Abstract. Requirements need be established for architecting a large scale, complex system for sustainable delivery of value to users. In this paper, we describe a general methodology to establish requirements on design of a complex system to provide sustainable delivery of value. The methodology involves a system architecture paradigm, a sustainability analysis, and the derivation of design requirements. The methodology is described in concrete terms as it is applied to an ad hoc sensor network, which is required to provide sustainable delivery of information for use within the context of a missile defense system. Bounds are then established on the network connectivity and interoperability measures. This work demonstrates a methodology to enable designing requirements for architecting a system for sustainable delivery of value.

Introduction

Our ongoing research aims at understanding network complexity and eventually translating it to engineering and architecting of complex systems. A research area of interest is to gain insights into architecting a large scale, complex system for sustainable performance. By sustainable performance it is meant sustainable delivery of value to the user of the system. We consider a complex system to consist of a large number of elements that interact with each other; complexity is related to the real-time, unplanned, evolving large size of a system. Not only does the complexity of a system induce vulnerability of the system (Gheorghe and Vamanu 2004), but lacking interoperability among the elements that make up the system also degrades the performance of the system (Huynh and Osmundson 2004).

To discuss the work in this paper in concrete terms, we choose an ad hoc sensor network within the context of a simplistic missile defense system (Figure 1) as a system whose performance is to be sustained. Examples of the notions espoused in this paper are drawn from this missile defense system. The missile defense system is assumed to have three main components – BMC2 (battle management, control and command), a sensor network, and shooters (interceptor launchers). The shooters need a fire solution (i.e., an intercept solution) for them to intercept a target (incoming missile). The BMC2 receives and combines the target state estimates from the participating sensors to derive an intercept solution. The target state can include the type of the target (missile), its position and uncertainty (associated error), and its velocity and uncertainty. A target state estimate from a sensor results from distributed information fusion – collaborative processing (i.e., acquiring, sharing, and processing) of data and information from all participating sensors that make observations of the target. The sensor network is assumed to be an ad hoc network, in the sense that its topology is not known a priori and must be established in real time and updated periodically (Deb et al. 2001; Chong et al. 2003).
Analysis of the performance of such a sensor network is often based on the assumptions that connectivity and interoperability among the sensors is perfect. By connectivity it is meant the sensors can discover and communicate with each other; by interoperability it is meant there is no semantic or syntactical problem that would prevent successful combining of the sensor data. In reality, sensors do drop out of the network as a result of malfunction or hostile acts, and interoperability might not exist or can degrade for some reason. In the presence of external factors (environment dynamics) that might affect these two measures — connectivity and interoperability, the issue of network sustainability arises. A sustainable network is one which is resilient and adaptive to the dynamics of the environment. Network sustainability is necessary for sustained delivery of distributed fusion performance of the sensor network. Network sustainability necessitates a sensor network architecture that maintains such sustained delivery.

The key question is: How can we design a system architecture that enables sustainable delivery of value, in the sense that the delivery of the desirable value continues in the face of adversity caused by environmental or mission changes? For the example at hand, the specific question is, “How does one architect a sensor network for sustainable delivery of distributed fusion performance?”

As connectivity and interoperability of the network can be affected by the environment dynamics, they need be represented or modelled in order to understand how they are related to sustainability. In (Huynh and Osmundson 2004, 2007) the connectivity and interoperability of an ad hoc sensor network are represented in terms of the size of the network and the probability of connection and the probability of interoperability. Huynh and Tran (2007) assess the sustainability the ad hoc sensor network by treating it as an ecosystem with its complexity and interoperability implicitly built-in and determining the critical connectivity for which the network fails to perform according to a fusion rule. Effects of the dynamics of the environment are reflected by the change in the complexity, which, in their work, is manifested by the change in the probability of connection; for simplicity, the interoperability is allowed to remain unchanged. The sustainability analysis uses the so-called sustainability index (Brown and Ulgiati 1997), a quantitative measure used in ecologically conscious process systems engineering (Bakshi 2000).

Crawley and Simmons (2006) formulate a preliminary system architecting paradigm, in which, as shown in Figure 2, architecting a system starts with function which is mapped to form by concept. Architecture is “the embodiment of concept, and the allocation of physical/informational function to elements of form, and [the] definition of interfaces among the elements and with the surrounding context” (Crawley and Simmons, 2006). The notions in italics in this definition of architecture will be elaborated later in the paper.

In our work, architecting for sustainable delivery of value involves concept and form. It is from these two notions of concept and form that we discuss ideas of architecting for sustainable delivery of value.
A sustainable architecture is one which enables sustainable delivery of desired value. The methodology sketched in this exploratory work to establish requirements for designing a sustainable architecture is described in concrete terms as it is applied to an ad hoc sensor network, which is required to provide sustainable delivery of sensor fusion performance beneficial (value) to the BMC2 component of the missile defense system. Specifically, we adopt the system architecting paradigm espoused by Crawley and Simmons (2006), define concept and form for the sensor network, and use the results of the sustainability analysis in (Huynh and Tran 2007) to derive the desired requirements. Bounds are established on the ability of elements of the network to discover and to communicate with each other and the ability of the elements to interoperate with each other. This work will thus demonstrate a methodology to enable the development of requirements for architecting a system for sustainable delivery of value.

Our goals in this paper are:

- Elucidate the architecting paradigm espoused in (Crawley and Simmons, 2006).
- Recapture the models of network connectivity and interoperability (Huynh and Osmundson 2004, 2007) and the sustainability analysis of ad hoc wireless sensor networks using the sustainability index (Huynh and Tran 2007).
- Combine the results of sustainability analysis of ad hoc sensor networks and the architecting paradigm to provide an illustration of thoughts on architecting for sustainable performance.
- Illustrate the methodology with an ad hoc wireless sensor network for distributed sensor fusion.

The rest of the paper is organized as follows. We elucidate the architecting paradigm espoused in (Crawley and Simmons, 2006). We then describe the binary hypothesis distributed fusion problem and the models of network connectivity and interoperability; the descriptions are excerpted from (Huynh and Osmundson 2004, 2007). We follow with a recapture of the sustainability analysis of ad hoc wireless sensor networks using the sustainability index, excerpted from (Huynh and Tran 2007). We then combine the results of sustainability analysis and the architecting paradigm to provide an illustration on architecting for sustainable performance. Finally, we end with some closing remarks.

**Systems Architecting**

We capture the definition of architecture (Crawley and Simmons 2006) stated in the Introduction as a quadruplet: (Function, Concept, Form, Interfaces; Context). We follow (Crawley and Simmons 2006) closely in explaining each term in the quadruplet.

A system executes externally delivered functions. A function is a process that acts (operates) on an operand. An operand is thus an entity that is acted on by an action, an operation, or a function. An operand may be thought of as an argument of an operator or a function. For example, a function of the missile defense system is to detect an incoming missile; detecting is a process and the missile is an operand; another function is to launch an interceptor; launching is a process and the interceptor is an operand. An external function of a system delivers benefit, and therefore value, of the system.
To define ‘form’ we need to define an ‘object’. An object is that which can potentially exist for some duration of time. It can be physical — visible or tangible and stable in form. It can be informational — intellectually apprehended. Processes can change the state of an object. Form is an instrument to deliver benefit to a user. For example, the ad hoc sensor network is a form to deliver estimates of the target state to the BMC2 component. A form results from synthesizing objects in a structure (configuration or arrangement) in which relationships exist among the objects. Objects are thus the elements of a form. The relationships among the elements of a form can be topological (relationships between linked objects, touching, belonging, within), spatial (separated, aligned), or connectivity (wired, wireless).

Concept is a system notion or idea, which maps functions to forms. It is the solution we seek. It includes an abstraction of form and the principle of operation, and it establishes the solution-specific vocabulary. A system is intended to perform a function or functions. A system is known as a form. The connection between the function and the form is concept. For example, concepts are determining air/space objects and intercept solutions (fire control solutions). The solution neutral statement is ‘determining intercept solutions’. The solution specific process is ‘target state estimation’. (This process includes receiving signals, processing the signals, fuse the processed signals, making inferences, and disseminating.) A solution-specific form for ‘target state estimation’ is fusion by networked sensors (consisting of sensing, processing, and disseminating). A concept in this case is thus ‘object state estimation with a distributed fusion sensor network.’

Interfaces include physical, logical, and human-system interfaces. If interfaces are incomplete and/or incompatible, systems cannot be connected physically and/or information transfer across the systems becomes impossible.

By ‘context’ it is meant the circumstances relevant to systems architecting. For example, ‘fire control solutions for missile engagement’ is the context in which the sensors are networked to provide the target state estimate.

A system is to deliver value. When the externally delivered functions of a system act on the operands to satisfy the needs of the system user (beneficiary) at a desirable cost, value is delivered. For example, as distributed fusion of sensor observations of the incoming missile to provide accurate estimates of the target state benefits the BMC2 component in formulating fire control solutions, value is delivered to the BMC2 component. The beneficiary is BMC2; the need is accurate target state estimates; the operand is fire control solution; the value attribute is the target state; and the transformation is estimating or distributed fusion. Value is associated with change of the operand, which is the fire control solution. An accurately estimated target state is of value to the fire control solution. The value that need be delivered in a sustainable manner is the estimated target state.

**Representation of Network Complexity & Interoperability**

Consider an ad hoc network of \( N \) sensors, connected at random. Two sensors in the network are connected if they discover each other — assumed with a constant probability \( p_d \) — and, upon discovery, the communication channel between them is established — with a variable probability \( p_x \). Then the probability \( p_c \) that a pair of sensors is connected is \( p_c = p_x p_d \), which, by virtue of \( p_x \), is not constant. The degree of a sensor (Bollobas 1985; Newman et al. 2001) follows a binomial distribution with parameters \( p_c \) and \( N - 1 \). The probability of degree \( \ell \), \( P(\ell) \),
is then \( P(\ell) = \binom{N-1}{\ell} p_c^\ell (1-p_c)^{N-\ell} \). As in (Aslaksen 2004), \( \chi_0 \) denotes the complexity of a network, defined as the mean number of links supported by a sensor of the network; that is, 
\[
\chi_o = \sum_{\ell=0}^{N-1} P(\ell).
\]
\( \chi_o \) is thus the connectivity measure of the network. Then a simple computation leads to 
\[
\chi_o = p_c (N-1) \quad \text{or} \quad \chi_o = p_o p_d (N-1).
\]
The more complex the network is, the higher is the value of \( \chi_o \). The ad hoc sensor network is thus modeled as a random network.

As in (Huynh and Osmundson 2004, 2007), we can think of each sensor as having a “spin”, \( s \), where \( s = \pm 1 \). Two sensors are said to be interoperable if they both have only \( (+1) \)–spins. Let \( p_s \) be the probability (assumed constant) that a sensor has a \( (+1) \)–spin. The number of \( (+1) \)–spin sensors then follows a binomial distribution with parameters \( p_s \) and \( N \); the probability that \( k \) sensors are interoperable is then given by 
\[
P(k) = \binom{N}{k} p_s^k (1-p_s)^{N-k}.
\]

The interoperability of the network, denoted by \( \chi_I \), is defined as 
\[
\chi_I = \sum_{k=0}^{N} kP(k).
\]
A simple computation then leads to 
\[
\chi_I = p_s (N-1) \quad \text{or} \quad \chi_I = p_o p_d (N-1).
\]
\( \chi_I \) is thus the mean number of interoperable sensors.

The state of a sensor is characterized by its degree and its spin. A sensor is said to be in state 1, denoted by \( \xi_{i+} \), if \( \ell \geq 1 \) and \( s = +1 \). It is in state 2, denoted by either \( \xi_{i-} \) or \( \xi_{0\ell1} \), if either \( \ell \geq 1 \) and \( s = -1 \) or \( \ell = 0 \) and \( s = \pm 1 \). In this case, the probability that a sensor is in state 1 is 
\[
P(\xi_{i+}) = \left[ 1-(1-p_c)^\ell \right] p_s,
\]
which, by virtue of \( \chi_o = p_c (N-1) \) and \( \chi_I = p_s (N-1) \), can be written as 
\[
\pi_1 = P(\xi_{i+}) = \left[ 1-(1-\chi_o/\ell N) \right]^N \chi_I/\ell N.
\]
If \( N \) is known, any property which can be expressed in terms of \( p_c \) and \( p_s \) can also be expressed in terms of \( \chi_o \) and \( \chi_I \).

The number of sensors in state 1, denoted by \( X_I \), takes the values of \( 0, 1, 2, \ldots, N \) and admits a binomial distribution with parameters \( N \) and parameter \( \pi_1 \). The average number of interoperable nodes \( \bar{K} \) is then 
\[
\bar{K} = E(X_I) = \pi_1 N, \quad \text{or} \quad \bar{K} = E(X_I) = \left[ 1-(1-\chi_o/\ell N) \right]^N \chi_I/\ell N.
\]
In the \( N \to \infty \) limit, 
\[
E(X_I) = \left[ 1-(1-\chi_o/\ell N) \right]^N \chi_I/\ell N \to \left( 1-e^{-\chi_o/\ell N} \right) \chi_I.
\]

Given the size of the network and the probability of discovery and the probability of communication between two sensors, the complexity and interoperability of the network can be determined. The mean number of the sensors in state 1 can then be readily obtained.

### Distributed Sensor Fusion Problem

The binary hypothesis distributed fusion problem is one in which sensors in a network of \( N \) sensors that observe a common phenomenon (e.g., a space object, a threat, etc.), pass their observations (measurements) among themselves, and independently process all the observations produces a binary output — either the phenomenon is present or absent. For simplicity, the local decision rules are assumed to be identical, and all sensors are assumed to have the same probability of detection, \( P_D \), and the same probability of false-alarm, \( P_F \). Let \( C_F \) denote the cost
of making a false-alarm decision and $C_D$ the cost of making a correct decision. In this work, we invoke the K-out-of-N fusion rule, for which the optimal value of $K$, $K_{opt}$, is given by (Varshney 1996)

$$K_{opt} = \begin{cases} \lceil K^* \rceil & \text{if } K^* \geq 0 \\ 0, & \text{otherwise,} \end{cases}$$

where $\lceil \cdot \rceil$ denotes the standard ceiling function, and

$$K^* = \frac{\ln \left( \frac{C_F}{C_D} \frac{1 - p_F}{1 - p_D} \right)^N}{\ln \left( \frac{p_D}{p_F} \right)}.$$  \hfill (2)

**Sustainability Analysis**

Sustainability of a sensor network depends on the resilience of the network in the face of the dynamics of the environment. In (Huynh and Tran 2007), assessing the sustainability of an ad hoc sensor network means determining impacts of the network complexity and interoperability on the distributed sensor fusion performance of the ad hoc sensor network in the presence of forces of change. In their work the ad hoc sensor network is treated as an ecosystem with its complexity and interoperability implicitly built-in. The sustainability of the ad hoc network is then assessed; that is, the critical connectivity for which the network fails to perform according to a fusion rule is determined. The sustainability analysis uses the so-called sustainability index (Brown and Ulgiati 1997), a quantitative measure used in ecologically conscious process systems engineering (Bakshi 2000), and, in so doing, invokes the concept of ‘emergy’.

By ‘emergy’ (i.e., ‘embodied energy’) it is meant the energy used directly or indirectly to make a product or service (Bakshi 2000). It has been used by systems ecologists for analyzing, assessing, and modeling ecological systems. Emergy-based metrics may be used to assess the economic and ecological feasibility and sustainability of processes (Bakshi 2000). Brown and Ulgiati (1997), in their work on monitoring economies and technology toward environmentally sound innovation, formulate a quantitative sustainability index (SI) as a ratio of the emergy yield ratio (EYR) to the environmental loading ratio (ELR). The emergy yield ratio (EYR) can be considered as the emergetic return on investment. The ELR is an indicator of the stress on the local environment. The sustainability index reflects a desire to have a higher emergy yield per unit of environmental loading.

![Figure 3 – Emergy flow diagram.](image)

In the parlance of a sustainable ecosystem, the sensor network plays the role of the ecosystem. In Figure 3, the fusion process requires the emergy $R$ to prosecute the objects (targets), and the emergy $Y$ is the unity function of $R$ in this case. The emergy $F$ is the unity function of the required optimal number of sensors for successful fusion.
Metrics used in economic analysis can be defined to determine the environmental “loading” (in this case, effects on or perturbations to the network) and the sustainability of sensor network in performing its task — providing the BMC2 accurate estimates of the target state. The net emergy associated with the target space is defined as \( Y - F \) (Odum 1996). For any sensor network to be ‘emergetically operational’, the net emergy must be positive. That is, the network must provide more emergy than the emergy needed for fusion success. The so-called emergy yield ratio,

\[ \text{EYR} = \frac{Y}{F}, \]

is the emergent return on network performance.

Following (Brown & Ulgiati 1997) they define emergy-based metrics to characterize the network effects (loading) and sustainability of the network. The network “loading” ratio \( ELR \) is unity in this case, as it is the ratio of its output to itself. In this case, the sustainability index is

\[ SI := \frac{EYR}{ELR} = EYR. \]

Determining the \( ELR \) and SI requires information about the emergy flow from the network and object (target) space. The complexity and interoperability are now related to emergy ‘flow’. In this case, \( \bar{Y} \) represents the expected value of the number of sensors in state 1, and \( F \) the optimal number of sensors required by the fusion rule. As in (Bakhi 2000), they express \( \bar{Y} \) and \( F \) as \( \bar{Y} = \bar{\chi}_1 \) and \( F = \tau K^* \), respectively, where \( \tau \) (mJ/sensor) is the so-called transformity. The sustainability index then, by virtue of (1), becomes

\[ SI = \frac{(1 - e^{-\bar{\chi}_1})}{K^*} \left\{ \frac{1}{\bar{\chi}_1} \right\}. \]

(3)

For the network to be able to sustain its performance, it is required that \( SI \geq 1 \), which implies that the critical probability of connection, \( \bar{p}_c \), below which the network would fail to perform, is given, by virtue of (2), by

\[ \bar{p}_c = \frac{1}{N} \ln \left\{ \frac{1}{\left( 1 - \frac{K^*}{\bar{\chi}_1} \right)} \right\}, \]

(4)

provided that \( \frac{p_s}{N} > \frac{K^*}{N} \). For a large sized sensor network, if an environmental perturbation causes the connectivity measure, \( \bar{\chi}_0 \), to fall below the critical value of \( \bar{\chi}_0 = \bar{p}_c N \), while the interoperability measure \( \chi_1 \) exceeds its critical value of \( \bar{\chi}_1 = K^* \), then the performance of the network cannot be sustained.

**Architecting for Sustainable Delivery of Value**

As Figure 2 depicts, architecting for sustainable delivery of value involves concept and form. It is from these two notions of concept and form that we discuss ideas of architecting for sustainable delivery of value.

Refer to Figure 4. The function to be executed by the sensor network is ‘provide the estimated target state’. A concept or an idea in the example at hand consists of a large ad hoc network of sensors of variable size and, as the principle of operation, distributed sensor fusion performed by the sensor network; the network connectivity is affected by the ability of the
sensors to discover and communicate with each other, and the network interoperability is determined by fusion algorithms and fusion rules implemented at the sensors and by the semantics and syntax compatibility of the participating sensors. The form is a network (arrangement) of sensors (objects). The relationships among the sensors are indicated by the sensors being connected in an *ad hoc* topology and communicating with each other via wireless communications channels of sufficient capacity. The interoperability among the sensors is realized by sensors having sufficient power, adequate bandwidth, satisfactory computing power, storage capability, etc.

<table>
<thead>
<tr>
<th>Function</th>
<th>Concept</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide target state</td>
<td>• <em>ad hoc</em> network of sensors</td>
<td><em>Abstraction of form:</em></td>
</tr>
<tr>
<td></td>
<td>• Large, varying network size</td>
<td>• Network</td>
</tr>
<tr>
<td></td>
<td><em>Principle of operation:</em></td>
<td>• Sensors</td>
</tr>
<tr>
<td></td>
<td>• Distributed sensor fusion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Connectivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Discovery</td>
<td><em>Relationships:</em></td>
</tr>
<tr>
<td></td>
<td>• Connection</td>
<td>• <em>ad hoc</em> topology</td>
</tr>
<tr>
<td></td>
<td>• Interoperability</td>
<td>• Connectivity</td>
</tr>
<tr>
<td></td>
<td>• Fusion algorithms</td>
<td>• Wireless communications</td>
</tr>
<tr>
<td></td>
<td>• Fusion rule</td>
<td>• Capacity</td>
</tr>
<tr>
<td></td>
<td>• Semantics and syntax compatibility</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 4. Requirements**

To establish the requirements for architecting a sensor network for sustainable delivery of the estimated target state, we now tie the results of the sustainability analysis of *ad hoc* sensor networks to the elements in Figure 4. Recall that value is the target state, which consists of the missile type, its position and velocity and their associated uncertainty. The accuracy of these parameters (constituting the target state) depends on the sensor network distributed fusion performance. From the sustainability analysis, for the sensor network to be able to sustain its performance, it is required that

\[ S_I \geq 1, \]

which implies that the critical probability of connection, \( p_c \), below which the network would fail to perform, is given by (4).

The *ad hoc* topology of the sensor network (assumed large) implies that the size of the sensor network \( N \) can change. By virtue of (2), \( K^* \) changes as \( N \) changes. From the sustainability analysis, as \( N \) changes, for the sensor network to be able to sustain its performance, it is required that, while \( \chi_I \) exceeds its critical value of

\[
\bar{\chi}_1 = K^*,
\]

\[
\chi_0 \geq \ln \left( \frac{1}{1 - \frac{K^*}{\bar{\chi}_1}} \right).
\]
Thus, as the network size $N$ can change in real time, for the *ad hoc* sensor network to be able to sustain its delivery of value to the BMC2 component of the missile defense system, the requirements in (5) and (6) must be levied, along with others, on the design of the network architecture.

**Conclusion**

In this paper, we describe a general methodology to derive requirements on architecting complex systems to provide sustainable delivery of value. The methodology involves the system architecture paradigm espoused in (Crawley and Simmons 2006), sustainability analysis such as the analysis discussed in (Huynh and Tran 2007), and the derivation of the requirements. The methodology is described in concrete terms as it is applied to binary hypothesis distributed sensor fusion in an *ad hoc* sensor network, which is required to provide sustainable delivery information for use within the context of a missile defense system. The *ad hoc* sensor network is modeled as a random network. A simple fusion rule is employed. The *ad hoc* sensor fusion network is amenable to a simple emery flow diagram. Bounds are then established on the network connectivity and interoperability measures. This work demonstrates a methodology to enable defining requirements for architecting a network for sustainable delivery of value.

As future work, this methodology will be extended to complex networks which are modeled not as random networks and for which the corresponding emery flow diagrams are complex.

**References**


**Biographies**

**Thomas V. Huynh** obtained simultaneously a B.S. in Chemical Engineering and a B.A. in Applied Mathematics from UC Berkeley and an M.S. and a Ph.D. in Physics from UCLA. He is an associate professor of systems engineering at the Naval Postgraduate School in Monterey, CA. His research interests include uncertainty management in systems engineering, complex systems and complexity theory, system scaling, simulation-based acquisition, and system-of-systems engineering methodology. Prior to joining the Naval Postgraduate School in 2003, he was a Fellow at the Lockheed Martin Advanced Technology Center in Palo Alto and Sunnyvale, CA, where he engaged in research in computer network performance, computer timing control, bandwidth allocation, heuristic algorithms, nonlinear estimation, perturbation theory, differential equations, and optimization. While he spent 23 years in the aerospace industry, he was also teaching part-time in the departments of Physics and Mathematics at San Jose State University. Dr. Huynh is a member of INCOSE.

**John S. Osmundson** received a B.S. in physics from Stanford University and a Ph.D. in physics from the University of Maryland. He is an associate professor with a joint appointment in the Systems Engineering and Information Sciences Departments at the Naval Postgraduate School in Monterey, CA. His research interest is applying systems engineering and computer modeling and simulation methodologies to the development of system architectures, performance models, and system trades of time-critical information systems. Prior to joining the Naval Postgraduate School in 1995, Dr. Osmundson worked for 23 years at Lockheed Missiles and Space Company (now Lockheed Martin Space Division) in Sunnyvale and Palo Alto, CA, as a systems engineer, systems engineering manager, and manager of advanced studies. Dr. Osmundson is a member of INCOSE.