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Entropy Measures for System Identification and Analysis

Joseph J. Simpson, Mary J. Simpson
System Concepts, LLC

Abstract

Whole system metrics and measures are valuable tools for use in systems science and engineering. Entropy measures are defined, developed and demonstrated in this paper. Based on classical systems engineering methods and practices, these entropy measures indicate the degree of order/disorder in any given system. A physical entropy based metric and an information based entropy metric are aligned with the two primary components of a system: objects and relationships. The physical entropy based metric is called a connection score, and the information based metric is called an object score. A well-defined process, using these metrics, is used to evaluate the reduction of entropy and complexity associated with any specific system. The metrics and processes developed in this work have a prose component, a graphic component, and a mathematical component. These three components are aligned with the systems science techniques developed by J.N. Warfield.

Introduction

A system may be defined in a number of similar ways. This paper uses two basic system definitions: a construction-rule definition and a functional definition. The construction-rule definition of a system¹ is "A system is a relationship mapped over a set of objects." The function rule definition for a system² is "A system is a constraint on variation." These basic system definitions are applied to classic systems engineering analysis techniques for the purpose of developing system entropy metrics and measures. These entropy measures and metrics then provide a direct connection between systems science and the practice of systems engineering. Systems description and analysis techniques have used mathematics, graphics, and prose in the definition and evaluation of systems. The common graphical representation (square matrix) of N-Squared Charts, Automated N-Squared Charts, and Design Structure Matrices is combined with prose and mathematics to develop and refine a common set of methods for use in analysis and evaluation of these system representation types.

System Structure and Order

Systems of all types have some common characteristics that include structure and behavior. The science of generic design, developed by John N. Warfield, has a well-defined process named Interpretive Structural Modeling (ISM)³. The goal of ISM is to develop a structured representation of a problem set or system that was previously viewed as unstructured and/or disordered. Design Structure Matrices (DSM), developed by Donald V Steward, provide a well-established process for system structural analysis⁴. DSM uses structural configuration values to determine if a given system structural configuration is more valuable than another structural configuration of the same system. N-Squared Charts (N2C), developed by R.J. Lano, are also used to evaluate the structure of a set of system nodes and their interfaces⁵. The N-Squared Chart approach provides a well-defined set of process steps that address system interface configurations and interface values. The automated N-Squared Chart (AN2C) method, developed by Derek K. Hitchins, adds the use of evolutionary computation to the evaluation and analysis of system structure.

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Each of these techniques has a well-defined process that address the reduction of disorder and complexity. The N2C approach uses manual methods to analyze and evaluate the system structure. The AN2C approach uses a combination of human and automated analysis procedures. The DSM approach also uses a combination of human and automated analysis techniques. The Abstract Relation Type (ART) AN2C and ART DSM approaches use similar automated analysis techniques. This paper expands the authors' previous work in complexity reduction, and adds a well-defined process for the reduction of system disorder. The primary contribution of these techniques is to address and integrate both human and automated aspects of system evaluation. One of the design goals of these new metrics and techniques is the application of computer resources in areas where computers have proven beneficial, and the development of a human accessible interface that supports and enhances human performance in manual system evaluation tasks. Figure 1 depicts an overview of methods discussed and/or introduced in this paper.

Systems Analysis Methods	<i>Aspects</i>					
	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>
N-Squared Charts (N2C)	X		X			
Design Structure Matrices (DSM)	X		X			
Automated N-Squared (AN2C)		X	X	X		
ART DSM (Forward)		X	X			
ART DSM (Cluster)		X	X	X	X	X
ART AN2C		X	X	X	X	X

Where

- A = Manual Systems Analysis*
- B = Application of Evolutionary Computation*
- C = System Complexity Reduction*
- D = System Physical Entropy Concept*
- E = System Information Entropy Concept*
- F = Automated System Complexity Reduction*

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Figure 1. System Concept Allocation

These system analysis techniques all address the reduction of disorder in systems. The concept of physical entropy is associated with the increase of disorder in any given system. The aforementioned system analysis techniques are related to the concept of physical entropy by the introduction of order into a system structure. The automated N-Squared Charts (AN2C), developed by Derek K. Hitchins, applies an 'N-Squared' Score to the structure that is designed to measure the maximum configuration entropy associated with a given AN2C⁶. The AN2C entropy connection is based on an appeal to energy efficiency and interface disorder; the more ordered the system, the lower the N-Squared Score.

Similar to the N2 Score developed by Hitchins, Simpson and Simpson developed a method to calculate the reduction of interface complexity associated with N-Squared Charts⁷⁸. This complexity reduction technique is represented as an Abstract Relation Type (ART). Abstract Relation Types have been

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published and discussed for both the N2C and DSM system analysis methods. The N2C ART calculation method uses a set of matrices designed specifically for this purpose. The N2C ART technique has a marking space, a value space, and an outcome space (see Figure 2). Each of these spaces must have at least one matrix, but can contain more than one matrix under some conditions. The N2C ART marking space matrix is used to record the *system structure*. The N2C ART value space matrix is used to record the *value associated with the system structure*. The N2C ART outcome space is used to record the output from the system value function that is applied to the marking space and the value space⁷.

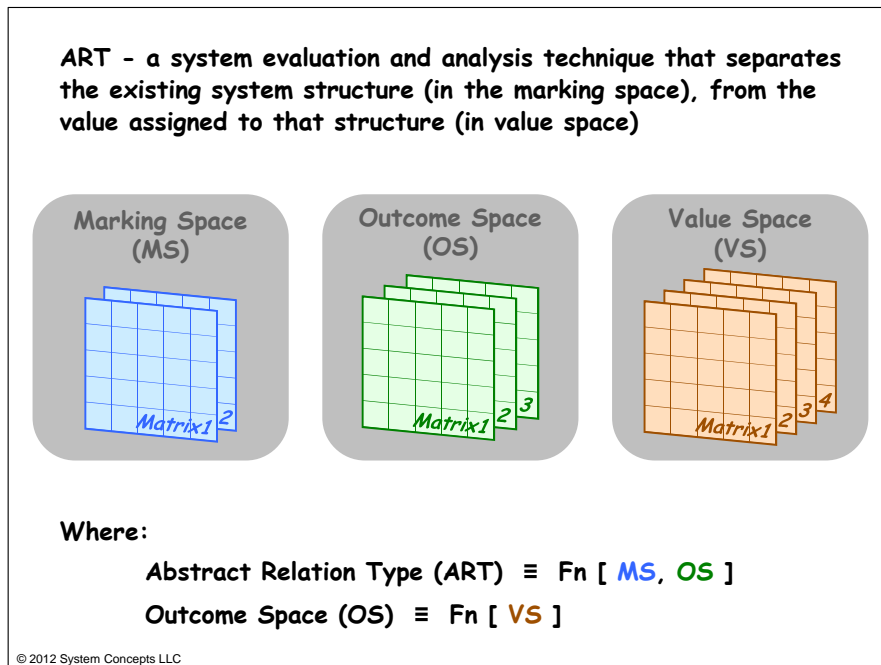


Figure 2. Notional depiction of Abstract Relation Type (ART)

The DSM ART approach is similar to the N2C ART approach; however, at this time the DSM ART approach has two basic clustering processes while the N2C ART approach only has one. In this work, the authors expand and refine the existing complexity reduction metrics to include specific physical entropy metrics and information entropy metrics. More N2C ART and DSM ART methods may be developed to expand the application of this technique. The concept of *system configuration entropy* (similar to physical entropy) is introduced as a total system metric. The concept of *system information entropy* (similar to information entropy from information theory) is also introduced as a total system metric. These concepts are discussed in more detail in the next section of the paper.

Entropy Forms and Types

Entropy is a 'whole-system' metric. Two forms or types of entropy are considered in this work: entropy in thermodynamics, and entropy in information theory. Thermodynamic entropy will be called physical entropy and information theory entropy will be called information entropy. The N2C ART and the DSM ART approaches use a matrix representation of a system structure. The diagonal of the matrix

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represents the system objects (or nodes) and the off-diagonal notations represent the connections among the system objects (or nodes).

The ART system representation focuses on the relationship that is mapped over the objects to create a system (see Figure 3). The “is connected to” relationship is used to create the N2C ART and the DSM ART.

The *physical entropy metric* is associated with the off-diagonal system connections, and is called the **connection score**.

The *information entropy metric* is associated with the system object sequence on the matrix diagonal, and is called the **object score**.

This approach to measuring system entropy provides a specific metric for each of the primary components of a system: the relationships (connection score) and the objects (object score).

Object A	Potential Connect	Potential Connect	Potential Connect	Potential Connect
Potential Connect	Object B	Potential Connect	Potential Connect	Potential Connect
Potential Connect	Potential Connect	Object C	Potential Connect	Potential Connect
Potential Connect	Potential Connect	Potential Connect	Object D	Potential Connect
Potential Connect	Potential Connect	Potential Connect	Potential Connect	Object E

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Figure 3. Graphical Map of System Definition

Physical Entropy Connection Score

The primary property or characteristic associated with physical entropy is the concept of disorder. System states of high disorder have a high entropy rating, system states of low disorder have a low entropy rating. The energy used to maintain the system in a state of high disorder is not available to do work. This form of entropy motivated Hitchens' work and the development of the N2 Score for AN2C analysis⁶.

The N2C ART connection score is based on the N2C concept of an interface feed forward connection,

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and an interface feed backward connection. Figure 3 provides a graphical map that depicts the system definition of “a system is a relationship mapped over a set of objects.” Each square located on the diagonal of an N2C matrix has four faces: top, right, bottom and left. Each of these four faces represents a specific type of system connection that, when taken together, create a connection flow through the matrix from the upper left corner to the bottom right corner. Figure 4 shows the four faces, and delineates the type of potential connection starting at the top and moving clockwise: top, Forward Receive (FR); right, Forward Send (FS); bottom, Backward Receive (BR); and left, Backward Send (BS). Each of the primary system description prose elements introduced here – the feed forward connection, the feed backward connection, forward send, forward receive, backward send, and backward receive – are mapped directly to a graphic and a mathematical representation. These system flow and connection concepts support more refined and detailed systems analysis techniques that are addressed later in the paper.

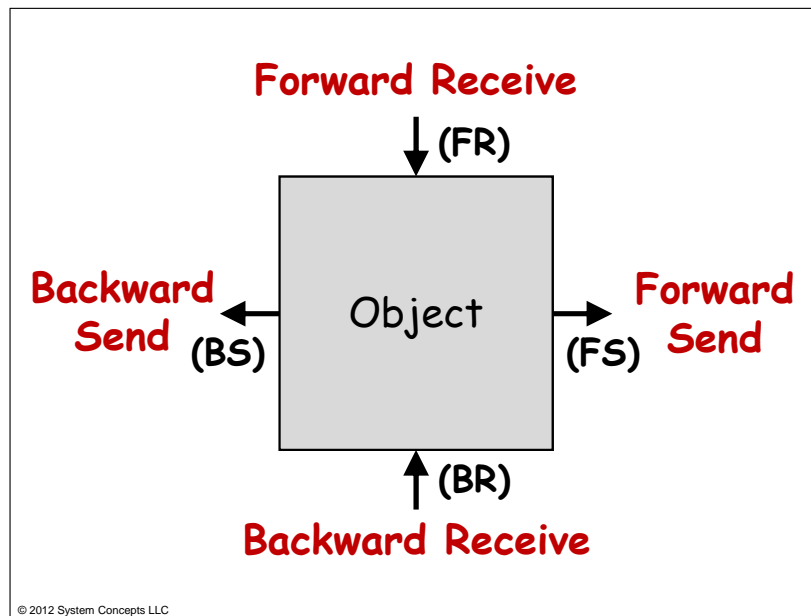


Figure 4. Object Connection Interfaces

Figure 5 provides the detailed combinatorial calculations of connections associated with a **9 by 9** N-Squared Chart. Since there is always one object in each row of a 9 by 9 N2C, the number of potential connection cells in any given row is (N-1), or eight (8). Figure 5, then, shows the number of different ways that each of the object interfaces may be combined. The Sum column represents the **total** number of combinations that can be achieved by that number of interface cells. This calculation procedure was modified and adapted from Hitchins’ Appendix A, “Configuration Entropy as a Useful Measure of Systems.”

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(N-1)	$(N-1)C_1$	$(N-1)C_2$	$(N-1)C_3$	$(N-1)C_4$	$(N-1)C_5$	$(N-1)C_6$	$(N-1)C_7$	$(N-1)C_8$	Sum: $\sum^{(N-1)}(C)$
1	1								1
2	2	1							3
3	3	3	1						7
4	4	6	4	1					15
5	5	10	10	5	1				31
6	6	15	20	15	6	1			63
7	7	21	35	35	21	7	1		127
8	8	28	56	70	56	28	8	1	255

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Figure 5. Combinations of (N-1) Connections for an N-Squared Chart

Each interface cell in a matrix can be filled with a one (1) to create a ‘maximum’ connection score for a fully populated matrix. The directional nature (asymmetric one-way links) of the N2C connections in a fully populated matrix completely defines the sequence order of the objects on the matrix diagonal. As shown in Figure 6, the connection score for each row is the sum of the forward-send (FS) score, the forward-receive (FR) score, the backward-send (BS) score and the backward-receive (BR) score for each object in the matrix. Based on the combinations shown in Figure 5, the first diagonal square in a nine (9) by nine (9) matrix of an N-Squared Chart (that is, the upper left corner square) has a ‘forward-send’ value of 255, a ‘forward-receive’ value of zero (0), a ‘backward-send’ value of zero (0), and a ‘backward-receive’ value of 255. Figure 6 displays a fully populated 9 by 9 matrix (on the left), and its associated matrix connection score board (on the right). The matrix connection score board is used to organize the computed data and values associated with the matrix of interest. Each matrix score board has five columns: 1) forward-send score, 2) forward-receive score, 3) backward-send score, 4) backward-receive score and 5) total connection score for the row. The 9 by 9 matrix in Figure 6 has a maximum connection score of 2008. The symmetry of the upper triangular (forward) and lower triangular (backward) portions of the matrix fully determine the order of the objects on the diagonal. The forward and backward connections determine the flow through the matrix from the upper left to the lower right.

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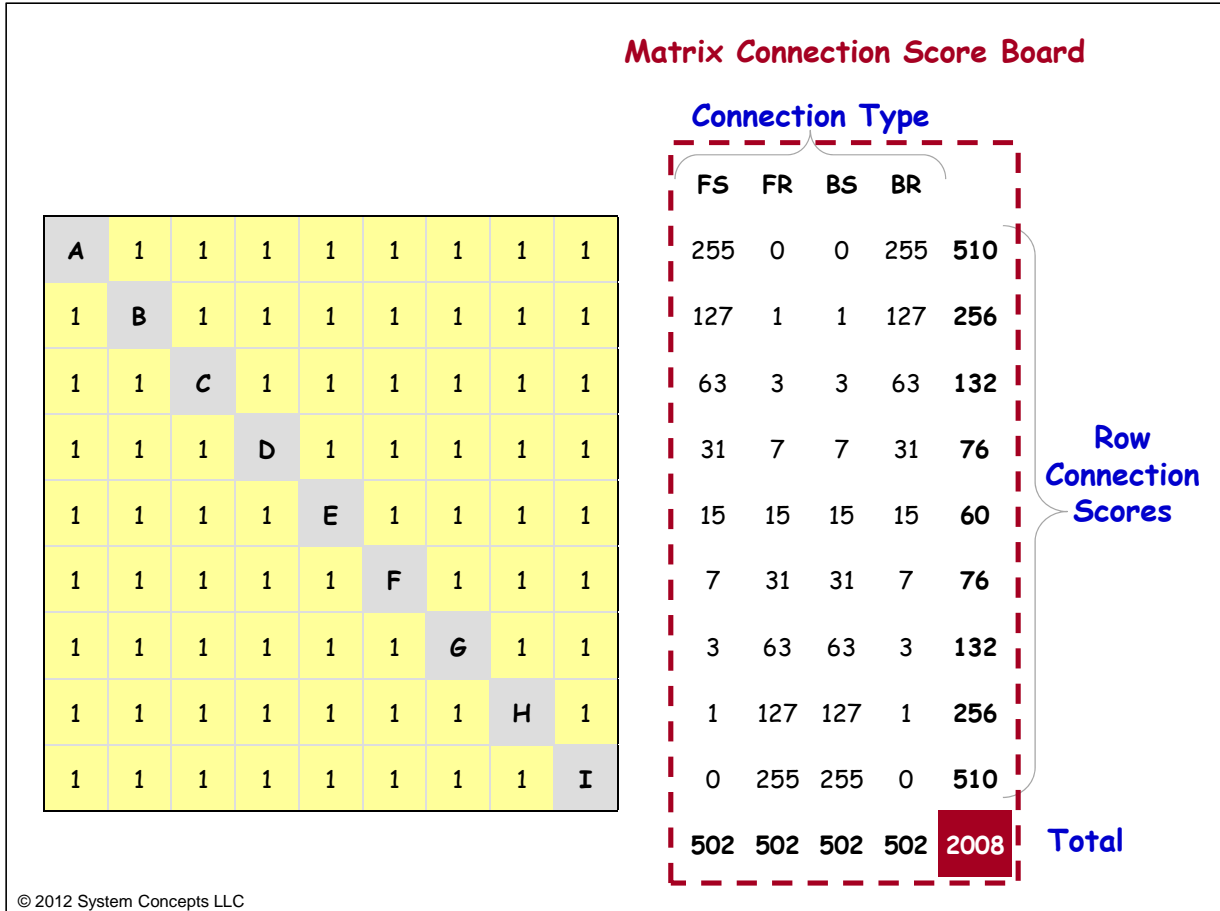


Figure 6. 'Fully Populated' 9 x 9 Matrix (N-Squared Chart)

Using the same basis (using the number of combinations shown in Figure 5, incorporating the same forward and backward connections, and applying the object interface definition), the matrix connection score board is created for a fully populated 5 by 5 matrix in Figure 7. As can be seen, the associated maximum connection score for the 5 by 5 matrix is 104.

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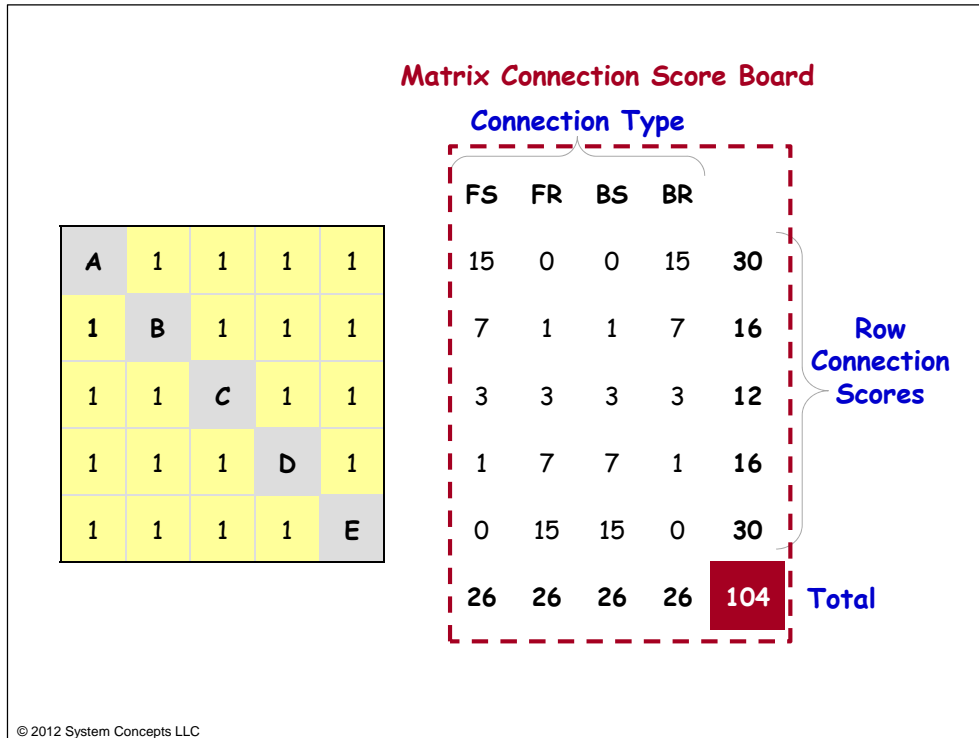


Figure 7. 'Fully Populated' 5 x 5 Matrix (N-Squared Chart)

Information Entropy Object Score

The object score has been developed to address the exchange of information between and among individuals using basic system engineering techniques (N2C, DSM, AN2C, ART DSM-Forward, ART DSM-Cluster, and ART AN2C) to enable and enhance the communication of large sets of data and information. This process of communication among individuals is similar to the types of message communications activities addressed by Shannon's Information Theory. The two primary components of information theory, message channel capacity and quantitative information metrics, are used as the basis of the object score that is developed in this work. The object score is associated with the specific sequence, or linear arrangement, of the objects on the diagonal of the marking space.

The primary purpose of N-Squared Charts, Automated N-Squared Charts, DSM, ART N2C or ART DSM is the encoding and communication of information associated with a system that is comprised of the objects displayed on the matrix diagonal. The quantitative value of the information contained in the arrangement of the objects on the diagonal can be expressed in the statistical terms of information theory. Take a case where three groups of technical professionals are needed to design, discover or otherwise address a specific system. Shannon created an information entropy metric associated with the message source that measures the average amount of information created by a message source. If the probability of a message occurring is 100 percent (well known in advance), the message contains zero (0) information. It then follows that if all three groups of professionals understand the system, and agree that the existing object sequence on the diagonal is the optimal arrangement, then an analysis of the system that produces that optimal arrangement will contain zero information.

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The prose, graphics and mathematical components of the ART N2C and ART DSM allow a graded use of the tools. A simple prose and graphical representation of a system can be prepared and used to support a discussion among the professional teams. If there is agreement that the current system arrangement is optimal, then the process is complete. If there is no agreement and/or existing information and data gaps are associated with the system structure, then a refined set of system configurations will contain a high degree of information. If there is a high degree of uncertainty associated with a system, and an analytical technique eliminates the uncertainty, then that analytical technique contains a high degree of information. The amount of information associated with any process is directly related to the reduction of uncertainty associated with the application of that process. These are the general information entropy concepts upon which the object score is based.

The object score is based on the number of permutations associated with the objects on the diagonal. Given X system objects, the number of permutations of these objects is X factorial. The maximum object score for a matrix with X objects on the diagonal is X factorial. The type of object sequence arrangements may be restricted by the object connections, and the system connection logic. The system connection logic is usually known by the system designers and/or operators. This type of system logic restricts the object sequence, so that operations and events that need to occur first are completed when needed. The object sequence restriction associated with system optimal-connection sequences is the focus of the evolutionary computational techniques developed by the authors, and is usually based on extensive computation activity. The maximum object score can be reduced using information from human designers as well as information from computer programs. The integration of these two sources of information create a powerful system entropy and complexity reduction approach.

In the preceding discussion, the manual example uses information from human designers and the AN2C example uses information from the evolutionary computational techniques.

Examples Demonstrating the Use of Connection Score and Object Score

The discussion of an existing N-Squared Chart analysis example from Lano's *A Technique for Software and Systems Design* was selected to support the examination of an N2C example that was completed using manual techniques. The system and design information was collected from human experts by the system engineering team. The manual N-Squared Charts were used to graphically encode and analyze the proposed system components, interfaces and structure. This examples' connection score calculation technique, and its respective values, are shown in Figure 8.

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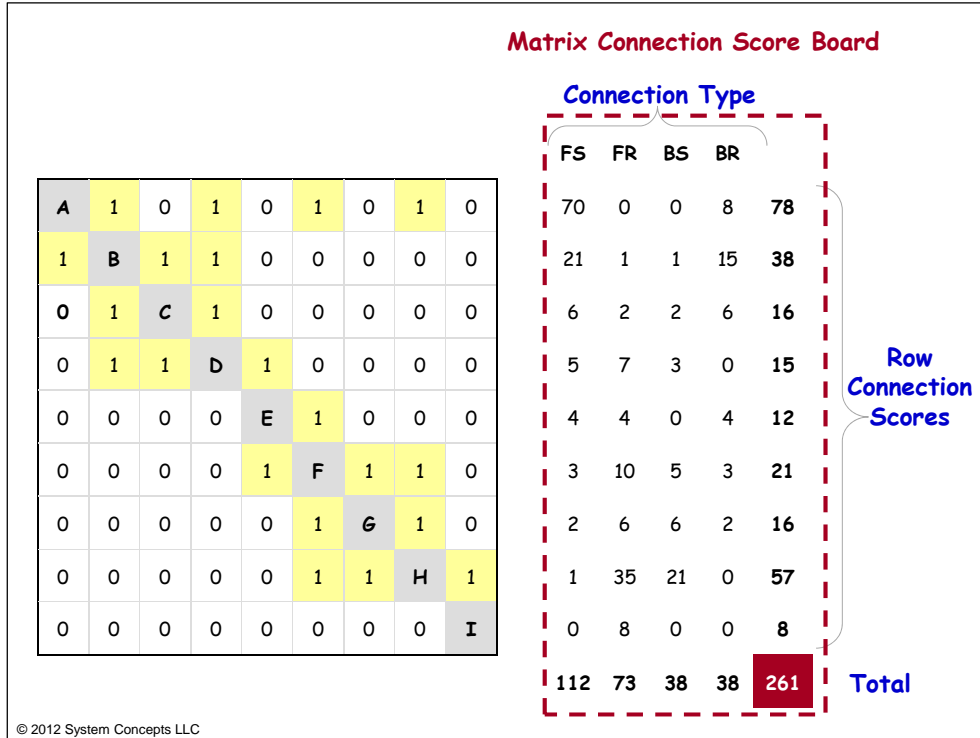


Figure 8. Manual N-Squared Chart Example

Here, the connection score is 261. This example presents the manual analysis discussed in Lano’s work, and provides the associated connection score for the physical entropy analysis. Lano’s matrix example also introduces a type of system analysis process that is similar to the information entropy process developed by the authors, and which is depicted in Figure 9. This systems analysis process identifies areas of “highly coupled” clusters, and reduces them into single subsystems represented by a single cell.

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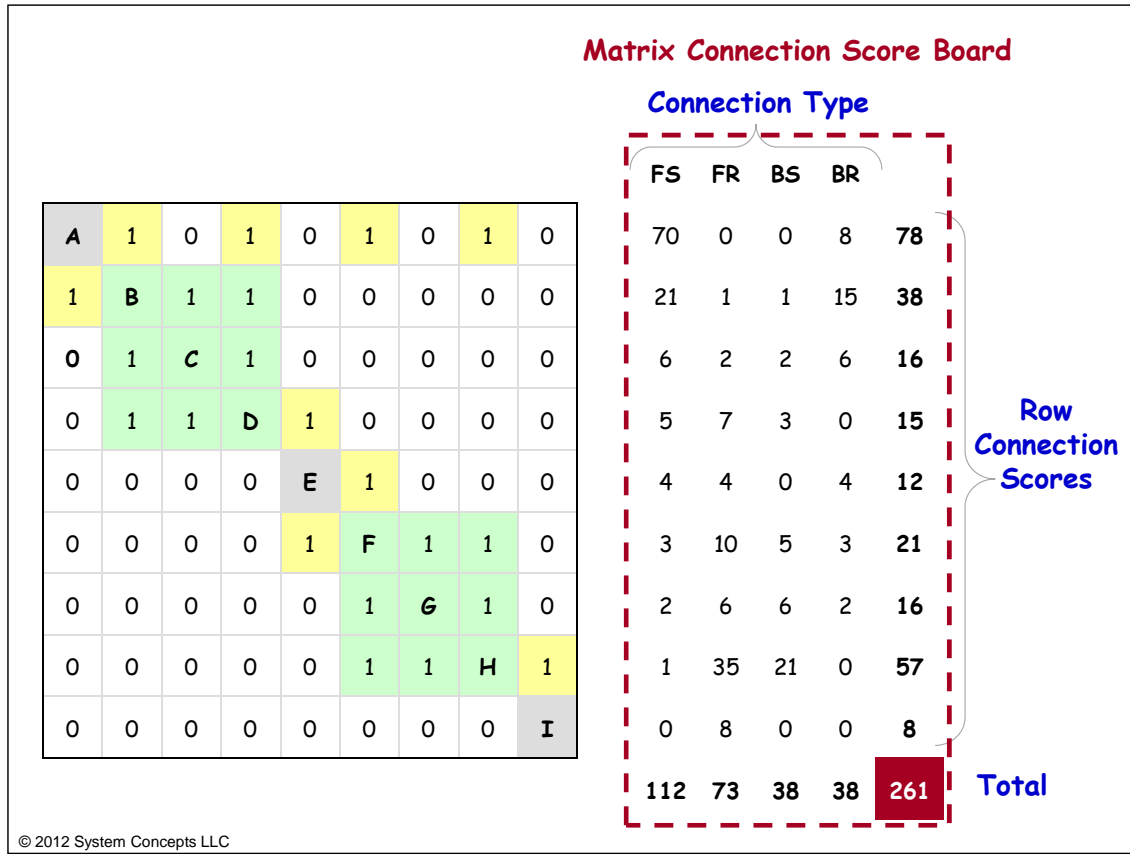


Figure 9. Well-Defined Object Sequence

The sequence of objects B, C and D is well defined by the connection marks highlighted in green in the upper left hand corner of the matrix. In a similar fashion the sequence of objects F, G, and H is well defined their associated connection marks. Because the sequence is well known in both cases each sequence can be reduced to a single cell. Because the sequence is defined and well known, this series of objects contains no information, and the information entropy is zero (0) for both cases. The information entropy metric will be discussed in greater detail in following sections of the paper.

In this manual example, systems analysts worked with the engineering team members, and produced a simpler system representation that is shown in Figure 10. This simpler representation of the system was a more effective conceptual design tool, due to the previously reported cognitive complexity reduction. (Simpson and Simpson papers) This simpler matrix representation is identical to the system produced if the two green highlighted areas in Figure 9 are collapsed into two one-cell object representations, cell D and cell F. The connection score for the reduced (5 x 5) manual example is 34. The maximum connection score for a 5 by 5 matrix was found to be 104; the maximum connection score for a 9 x 9 matrix was 2008. This simplified matrix example reduces the maximum connection score from 2008 to 104 or **a factor of 19.3**. This manual example also shows the original larger 9 x 9 matrix connection score of 261 and the simplified matrix (5 x 5) with a connection score of 34, which reduces the connection score from 261 to 34 or **a factor of 7.7**.

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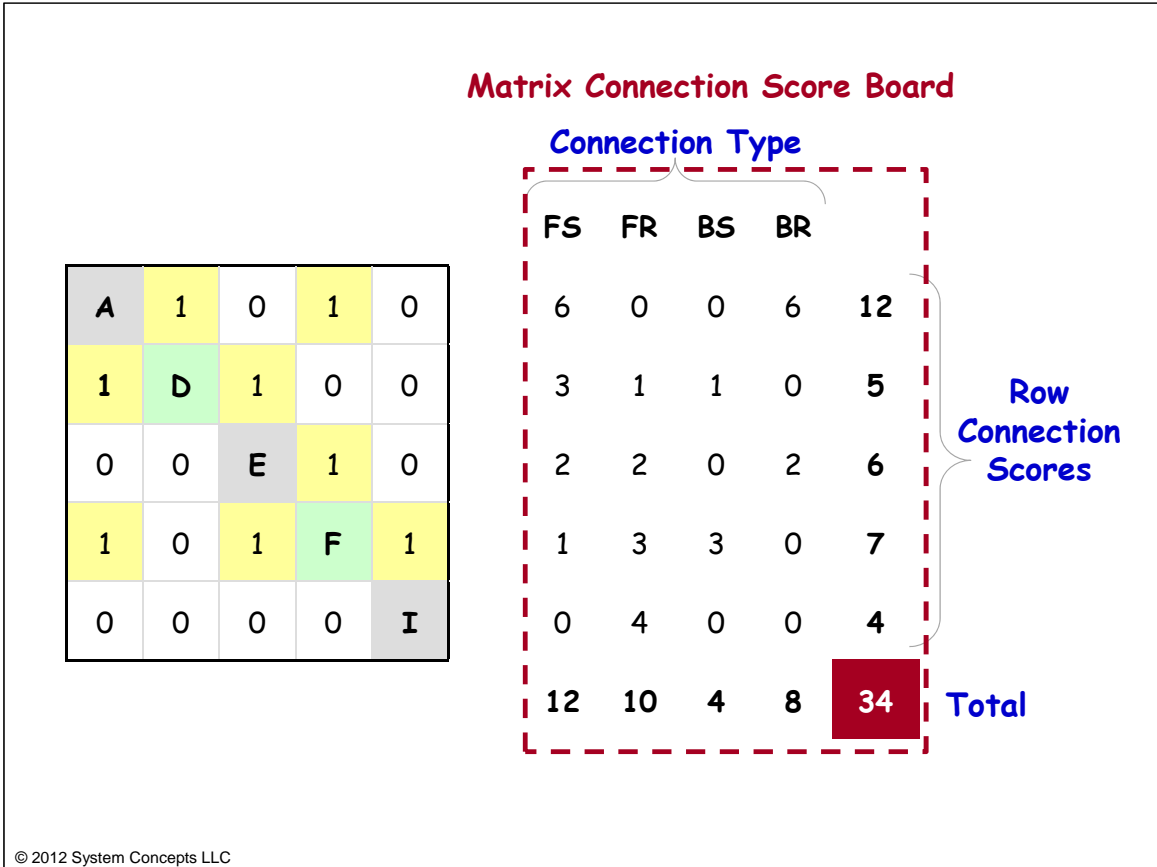


Figure 10. Connection Score for Reduced Matrix Example

Information Entropy Object Score

As shown in Figures 9 and 10, columns B, C and D were collapsed onto column D and columns F, G and H were collapsed onto column F. This resulted in a smaller number of system objects and a different object sequence. An information entropy metric has been developed to address the object sequence permutations on the matrix diagonal. In this example, since all connections for these two groups of objects are known, the order for these objects is well known. There can only be an object sequence of B,C,D and F,G,H. There is no possibility of changing the object arrangement. Therefore, the sequence is well known, with a 100 percent probability. Shannon created an information entropy metric associated with the message source that measures the average amount of information created by a message source. If the probability of a message is 100 percent (well known in advance) the message contains zero (0) information, and also has an information entropy rating of zero (0). The sequences B, C, D and F, G, H contain zero information, and can therefore be condensed into two object nodes (D and F) on the matrix diagonal without losing any associated message information potential. Each of these two sequences has an object score of zero (0).

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System Entropy Metric Calculation Process (N2C)

The system evaluation process associated with the manual N-Squared Charts is different than the system evaluation process that includes an automated or evolutionary computational component. In this N2C case, only one larger system representation was developed – an ordered representation. The system entropy calculation steps have been adjusted for the manual process analysis.

The system entropy metric calculation process has thirteen basic steps.

- M-1. Identify the system of interest and collect data.
- M-2. Develop original unstructured system marking and value spaces.
- M-3. Calculate the maximum connection score for the system.
- M-4. Calculate the maximum object score for the system.
- M-5. Use manual techniques to find a minimum connection score (structure system).
- M-6. Evaluate the system structure with the minimum connection score, and find areas that have a zero (0) object score.
- M-7. Reduce each 'object-score zero area' into one diagonal object node.
- M-8. Calculate the maximum connection score for the new reduced system structure.
- M-9. Calculate the reduction in the system maximum connection score entropy between the two different sized matrices.
- M-10. Calculate the minimum connection score for the new reduced system structure.
- M-11. Calculate the reduction in the minimum connection score.
- M-12. Calculate the maximum object score to the new reduced system structure.
- M-13. Calculate the reduction in the system maximum object score.

Table 1 shows the calculation steps, and scores, for the N-Squared Chart example shown in Figures 8, 9 and 10.

Table 1. Evaluation of Lano's N-Squared Chart Example

Process Step	Matrix Size	Number of Connections	Maximum Connection Score	Maximum Object Score	Minimum Connection Score	Connection Score Reduction	Maximum Object Score Reduction
Step 1	9 x 9	21					
Step 2	9 x 9	21					
Step 3	9 x 9	21	2008				
Step 4	9 x 9	21	2008	362880			
Step 5	9 x 9	21	2008	362880	261		
Step 6	9 x 9	21	2008	362880	261		
Step 7	5 x 5	8					
Step 8	5 x 5	8	104		34		
Step 9	5 x 5	8	104		34	2008 to 104	
Step 10	5 x 5	8	104	120	34		
Step 11	5 x 5	8	104	120	34	261 to 34	
Step 12	5 x 5	8	104	120	34		
Step 13	5 x 5	8	104	120	34		362880 to 120

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Lano's N-Squared Chart example (referenced in Figures 8, 9 and 10) was developed using manual analysis techniques. The following section will explore the system entropy metric calculation process in detail using an automated N-Squared Chart example from Hitchins' work.

Automated N-Squared Chart Example

System analysis tasks may be performed on systems that are poorly defined and documented. The first step in the system entropy metric calculation process is the identification of the system of interest (set system boundaries), and the collection of relevant data associated with the system. In many cases, individuals associated closely with one component (object) of the system may have limited knowledge about the total system, but maintain a high degree of useful information about the specific component. In these cases, the amount of manual effort directed toward the total system analysis can be reduced using evolutionary computation techniques.

The example considered next is taken from the work of Derek J. Hitchins (reference p.148), and is discussed in some detail in the following sections. The basic steps given in Hitchins work is expanded here to add further detailed analytical steps. Unlike Lano's work, the Automated N-Squared Chart example starts with a disordered system representation, and uses evolutionary computation techniques to reduce the disorder and to identify sub-systems within the total system. The identification of sub-system groupings is the main feature of the AN2C approach presented by Hitchins. The N2 Score proposed by Hitchins has proven effective in identifying and clustering subsystems.

When a more detailed connection score and object score analysis are performed on the example, it becomes clear that there may be a missing connection in the analysis published in Figure 8.13 presented in Hitchins' book. Figure 11 shows two AN2C matrix configurations. On the upper left, the original AN2C matrix configuration – a disordered 9 by 9 matrix – and its associated connection score using the system entropy metric calculation process are detailed. The upper left figure also shows the N-Squared Score for that matrix found by applying Hitchins N-Squared Score procedure (reference Appendix A). The lower right figure addresses the same disordered 9 by 9 matrix, but now contains the "missing" connection – along with the applicable changes in both the system entropy metric calculation and Hitchins N-Squared Score.

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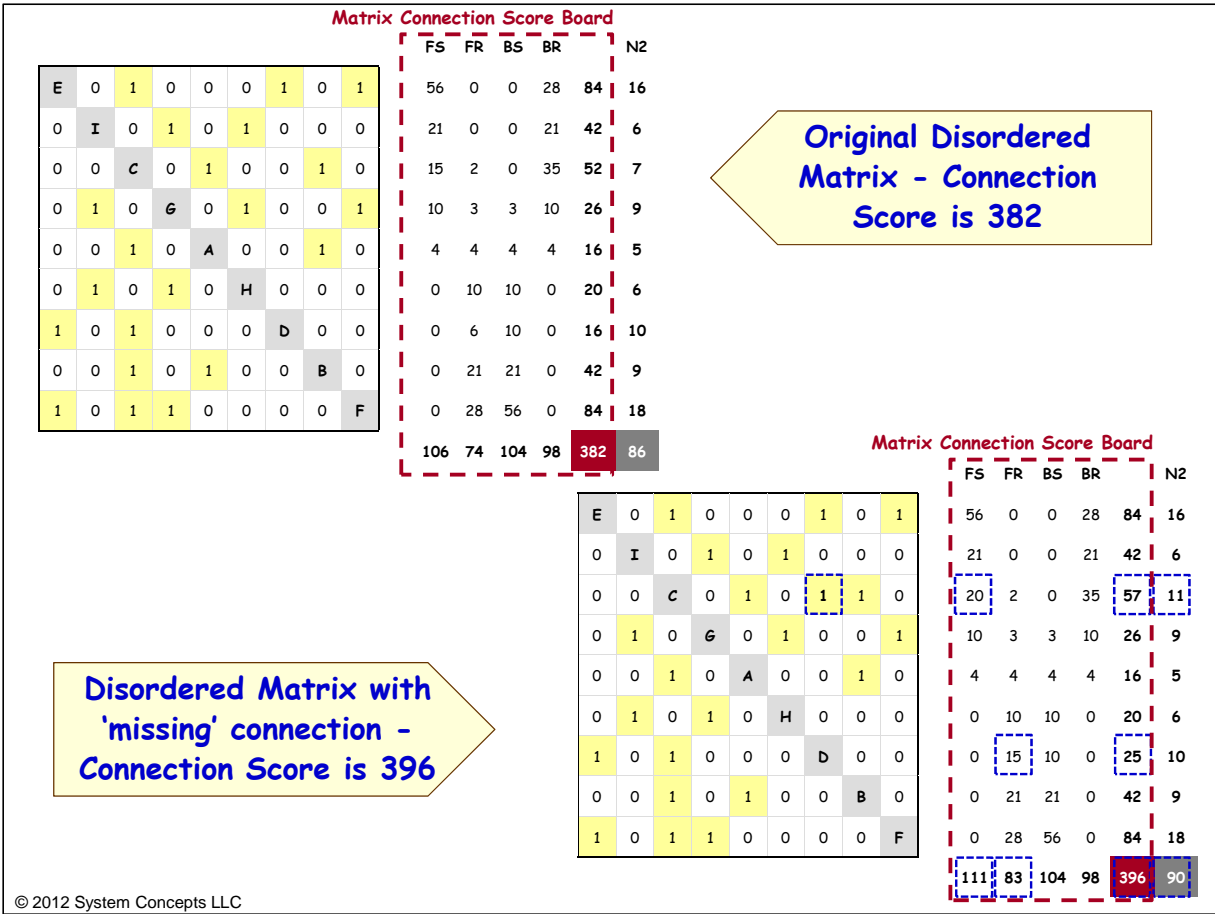


Figure 11. Disordered 9 x 9 Matrices

The more detailed connection scores associated with the disordered matrices presented in Figure 11 highlight the fact that objects H, D, B, and F have no forward-send or backward-receive connection interfaces, with a zero (0) associated with each of these objects in the applicable scoring column. The numerical values in the scoring columns provide the basis upon which the mathematical functions associated with the prose descriptions of the matrix configurations can be built and deployed.

Once the disordered matrix shown in Figure 11 has been ordered using evolutionary computation, the missing feed-forward connection between object C and Object D is readily identified by the zero (0) in the forward-send column for object C and the zero(0) in the forward-receive column for object D. While the objects are still clustered in the same pattern, the more detailed connection configuration information provides further connection and flow information. For example, in Figure 12 it is clear that the system forward connection path from object C to object D does not exist. The absence of this connection prevents the forward connection from objects A, B, and C, to the rest of the system and creates a distinct boundary in the internal system flow. Once the missing system connection is identified and repaired, as shown in Figure 12, there is a clear pathway for internal system flow between and among each of the objects.

An analysis of the detailed connection scores presented in the matrix connection score board sections

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of Figure 11 shows the presence of zero (0) valued connections in both of the disordered system connection score boards. Figure 12 shows the absence of zero valued connections in every row of the corrected ordered system connection score board, except the first row and last row. These numerical patterns provide an indicator of the relative order or disorder in a given system structure. Automated evaluation of system order, or disorder, can be based – in part – on this numerical indicator associated with the system connection scores that are organized and displayed in the system connection score boards.

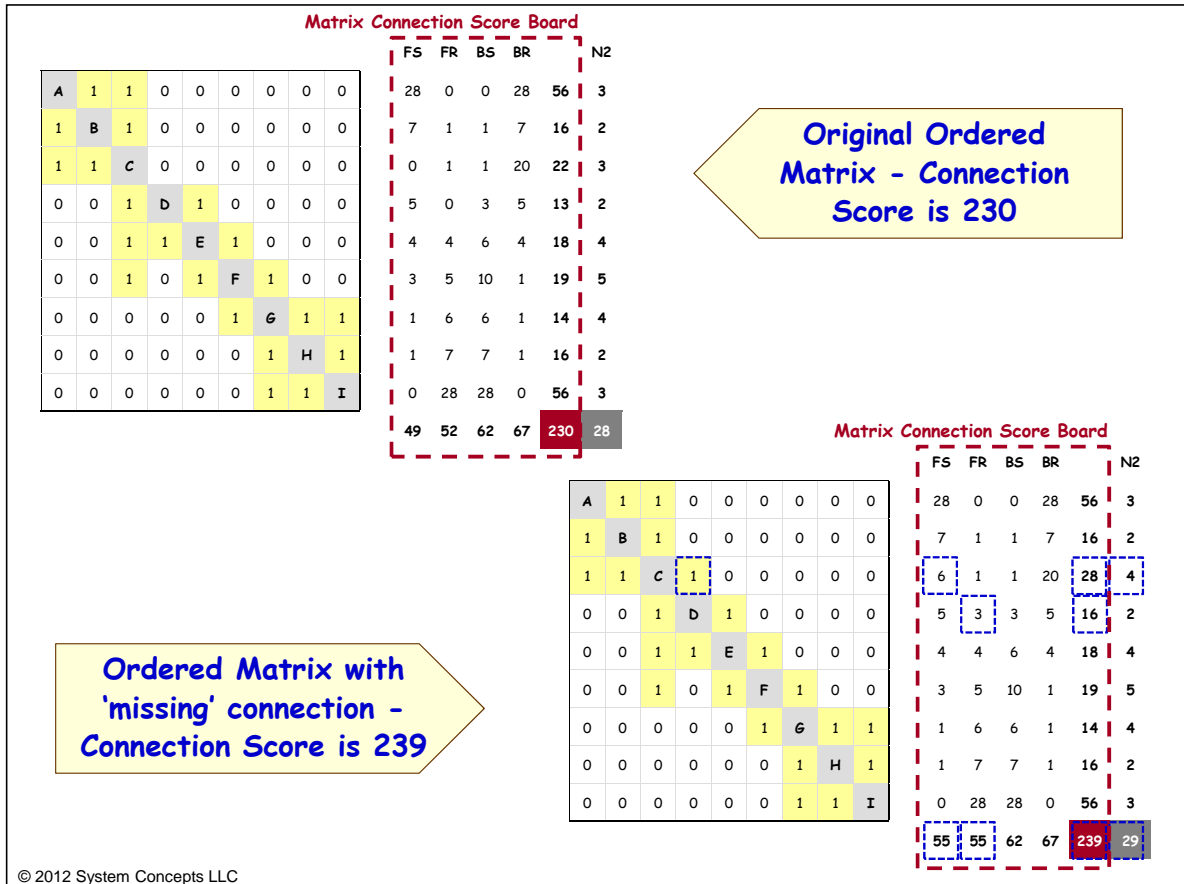


Figure 12. Ordered 9 x 9 Matrices

The ordered system shown in Figure 12 has two areas that have a zero (0) object score. These areas are the object sequence A, B and C and the object sequence G, H and I. The connection markings for the objects in Figure 12 completely determine the object sequence. Because the object sequence is now well known, these object sequences contain no information, and have an information entropy rating of zero (0). Once a sequence of objects obtains an object score of zero (0), that sequence of objects can be reduced (or collapsed) into a single object cell on the diagonal without losing any system information. The system shown in Figure 12 has been reduced using the object score technique, and the resulting system configuration is shown in Figure 13. Once the original system representation has been reduced to a 5 x 5 matrix representation, it is very clear that the missing connection interfaces between object C and object D may create internal system interaction restrictions. However, once the missing connections are added to the system interfaces, the system interaction restrictions are lifted.

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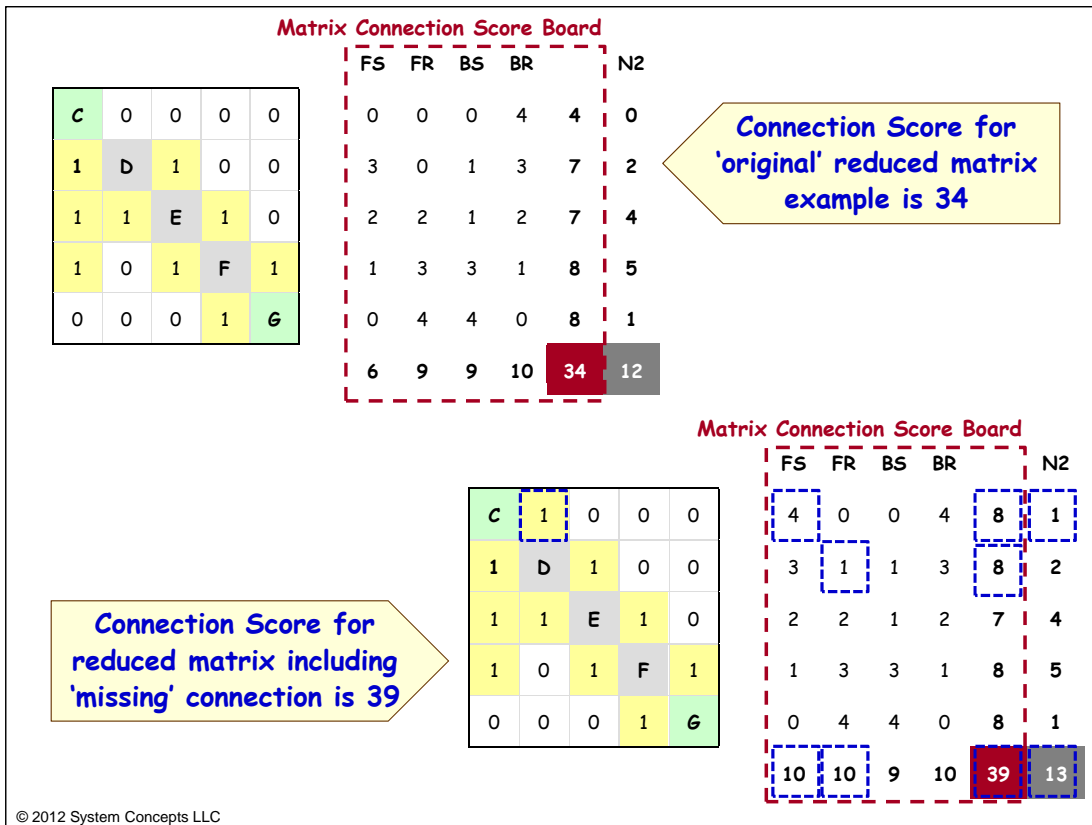


Figure 13. Ordered 5 x 5 Matrices

System Entropy Metric Calculation Process (AN2C)

The system evaluation process associated with the Automated N-Squared Charts includes an automated or evolutionary computational component. In the automated case, the first step is the identification of the larger, disordered matrix. Once the larger disordered system has been identified, then evolutionary computation can be used to search for other, more ordered or optimal system configurations. The identification of these alternative system configurations is a major road block in the effective use of these types of techniques. Evolutionary computation techniques are viewed as a technology that can remove this road block. The general automated process steps are listed below.

The system entropy metric calculation process has thirteen basic steps.

- A 1. Identify the system of interest and collect data.
- A 2. Develop original unstructured system marking and value spaces.
- A 3. Calculate the maximum connection score for the system.
- A 4. Calculate the maximum object score for the system.
- A 5. Use automated techniques to find a minimum connection score (structure system).
- A 6. Evaluate the system structure with the minimum connection score, and find areas that have a zero (0) object score.
- A 7. Reduce each 'object-score zero area' into one diagonal object node.

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- A 8. Calculate the maximum connection score for the new reduced system structure.
- A 9. Calculate the reduction in the system maximum connection score entropy between the two different sized matrices.
- A 10. Calculate the minimum connection score for the new reduced system structure.
- A 11. Calculate the reduction in the system minimum connection score entropy.
- A 12. Calculate the maximum object score for the new reduced system structure.
- A 13. Calculate the reduction in the system maximum object score.

Table 2 shows the calculation steps, and scores, for the Automated N-Squared Chart (AN2C) example shown in Figures 11, 12 and 13.

Table 2. Evaluation Hitchins' Automated N-Squared Chart Example

Process Step	Matrix Size	Number of Connections	Maximum Connection Score	Maximum Object Score	Minimum Connection Score	Connection Score Reduction	Maximum Object Score Reduction
Step 1	9 x 9	22					
Step 2	9 x 9	22					
Step 3	9 x 9	22	2008				
Step 4	9 x 9	22	2008	362880			
Step 5	9 x 9	22	2008	362880	396		
Step 6	9 x 9	22	2008	362880	396		
Step 7	5 x 5	10					
Step 8	5 x 5	10	104				
Step 9	5 x 5	10	104			2008 to 104	
Step 10	5 x 5	10	104	120	39		
Step 11	5 x 5	10	104	120	39		
Step 12	5 x 5	10	104	120	39	239 to 39	
Step 13	5 x 5	10	104	120			362880 to 120

Hitchins' Automated N-Squared Chart (AN2C) example (referenced in Figures 10, 11 and 12) was developed using automated analysis techniques based on evolutionary computation. The system entropy metrics used for the evaluation of both the manual and automated system analysis techniques support the automation of detailed system configurations. The automation of these processes allow the evaluation of much larger systems, and enable the reduction of the human effort required to effectively process systems of a very large size.

Summary and Conclusions

System entropy metrics that are directly related to basic systems definitions have been presented in this paper. These metrics expand the existing set of system complexity metrics developed by the authors, and create the foundation for more advanced system analytical procedures and automated tools. The system connection score is a metric that is related to physical entropy measures. The system object score is directly related to information entropy measures. Taken together, these system metrics cover the two primary aspects of any system: relationship (connection score) and objects (object score).

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The system connection score board provides an organized data structure upon which system configuration analytical tools can be based. This working paper outlines the foundational systems concepts upon which other more detailed automated tools can be constructed.

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