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SoS Explorer Application with Fuzzy-Genetic Algorithms to Assess an Enterprise Architecture – A Healthcare Case Study

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Abstract

Kevin Dooley (1997), defined Complex Adaptive System (CAS) as a group of semi-autonomous agents who interact in interdependent ways to produce system-wide patterns, such that those patterns then influence behavior of the agents. A healthcare system is considered as a Complex Adaptive System of system (SoS) with agents composed of strategies, people, process, and technology. Healthcare systems are fragmented with independent systems and information. The enterprise architecture (EA) aims to address these fragmentations by creating boundaries around the business strategy and key performance attributes that drive integration across multiple systems of processes, people, and technology. This paper uses a SoS Explorer to select an optimal architecture that provide the necessary capabilities to meet key performance attributes (KPAs) in a dynamic, complex healthcare business environment. The SoS Explorer produced an optimal meta-architecture where all but two systems (disease and facility processes) participated with many of the systems having at least four interfaces. The healthcare meta-architecture produced in this study is not a solution to address the challenges of the healthcare enterprise architecture but provides insight on the areas – systems, capabilities, characteristics, and interfaces – to pay attention to where agility is an important attribute and not to be severely compromised.

Keywords: enterprise architecture; genetic algorithms; system-of-systems; Meta-Architectures; healthcare

1. Introduction

Kevin Dooley [1] defined Complex Adaptive System (CAS) as a group of semi-autonomous agents who interact in interdependent ways to produce system-wide patterns, such that those patterns then influence behavior of the agents.

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A healthcare system which recognized to have 20 industry stakeholders [2], is considered as a Complex Adaptive System of system (SoS) with agents composed of strategies, people, process, and technology [3]–[5]. A hospital has multiple types of branches, professions and varying work conditions across clinical environments such as pharmacy, nuclear medicine, radiotherapy, and blood transfusion. All of these rely heavily on automation and information technology to communicate the thread of patient information and dictate the patient's treatment journey. The day-to-day conditions demand adaptation and flexibility to maintain control over a large variety of patients, flow of information, the complexity of their symptoms and the vulnerabilities of the healthcare system. Many successful, valuable efforts to improve safety and quality of healthcare have been inspired by other industries such as aviation and nuclear, yet the complex diversity, intimacy, and sensitivity of healthcare cannot be compared to these other industries [6].

Today, healthcare systems are fragmented. A quarter of the hospitals and half of the nursery homes in the United States are independent and biotechnologies are provided by thousands of small firms [7]. The enterprise architecture (EA) aims to address the fragmentations by creating boundaries around the business strategy and drive information integration across multiple systems of processes, people, and technology [8]–[10]. Since the competitive landscape changes rapidly over time, companies are forced to change their strategic objectives which affects organizational structure, its culture, and the technologies used. These changes become more frequent in healthcare rendering the need for an agile enterprise architecture [11] [12]. This paper proposes the application of the SoS Explorer utilizing computational intelligence to generate the best possible enterprise architecture that provide the necessary capabilities to meet key performance attributes (KPAs).

1.1. Business Agility

Companies' business systems must be flexible and adaptive to cater changing business requirements and strategies. Business agility is a key attribute to ensure the continuation of company function and performance by managing the necessary changes to adapt to both the market and technological changes [13], [14]. Alberts and Hayes [15] believe the key dimensions of agility have the following six attributes:

1. Robustness: the ability to maintain effectiveness across a range of tasks, situations, and conditions.
2. Resilience: the ability to recover from or adjust to misfortune, damage, or a destabilizing perturbation in the environment.
3. Responsiveness: the ability to react to a change in the environment in a timely manner.
4. Flexibility: the ability to employ multiple ways to succeed and the capacity to move seamless between them.
5. Innovation: the ability to do new things and the ability to do old things in new ways; and
6. Adaption: the ability to change work processes and the ability to change the organization.

Several researchers consider responsiveness as a key attribute of agility [16]–[18]. The theme of agility is the capability to respond and adapt to changes in a way to meet strategic goals. In the selection of an optimal enterprise or business architecture, this paper proposes to use the following KPAs: Cycle Performance, Robustness, Flexibility, and Scalability where cycle performance is a measure of responsiveness.

1.2. Architecture Framework

The TOGAF ADM (The Open Group Architecture Framework Architecture Development Method) is the selected architecture framework due to its recognition as a global best practice for enterprise architecture and provides flexibility and balance between IT efficiency and change in business strategy [19]. TOGAF is used by businesses to drive business goals and requirements into business infrastructures with process & tool solutions. Using the TOGAF ADM to define the components of the system architecture, the initial step is to define the scope of the problem and need which is the Preliminary Phase and Architecture Vision. The vision of the healthcare architecture is to provide a system solution that ensures high healthcare service quality, increased patient satisfaction, and reduced deaths and accidents.

Fig. 1 is a TOGAF model of the healthcare system from the works of Haghighathoseini, et. al. [20], where each layer – business, application, data, and technology – is linked with informational, behavioral, and structural aspects.

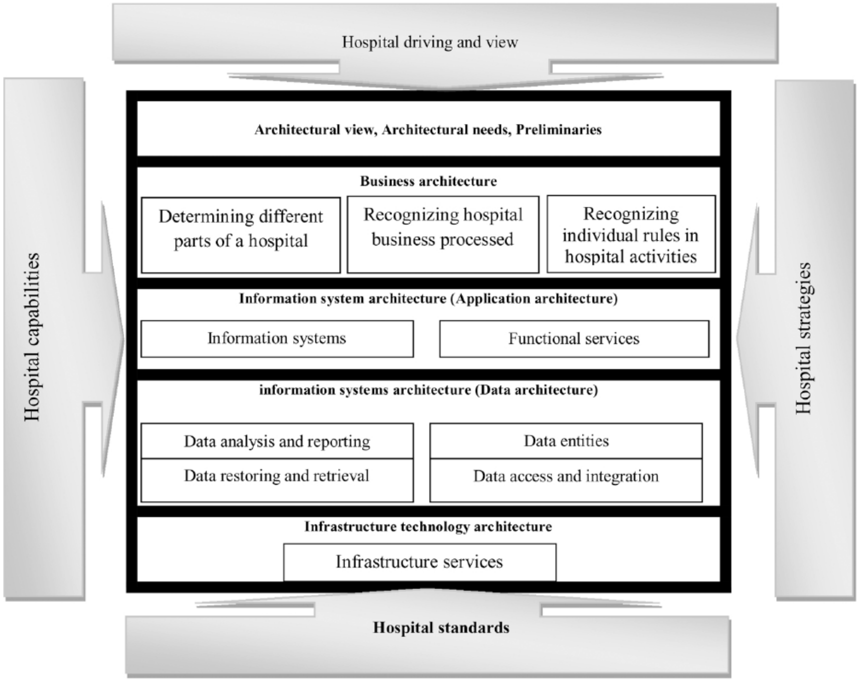

Fig. 1: TOGAF model of healthcare by Haghighathoseini, et. al. [16]

The business objects such as hospital services are not linked to data directly, but linked through behaviors known as services or business scenarios where they are usually operated in the application level. This generates an interface between the business and application layers. Data objects such as a medical record are represented at the lower technology layer as artifacts. The next section provides a methodology to consider the variables in the healthcare TOGAF model and produce an architecture that aligns the objectives of the healthcare system.

2. Methodology

Architecture evolution and selection is made using SoS Explorer which is a multi-objective optimization tool utilizing a fuzzy intelligent learning architecture to assess and optimize the architecture against Key Performance Attributes (KPAs) [21]. The SoS Explorer was developed as part of "Flexible Intelligent Learning Architectures for System of Systems (FILA-SoS) research project of the Systems Engineering Research Center (SERC) and used on several applications [22]–[26]. The goal for using the SoS Explorer is to develop, improve, and realign the current enterprise architecture to meet ambitious strategies aligned to key capabilities and KPAs.

We perform the in the SoS Explorer the set of systems and interfaces ae defined by a vector called a chromosome by the evolutionary algorithms used to optimize the architecture. The functions **S** and **I** extract the system and interface information from a chromosome and are defined as:

$$\mathbf{S}(X,i) = \begin{cases} 1 & \text{if the } i^{th} \text{ system is selected in } X \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

and

$$\mathbf{I}(X,i,j) = \begin{cases} 1 & \text{if the } i^{th} \text{ and } j^{th} \text{ systems have an interface in } X \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where X is the chromosome.

The SoS Explorer variables are:

OC The overall capability or goal of the SoS achieved from the system-level capabilities of selected systems.
C Characteristics matrix Ns, X, Nc composed of each system and its properties represented by real numbers
C' Capability matrix Ns, X, Nc' is composed of each system represented by Boolean values and its elements of functionality
Ns Number of systems
Nc Number of characteristics
Nc' Number of capabilities
I Boolean interface information between systems

2.1. Identifying SoS Capability

The individual systems such as IT systems, roles, facilities, and processes come together to meet the overall SoS capability. Each of the SoS system-level components have their own capabilities as required by the SoS and any loss of these capabilities have implications on certain KPAs. A highly capable healthcare system integrates data, workflow, and functions with the aim for high healthcare service quality, increased patient satisfaction, and reduced deaths and accidents (Fig. 2). For example, when a patient is admitted in to the Emergency Room (ER), each system ensures that data (i.e. registration, medical records, etc.) are carried by various roles through various processes and IT systems to ensure the patient receives the right priority for medical attention, the right doctor, and contains information (i.e. medical history) to ensure the patient receives good treatment and a plan for exit. Therefore, each system ensures the following capabilities: data (i.e. medical records) integration, workflow (i.e. across processes and IT) integration, and functional (i.e. administration, Oncology, etc.) integration.

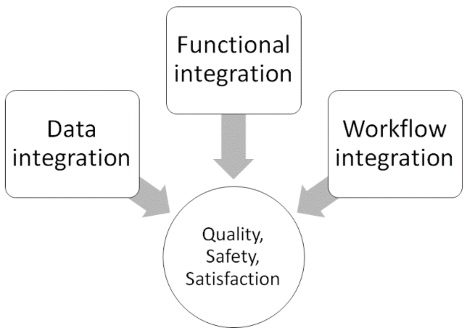

Fig. 2: Healthcare SoS Capabilities

2.2. Identifying SoS Key Performance Attributes

Agility is key to success of the enterprise architecture and the key performance attributes for a healthcare SoS are:

1. Robustness: the ability to maintain effectiveness without failure and is modeled as interface redundancy:

$$\text{Robustness}(X) = -Ns + \sum_{i=1}^{Ns} \mathbf{S}(X,i) \sum_{j=1}^{Ns} \mathbf{S}(X,j)\mathbf{I}(X,i,j) \tag{3}$$

2. Cycle-time: the average performance time required to move information by a system component:

$$\text{Cycle Performance}(X,C) = \frac{\sum_{i=1}^{Ns} \mathbf{S}(X,i) C_{cycle\,performance}, i}{\sum_{i=1}^{Ns} \mathbf{S}(X,i)} \tag{4}$$

3. Flexibility: the ability to employ multiple ways to succeed and the capacity to move seamless between them which is calculated by subtracting the required capabilities from the total capabilities provided by the corresponding SoS meta architecture:

$$\text{Flexibility}(X, C') = -N_{c'} + \sum_{i=1}^{Ns} \mathbf{S}(X, i) \sum_{j=1}^{N_{c'}} C'_{ji} \tag{5}$$

4. Scalability: the ability to adapt to additions or deductions of facilities, processes and/or technologies:

$$\text{Scalability}(X, C) = \frac{\sum_{i=1}^{Ns} \mathbf{S}(X, i) C_{scalability_{,i}}}{\sum_{j=1}^{N_s} \mathbf{S}(X, i)} \tag{6}$$

5. Adaptability: the ability of a system to restructure itself in the face of business changes. This attribute is calculated using the fuzzy assessor [22] where the characteristic contributing to this attribute is the ability to be modular or restructure itself with minimal effort without disrupting the capabilities.

2.3. Identifying healthcare systems and characteristics

Haghighathoseini, et al. [20] provided a model on an Iranian hospital which loosely identifies the systems and its characteristics in Table 1. There are a total of 20 systems and the 7 characteristics are: *cycle-time, scalability, modularity, data interoperability, benefit to patient, reusability, and decision making velocity*.

Table 1: Hospital system characteristics

	Cycle time	Scalability	Modularity	Decision Making Velocity	Benefit to patient	Reusability/Standardization	Data Interoperability
Administrative Process	1	9	8	2	1	1	1
Heath Providing Process	1	4	4	6	1	1	1
Registration Process	1	2	9	1	0	1	1
Patient Management Process	1	5	5	8	1	1	1
Facility Process	0	1	7	3	0	0	0
Disease Process	1	2	7	7	0	0	1
Public Health Warn Process	1	8	9	9	1	1	1
Doctor Selection Process	1	8	7	6	1	0	1
Intensive Care Ward	1	4	4	9	1	1	1
Hospital Clinics	1	7	6	5	1	1	1
Laboratories	1	5	7	2	1	1	1
Pharmacy	1	8	7	2	1	0	1
Headquarter Unit	1	3	2	3	1	0	1
Adminstrative units	1	7	3	4	1	1	1
Medical Doc Information System	1	8	3	8	1	1	1
Admission Information System	1	8	6	3	1	0	1
Hospital Ward Information System	1	4	4	8	1	1	1
Surgery Information System	1	4	3	8	1	1	1
Laboratory Information System	1	3	4	8	1	1	1
Pharmacy Information System	1	5	5	6	1	1	1

2.4. Identifying system interfaces

The systems constituting the SoS are individual entities performing their own functions until they interface and connect with each other. The emergent behavior of the SoS is only because of the coming together of individual systems and hence interfaces between the individual systems play an important role in the SoS exhibiting its capability. For the healthcare SoS, feasible interfaces between the systems are identified.

2.5. Meta-Architecture Generation with Fuzzy-Genetic Algorithm

The purpose of the SoS Explorer application and the fuzzy-genetic algorithm is to utilize the inputs of system components and its capabilities, interfaces, and the system characteristics to generate, evaluate and optimize meta-architectures. The process of the SoS Explorer is shown in Fig. 3.

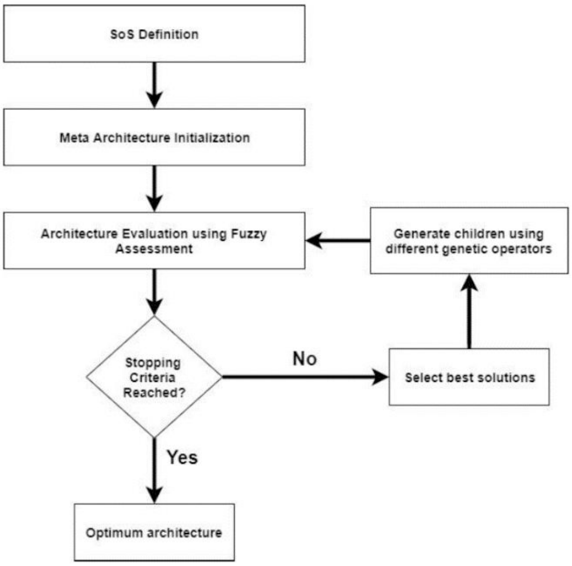

Fig. 3: SoS Process Flowchart

The genetic algorithm where in this case we will use a Non-dominated Sorting Genetic Algorithm III, will search the space of candidate architectures and generate populations of "optimal" fitness based on key performance attributes with the objective to maximize the effectiveness of the healthcare architecture. After defining the SoS, a set of chromosomes representing the meta architecture can be randomly generated with size $n+(n^2-n)/2$ where n is the number of systems assuming that the interfaces are bi-directional. The five key performance attribute crisp values are input into a fuzzy inference system (FIS) in MATLAB© which are integrated into the fitness function of the genetic algorithm. The output of the algorithm is the overall KPA value of the SoS architecture based on the defined membership functions and fuzzy rules. This inference system acts as the assessment for the generated chromosomes. The best solutions from the iterations are used to generate children using different genetic operators. These chromosomes are once again evaluated using FIS. This process is repeated until the stopping criteria is reached, which is the number of iterations for the genetic algorithm and the best solution will be the final meta architecture for the SoS.

3. Results

The SoS Explorer produced an optimal meta-architecture, as a result of the genetic algorithm optimization, shown in Fig. 4 with results of KPA values and overall score shown in Table 2. The systems in the meta-architecture shown in filled circles represent an active system with lines between circles as bi-directional interfaces. All but two systems (disease and facility processes) participated with many of the systems having at least four interfaces. The reason for not including the disease and facility processes is their inability to integrate data and workflow in the architecture. However, the IT systems are utilized to manually manage data for disease and facilities and are integrated into the overall architecture, but there is an opportunity to explore ways to facilitate the integration with automation.

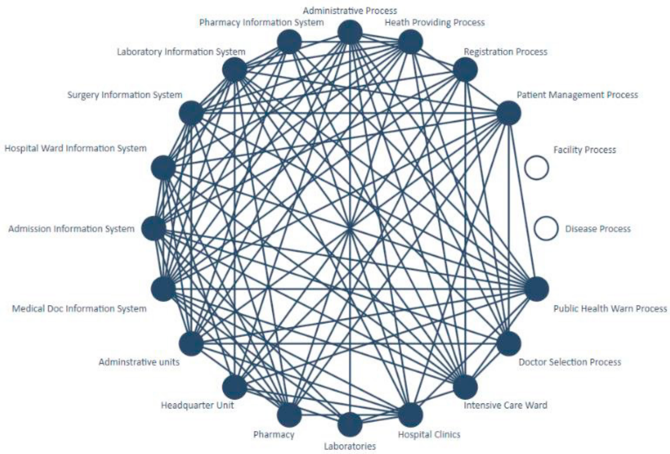

Fig. 4: Healthcare SoS Meta-Architecture

Table 2: Meta-Architecture Results

Algorithm	NSGA-III
Division	3
Probability of mutation	0.005
Probability of crossover	1
Optimal Architecture	
Scalability	100
Robustness	100
Flexibility	97.5
Cycle Performance	58.02
Overall	50

4. Conclusion and Future Work

The design and assessment of an enterprise architecture is a complex and extremely expensive task. This paper offers an affordable example of using computational intelligence approaches to assess a common, yet complex enterprise architecture of the healthcare system with the objective to provide high healthcare service quality, increased patient satisfaction, and reduced deaths and accidents. To meet the objective is to have an interoperable healthcare processes, services, and systems where agility is a key attribute. The SoS Explorer application was used with fuzzy logic, genetic algorithms, and mathematical programming to generate, assess, and optimize meta-architectures against key performance attributes of agility.

The healthcare meta-architecture produced in this study is not a solution to address the challenges of the healthcare enterprise architecture but provides insight on the areas – systems, capabilities, characteristics, and interfaces – to pay attention to where agility is an important attribute and not to be severely compromised. The results provide possibilities for future work such as exploring accurate mathematical modeling to best fit the problem scheme and evaluating the validity of the meta-architecture model against real world enterprise architectures.

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