[F]**.

$$G = {}^{L}/_{n_{predator}} \quad (13)$$

Vulnerability (V) is the average number of predators per prey in **[F]**.

$$V = {}^{L}/_{n_{prey}} \quad (14)$$

Cyclicity (λ) measures the presence and extent of cyclic pathways in a FW [14]. A value of zero for λ indicates an absence of cyclic pathways. A value of one reveals weak cycling; a value greater than one for λ indicates strong cycling. One determines cyclicity by finding the maximum real eigenvalue of a FW's adjacency matrix **[A]**, and the adjacency matrix is the transpose of **[F]**.

$$[A] = [F]^T \quad (15)$$

2.2. Ecological Metrics in Power Cycles

As a starting point for analysis, this work uses previously developed thermodynamic network representations [4]. These thermodynamic networks represent the system topology of a series of increasingly complex ideal Brayton and Rankine thermodynamic power cycles. Fig. 2 depicts the equipment present in a basic Brayton Cycle. Conversion of this diagram into an array analogous to a food web illustrates the process used for each analyzed cycle.

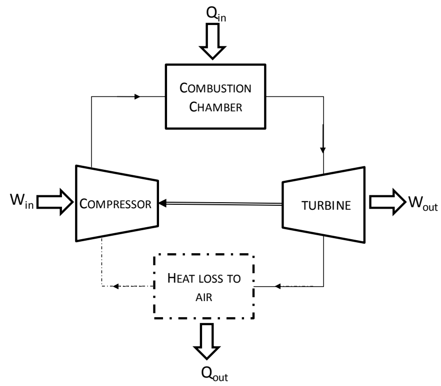


Fig. 2, Equipment diagram for a basic Brayton Cycle

The major components in each cycle's equipment diagram serve as vertices (also known as nodes) in a thermodynamic network with edges formed by flows of energy. Energy flows between vertices appear as work, heat, and working fluid containing embodied energy above that of the cycle's initial state (See Fig. 3).

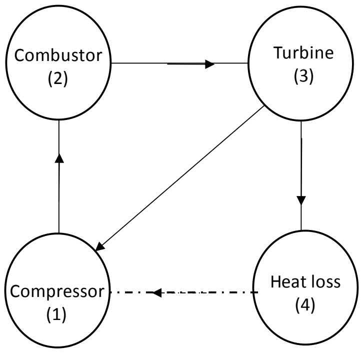


Fig. 3, Thermodynamic network diagram of Basic Brayton Cycle

One converts these network graphs to arrays analogous to food web arrays (See Fig. 4). The vertices are analogous to species (S), and the edges serve as links (L). Once converted, one calculates structural ecosystem metrics for each array.

$$\begin{array}{c c} & \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} \\ \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} & \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \end{array}$$

Fig. 4, Array for Basic Brayton Cycle

One compares values for the suite of structural ecosystem metrics with the classical 1st Law thermodynamic efficiencies (η_I) determined for each cycle in prior work [4] using Eq. 16.

$$\eta_I = \frac{\sum_i W_{out,i} + W_{in,i}}{\sum_i Q_{in,i}} \quad (16)$$

A simple description for each of these cycles appears in Table 1 and Table 2. Those interested in more detailed information concerning thermodynamic cycles and calculations leading to thermal efficiency should consult a thermodynamic text e.g. [15].

Table 1, Descriptions of Rankine Cycles

Rankine Cycle Description	Cycle Name
Basic Rankine Cycle	R1
With reheat	R2
With 1 open feed water heater (FWH) and trapped condensate	R3
With 1 open FWH	R4
With 2 open FWHs	R5
With 1 closed FWH and pumped condensate	R6
With 3 open FWHs	R7
With 1 open and 1 closed FWH	R8
With 4 open FWHs	R9
With 5 open FWHs	R10
With 6 open FWHs	R11
With 7 open FWHs	R12
With 8 open FWHs	R13
With reheat and 1 open FWH	R14
With reheat and 2 open FWHs	R15
With reheat and 3 open FWHs	R16
With reheat and 4 open FWHs	R17
With reheat and 5 open FWHs	R18
With reheat and 6 open FWHs	R19

Table 2, Descriptions of Brayton Cycles

Brayton Cycle Description	Cycle Name
Basic Brayton Cycle	B1
With regeneration	B2
With regeneration, intercooling, and reheat using 2 turbines	B3
With regeneration, intercooling, and reheat using 3 turbines	B4
With regeneration, intercooling, and reheat using 4 turbines	B5
With regeneration, intercooling, and reheat using 5 turbines	B6
With regeneration, intercooling, and reheat using 6 turbines	B7
With regeneration, intercooling, and reheat using 7 turbines	B8

2.3. Testing Predictions with the Carpet Tile Model

If a noteworthy correlation between thermal efficiency and an ecosystem metric appears, one expects that the correlating ecosystem metric would more substantially influence an industrial resource network's environmental performance. To test this prediction, one exercises the previously developed carpet tile manufacturing, distribution, reuse and recycling model [5, 6]. The model only needs a couple small modifications to evaluate the influence of a single structural metric instead of multiple structural and flow metrics.

The carpet tile model represents a proposed network for manufacturing, distribution, reuse, recycling and disposal of carpet tile in the metropolitan area of Atlanta, Georgia, USA. The following description is a brief overview; those seeking a detailed description are invited to consult the provided references. Steady-state material flows in the network connect a carpet tile producer, consumers, reuse centers, recycling centers and landfills for Atlanta's 13 county metropolitan region. Though steady in time, material flows and network structure can change with the design of the network. A designer can choose to send waste carpet tile from each county to either reuse or recycling centers. This choice creates a design vector of 26 variables, two flows of potentially recoverable waste carpet tile for each of the 13 counties. One uses the chosen values for each of these independent variables to solve the material flow network from which one calculates all of the discussed metrics. In the original model, these directed flows can vary from zero to the capacity constraint of the link. If set to zero, a link ceases to exist, changing the network's structure as well as its flow regime.

Exercising the model for a design vector generates values for traditional (Z_{trad}) and bio-inspired (Z_{bio}) objective functions. Smaller values for Z are associated with designs closer to the desired goals for the network. The traditional objective function consists of metrics for monetary cost (C) and environmental emissions (E_i) normalized by goal values. Environmental emissions include CO_2, SO_2, Pb, etc. Goal constants appear with g subscripts in the following equations. All of the normalized values receive equal weighting (w_{trad}) as seen in Eq. 17.

$$Z_{trad} = w_{trad}\left[\left(1-\frac{C_g}{C}\right)+\sum_{i=1}^{12}\left(1-\frac{E_{i,g}}{E_i}\right)\right] \qquad (17)$$

In the original model, a similar arrangement generates Z_{bio} (See Eq. 18). However, ecological structural and flow metrics take the place of cost and emissions. Section 2.1 introduced the structural metrics found in Eq. 18. Cycling Index (CI) and Path Length (P_L) are flow metrics which are not the focus of this work. The weighting for each metric can be set via $w_{bio,I}$ by choosing a value between 0 and 1, such that they equal one when summed. In the original model, all weights equal 1/9.

$$Z_{bio} = w_{bio,1}\left(1-\frac{L_d}{L_{d,g}}\right)+w_{bio,2}\left(1-\frac{C_{con}}{C_{con,g}}\right)+w_{bio,3}\left(1-\frac{G}{G_g}\right)+w_{bio,4}\left(1-\frac{V}{V_g}\right)+w_{bio,5}\left(1-\frac{\lambda}{\lambda_g}\right)+w_{bio,6}\left(1-\frac{P_L}{P_{L,g}}\right)+$$

$$w_{bio,7}\left(1-\frac{CI}{CI_g}\right)+w_{bio,8}\left(1-\frac{p_{r,g}}{p_r}\right)+w_{bio,9}\left(1-\frac{p_{special,g}}{p_{special}}\right) \quad (18)$$

Following the method used by Layton [7] to test the predictive capabilities of a thermal efficiency correlation with a single structural metric, two modifications to the original carpet tile network model are made. First, one uses a design vector with constant magnitude flow elements. This dampens the effect of changing flow amounts on Z_{trad} which allows a clearer picture of the effect caused by changes in network structure. Second, one must place all of the weight for Z_{bio} on the evaluated structural metric. The weighting for the desired structural metric would equal one while the others would equal zero.

Having executed these changes, one can evaluate the influence of a single metric on the carpet tile network's environmental performance. First, one solves the model multiple times with stochastically generated design vectors. This work uses 1,000 model runs. The randomness in the constant magnitude vectors is achieved by activating and deactivating links. This means that each element of a given design vector either takes the value of zero or its previously fixed magnitude. Then, one checks for a correlation between Z_{trad} and Z_{bio}, recalling that a single structural metric now drives Z_{bio}. A positive correlation between the two indicates that traditional environmental and cost performance relate to the selected ecological metric.

III. RESULTS

3.1. ECOLOGICAL METRICS AND THERMAL EFFICIENCY

Using Eq. 1-14, this section calculates structural ecosystem metrics for each of the power cycles described in Table *1* and Table *2*. The metric values for all cycles appear in Table 3. One should note that the thermal efficiency values (η_I) found in Table 3 originate in the work of Layton and coauthors [4]; the other metrics are determined as part of this work.

A cursory review of the data set in Table *3* reveals potentially suspicious prey-to-predator ratio (P_r) values for the Rankine Cycles. P_r equals one for all of these cycles. Given the structure of the Rankine Cycle thermodynamic network, this behavior is expected. For these cycles, each component functions as both prey and predator with the exception of the first pump and the condenser. Consider the boiler in a simple Rankine Cycle. It receives high pressure working fluid from a pump while delivering high temperature, high pressure steam to a turbine. In an ecological network sense, it feeds on the pump and is fed upon by the turbine. Similarly, the turbine feeds upon the boiler and is fed upon by the condenser. The first pump supplies high pressure working fluid to the boiler, but since it only receives working fluid at its ground state, it does not receive any energetic inputs from other actors in the system. The pump serves only as prey from an ecological perspective. Conversely, the condenser receives working fluid from the turbine in a state above that of the ground state, but it does not pass any energetic inputs to other network constituents. The condenser serves only as a predator when taking an ecological perspective. The result of these interactions is that the simple Rankine Cycle contains three elements that act as predators and three that act as prey, giving a prey-to-predator ratio of one. This is a pattern that repeats for the more complicated Rankine Cycles.

One sees that a similar relationship is not present for the Brayton Cycles. The large work inputs from the turbines needed to drive the compressors prevent the even balance between prey and predator elements. However, these work inputs coupled with other energetic connections to the regenerator create the constant vulnerability value observed for cycles B2-B8 in Table 3.

Table 4 lists coefficients of determination between thermal efficiency and the newly calculated structural metrics for both sets of cycles.

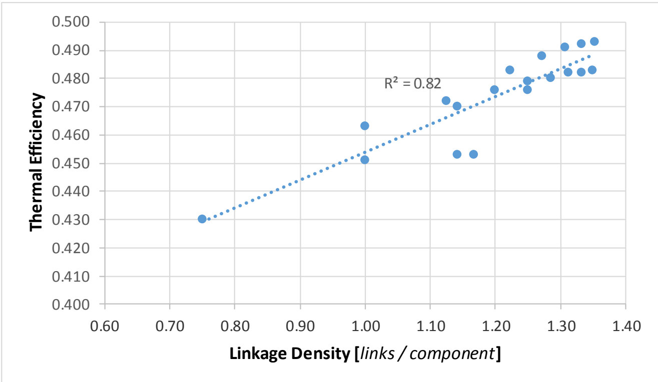


Fig. 5, Correlation between thermal efficiency and linkage density for Rankine Cycles

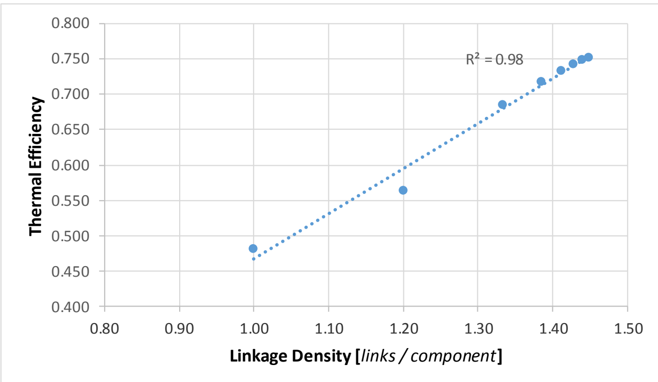


Fig. 6, Correlation between thermal efficiency and linkage density for Brayton Cycles

Table 3, provides structural metric values for Rankine and Brayton power cycles. Note that thermal efficiency values (η_I) were determined by Layton and coauthors [4]

Cycle Name	S	L	L_d	P_r	$P_{special}$	G	V	C_{con}	λ	η_I
R1	4	3	0.75	1.00	1.00	1.00	1.00	0.19	0.00	0.430
R2	5	5	1.00	1.00	0.75	1.25	1.25	0.20	1.00	0.451
R3	6	7	1.17	1.00	0.60	1.40	1.40	0.19	1.00	0.453
R4	6	6	1.00	1.00	0.80	1.20	1.20	0.17	1.00	0.463
R5	8	9	1.13	1.00	0.71	1.29	1.29	0.14	1.15	0.472
R6	7	8	1.14	1.00	0.67	1.33	1.33	0.16	1.17	0.453
R7	10	12	1.20	1.00	0.67	1.33	1.33	0.12	1.21	0.476
R8	8	10	1.25	1.00	0.71	1.43	1.43	0.16	1.32	0.476
R9	12	15	1.25	1.00	0.64	1.36	1.36	0.10	1.24	0.479
R10	14	18	1.29	1.00	0.62	1.38	1.38	0.09	1.25	0.480
R11	16	21	1.31	1.00	0.60	1.40	1.40	0.08	1.26	0.482
R12	18	24	1.33	1.00	0.59	1.41	1.41	0.07	1.27	0.482
R13	20	27	1.35	1.00	0.58	1.42	1.42	0.07	1.27	0.483
R14	7	8	1.14	1.00	0.67	1.33	1.33	0.16	1.27	0.470
R15	9	11	1.22	1.00	0.63	1.38	1.38	0.14	1.36	0.483
R16	11	14	1.27	1.00	0.60	1.40	1.40	0.12	1.39	0.488
R17	13	17	1.31	1.00	0.58	1.42	1.42	0.10	1.40	0.491
R18	15	20	1.33	1.00	0.57	1.43	1.43	0.09	1.41	0.492
R29	17	23	1.35	1.00	0.56	1.44	1.44	0.08	1.41	0.493
B1	4	4	1.00	0.75	1.00	1.00	1.33	0.25	1.00	0.482
B2	5	6	1.20	0.80	0.80	1.20	1.50	0.24	1.22	0.563
B3	9	12	1.33	0.89	0.67	1.33	1.50	0.15	1.39	0.685
B4	13	18	1.38	0.92	0.62	1.38	1.50	0.11	1.46	0.718
B5	17	24	1.41	0.94	0.59	1.41	1.50	0.08	1.50	0.733
B6	21	30	1.43	0.95	0.57	1.43	1.50	0.07	1.52	0.742
B7	25	36	1.44	0.96	0.56	1.44	1.50	0.06	1.53	0.748
B8	29	42	1.45	0.97	0.55	1.45	1.50	0.05	1.54	0.751

Table 4, Coefficients of determination between thermal efficiency and the stated structural metric for each cycle

	Coefficient of Determination (R^2)	
Metric	*Rankine*	*Brayton*
Linkage Density (L_d)	0.82	0.98
Prey-to-predator ratio (P_r)	NA	0.99
Specialized predator ratio ($P_{special}$)	0.65	0.98
Generalization (G)	0.66	0.98
Vulnerability (V)	0.66	0.62
Connectance (C)	0.70	0.93

3.2. Ecological Metrics and Environment

This section presents correlations between the carpet tile model's environmental performance (Z_{trad}) and structural metrics. Plots focus on metrics predicted to correlate by the prior section's thermodynamically rooted analysis. In all cases where correlations between Z_{trad} and Z_{bio} appear, the independent variable is a normalized form of one of the previously mentioned ecological metrics. When used as an independent variable, each normalized metric receives 100% weighting in Z_{bio}.

The plots in Fig. 7 and Fig. 9 represent variation in environmental performance of the carpet model with changes in linkage density and cyclicity, respectively. The normal probability plot in Fig. 8 is present as a check of the normality assumption underlying the curve fit in Fig. 7. Coefficients of determination in Table 5 summarize findings for the relationships between Z_{trad} and metrics not predicted to correlate by the prior thermodynamic analysis. The only exception to this is Cycling Index (CI), a flow metric introduced for purposes of comparison.

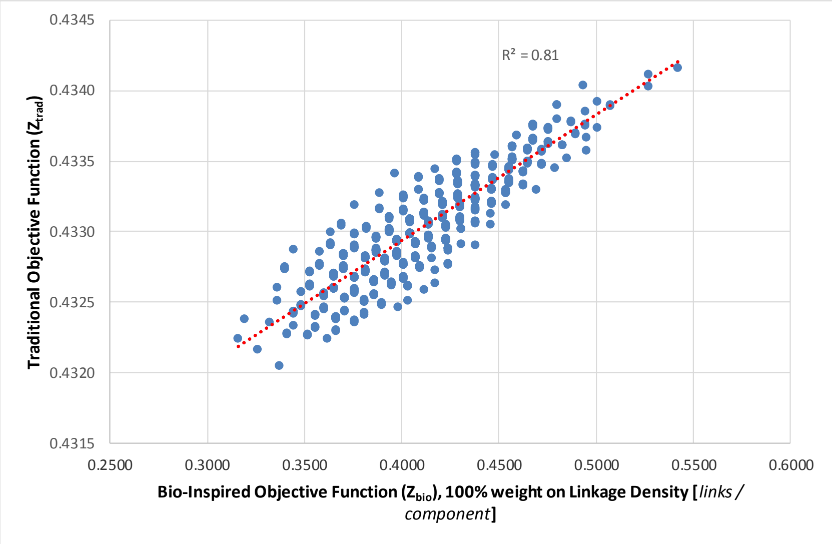


Fig. 7, Correlation between the carpet model's traditional objective function (Z_{trad}) and the bio-inspired one (Z_{bio}) when linkage density (L_d) receives 100% weight; plot based on 1000 randomly generated design vectors

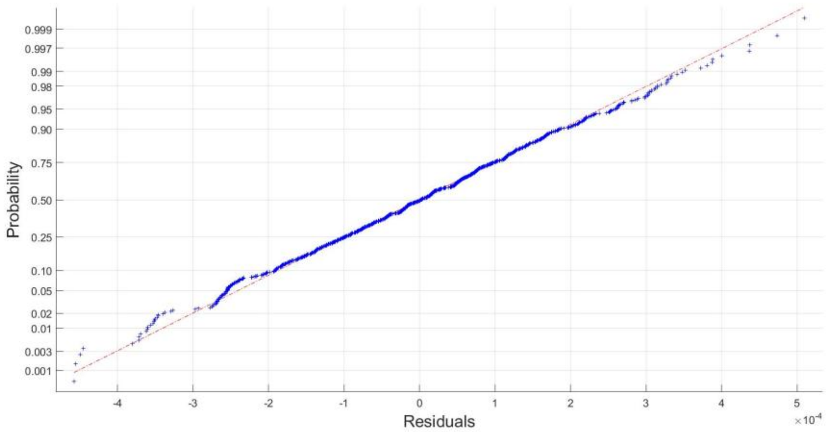


Fig. 8, Normal probability plot for data in Fig. 7

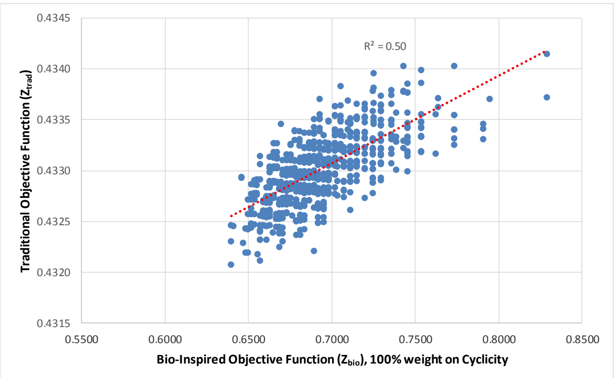


Fig. 9, Correlation between the carpet model's traditional objective function (Z_{trad}) and the bio-inspired one (Z_{bio}) when cyclicity (λ) receives 100% weight; plot based on 1000 randomly generated design vectors

Table 5, Coefficients of determination between Z_{trad} and Z_{bio} achieved when listed ecological metrics receive 100% weight; based on 1000 randomly generated design vectors

Metric with 100% Weight in Z_{bio}	**Coefficient of Determination (R^2)**
Prey-to-predator ratio (P_r)	0.62
Specialized predator ratio ($P_{special}$)	0.52
Generalization (G)	0.80
Vulnerability (V)	0.22
Connectance (C)	0.02
Cycling Index (CI)	0.96

IV. Discussion

4.1. Clarity Among Thermodynamic Correlations

One may infer the thermal efficiency (η_I) of Rankine and Brayton power cycles from linkage density (L_d). For the analyzed cycles, the most robust relationship between the newly calculated structural metrics and thermal efficiency occurs with linkage density (See Fig. 5 and Fig. 6). The coefficient of determination (R^2) between the two reaches 0.82 for the Rankine Cycles and 0.98 for the Brayton Cycles (See Table 4). This level of correlation corresponds to that determined by Layton and coauthors when comparing cyclicity with thermal efficiency for these cycles [4]. They concluded, "…the structural method for computing energy cyclicity accurately predicts maximum thermal efficiency…" for these cycles [4]. This work suggests that one may add linkage density as a predictor of maximum thermal efficiency.

The value of comparing structural metrics with thermal efficiency across multiple cycle types became apparent during this analysis. Viewing only coefficients of determination for Brayton Cycles in Table 4, one would conclude that all structural metrics except vulnerability possess predictive power. Further comparison with Rankine Cycle correlations reduces the viable metrics to linkage density. Correlations with the carpet tile model in Table 5 reinforce the finding that many of the other structural metrics only weakly associated with environmental impact. From a mathematically mechanical point of view, the substantial thermodynamic work flows from the turbines to the compressors increase the number of connections in the Brayton Cycle FW arrays. The increased number of connections and the cyclic paths which form as a result appear to enhance the correlations. If one takes a more philosophical view of the correlation differences between cycles, interesting questions emerge. Is one type of cycle more appropriate for identifying a connection with thermal efficiency? The perspective taken thus far is that a composite is more informative. Would the observed correlations hold for variants of other thermodynamic power cycles such as Otto, Diesel, Sterling, etc.? What findings might emerge from exploration of refrigeration cycles; would correlations with coefficient of performance surface?

4.2. Reflections on Carpet Model Correlations

Application of thermodynamic cycle correlations to the carpet tile model contains some surprises. Thermodynamic correlations indicate that improving cyclicity and linkage density should improve environmental performance (Z_{trad}) of the carpet tile network. The expected positive correlation (R^2 = 0.81) between linkage density and environmental performance appears in Fig. 7. However, cyclicity only weakly correlates ($R^2 = 0.50$) with environmental performance (See Fig. 9). As predicted, most of the other structural metrics in Table 5 exhibit weak relationships with Z_{trad}, but generalization displays a surprisingly strong correlation (R^2 = 0.80).

The correlation between Z_{trad} and linkage density is the strongest observed for the structural metrics despite indications that the selected simple linear fit may be less than ideal. This outcome aligns with expectations based on thermodynamic analysis. The normal probability plot in Fig. 8 displays a degree of nonlinearity. This suggests that the residuals may result from something other than normally distributed error and that a better curve fit is possible [16]. One should consider the purpose of such a fit, though. Curve fitting serves as a simple screening tool in this work; it identifies obvious relationships between selected metrics. The simple fit satisfies this role.

Cyclicity's weak correlation surprises for two reasons. A system needs a cyclic structure to reuse materials and energy. A system achieves lower environmental impacts if it establishes and uses its capacity to reuse resources. Since cyclicity measures the extent of a system's cyclic structure, one expects that environmental impact would correlate. The carpet tile network's high correlation (R^2=0.96) with Cycling Index (CI) provides the second reason. Unlike the purely structural metrics upon which this work focuses, CI is the cyclic fraction of flow through a system divided by the total flow through the system [17, 18]. It depends on cycling flow, and flow cycling cannot occur without a cyclic structure. So, one might expect high CI with high cyclicity. However, a possible explanation for both unexpected differences exists. The modeled system provides 26 different paths for reusing or recycling waste carpet tile, but not all paths deliver the same environmental benefits. Reuse paths generally save more energy and material per unit mass than recycling paths. The documented experiments randomly deactivate paths. This can generate networks with similar structural metric values, but one set of networks can possess more reuse links while the other contains more recycling links. In such instances, similar structures produce different environmental performance. The different flow regimes caused by favoring reuse over recycling would influence CI, thus allowing it to track environmental performance. The overall result is a set of networks that appear similar when viewed in terms of cyclicity but that one can differentiate with CI and Z_{trad}.

Generalization's (G) strong correlation, though not predicted, is less surprising than other findings. Generalization is the average number of prey consumed per predator. Increasing the number of counties sending material to the central recycling facility is the most obvious way to increase this value in the carpet model. This increase in recycling would lead to a reduction in overall environmental impact (Z_{trad}) by displacing virgin plastic inputs to carpet tile manufacture. From a more philosophical perspective, this find is also less than surprising. This work focuses on links between thermodynamic efficiency and network structure. However, network structures likely provide properties in addition to energetic efficiency. The ability to maintain function despite the loss of a network's edges or vertexs comes to mind. In an ecosystem, this might take the form of a predator that adapts to feed upon multiple prey. This adaptation enhances the predator's survival if a particular set of prey species disappears. The ecosystem gains alternative paths for resource flow. In an EIP, a facility might source a particular type of waste, which it uses as an input, from multiple other EIP facilities.

4.3. Implications for Resource Network Design

From a design perspective, this work makes progress on identifying more influential metrics and on demonstrating a general method for screening metrics. It adds linkage density to the short list of metrics that bare some connection with thermal efficiency. As a result, this finding increases the importance of linkage density when designing industrial resource networks such as EIPs. However, though tempting, one should not yet embrace the idea that linkage density drives thermal efficiency or vice versa. These data present only a correlation. The old warning concerning the difference between correlation and causality still holds. Other factors apart from those measured might drive both.

Comparisons between ecological metrics and thermodynamic cycle efficiencies show some, limited promise as a screening method. Screening methods only work if they detect a difference among screened entities. Coefficient of determination values for the various metrics differ within each cycle. They differ between the two cycles as well (See Table 3). The differences prove substantial enough to sort the metrics. Furthermore, one can generate these comparisons rapidly since thermal efficiencies and cycle structures remain fixed after one models them. If one chooses to use a new metric for ecological structure, he simply draws the relevant structural data from the FW arrays for the cycles in order to calculate it. However, one should use this screening method with caution. While successfully identifying linkage density as a metric that correlates with environmental performance, it fails to spot generalization and over emphasizes cyclicity. In the very least, this indicates the need for additional means of screening metrics used in resource network design.

The noteworthy correlations between Z_{trad} and both G and CI suggest further investigation of these types of metrics. This study's method aims to detect the potential influence of the 1st Law of Thermodynamics on network structure. Generalization's (G) value may emerge from an influence on network robustness, not thermodynamic efficiency. This suggests that work on screening networks for robustness may prove beneficial. The high correlation with CI underscores the importance of flow metrics when quantifying the environmental performance of industrial resource networks. Investigating the underlying causes of this connection should prove fruitful.

4.4. On Thermodynamic Foundations

Whether ecological or industrial, thermodynamic laws bind resource networks. The hypotheses of this work are that industrial resource networks possess structural differences related to 1st Law Thermodynamic efficiencies and that these differences translate into differences in environmental performance. The power cycle correlations in Table 4 coupled with findings in earlier work [4] reveal that some metrics of ecological structure appear to possess a relationship with 1st Law thermal efficiencies. The results presented in Section 3.2 and discussed in Section 4.3 show that this relationship does not always translate into differences in environmental performance, though.

Generalization appears unimportant from a thermodynamic perspective, but it correlates well with environmental performance in the carpet model. However, one should not expect every important network property to correlate with just one physical principle. The unexpected value of G argues less against a thermodynamic explanation as for the influence of other principles.

Cyclicity's lack of correlation presents a more difficult problem. This outcome suggests that thermal efficiency relationships hold limited power of prediction. This, in turn, weakens any arguments for a thermodynamic foundation for observed environmental performance. As a counter, the fault may rest with the type of relationship between cyclicity and environmental performance, not the presence. Rationally, one knows that cyclic networks must exist to reuse materials and energy. Reuse lowers environmental impacts by preventing inputs of new materials. The thermodynamic correlation may simply indicate that cycles are important or that the relationship is highly nonlinear.

V. Closure

The presented work sought to achieve two goals. First, it is meant to advance bio-inspiration in resource network design by enhancing understanding of metrics previously used for this purpose. Second, it explores a potential link between environmental improvements gained through bio-inspired resource network changes and well established thermodynamic theory.

With regard to advancing bio-inspiration in network design, this work identifies a structural metric, linkage density (L_d), that correlates with thermal efficiency for Brayton and Rankine power cycles. This metric is further shown to correlate with improved environmental performance. Earlier research suggested the potential for using thermodynamic cycles to identify environmentally noteworthy network metrics. Results presented in this work provide a better understanding of the potential and limitations of using thermodynamic cycles to screen metrics for resource network design. This new evidence suggests that cycle correlations can identify important metrics. However, one cannot rely upon cycle correlations to identify all metrics with influence on environmental performance. As suggested by the case of the generalization (G) metric, other principles may explain environmental performance correlations with network metrics that fail to correlate with thermal efficiency. Principles related to network robustness and resilience deserve particular attention in future investigations.

At this point, one cannot draw a durable conclusion concerning a thermodynamic foundation. Generated information argues both for and, potentially, against the presence of such a foundation. Analysis of more thermodynamic cycles as well as more industrial resource models will provide additional, needed evidence.

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