

# A Systems Approach to Information Technology (IT) Infrastructure Design for Utility Management Automation Systems

A. Fereidunian\*, H. Lesani\*, C. Lucas\*, M. Lehtonen\*\* and M. M. Nordman\*\*

**Abstract:** Almost all of electric utility companies are planning to improve their management automation system, in order to meet the changing requirements of new liberalized energy market and to benefit from the innovations in information and communication technology (ICT or IT). Architectural design of the utility management automation (UMA) systems for their IT-enabling requires proper selection of IT choices for UMA system, which leads to multi-criteria decision-makings (MCDM). In response to this need, this paper presents a model-based architectural design-decision methodology. The system design problem is formulated first; then, the proposed design method is introduced, and implemented to one of the UMA functions—feeder reconfiguration function (FRF)—for a test distribution system. The results of the implementation are depicted, and comparatively discussed. The paper is concluded by going beyond the results and fair generalization of the discussed results; finally, the future under-study or under-review works are declared.

**Keywords:** Architectural Design, Distribution Automation (DA), Energy Restoration, Feeder Reconfiguration Function (FRF), IT Infrastructure, Multi-Criteria Decision-Making (MCDM), Power Distribution Systems, Utility Management Automation (UMA), Wymorian Scoring Functions.

## 1 Introduction

### 1.1 IT in Power

Electric power systems are the most important energy conveyors in modern civil life. An energy utility company –or briefly, a utility– is an enterprise that delivers electric energy to the end consumers; most recently, minor energy generations are distributed within the distribution system (i.e. DG). Due to the importance of service continuity for the electricity distribution systems (DS), they shall be maintained in a perfectly reliable manner. Therefore, the distribution networks need a fast recovery system to react in contingency situations, known as utility management automation (UMA) system.

Operation and management of the power system needs the ability to deal with enormous amount of data gathered from the field by various sorts of sensors and

measurement devices, today known as intelligent electronic devices (IEDs). The idea of computer-based energy management systems application in electric utility companies was introduced in early 1960s and gradually was utilized in electric power system control centers.

Thomas E. Dy Liacco -who is often referred as the father of modern energy control centers- introduced basic structures of power control systems and systems for interpreting SCADA (supervisory control and data acquisition) alarms in power systems to improve their reliability [1,2]. Improvements in information technology and need to innovative data management techniques have turned distribution automation (DA) to a hot research topic in power systems engineering field. Like many developing countries, Iranian electric utility companies are improving their IT systems to wheel their businesses –technically and financially– in the newly restructuring power system [4,5]. Of those companies, Tehran Regional Electric Company (TREC) is incrementally developing its UMA system; whereas, it has developed distributed systems for event recording (ENOX), a central customer information system/customer relationship management (CIS/CRM, called there: 121 system); and it is now developing IT-

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based maintenance management systems (called PM), geographical information systems (GIS) and distribution SCADA system, as well as some already-working pilot remote monitoring and switching projects.

Approximately over US\$10 trillion is annually spent on IT-enabling projects for different enterprises around the world [6]; although great improvements seen, however, more than half of IT (or ICT<sup>1</sup>) projects fail to meet functional requirements, cost estimates, or schedule estimates [7]. IT strategies should be in line with the whole enterprise strategies, to gain successful IT-enabling projects; therefore, fair architectural design of IT infrastructures of enterprises can minimize and mitigate the risk of IT projects failure [3].

Different variants of information systems (IS) have been introduced to automate offices and industries; as a result, selection of "right" choices of IT solutions is rather a complex multi-criteria decision-making problem [3,8,9]. Systems architectures and designers of energy utilities make decisions in design procedure of energy system and utility management automation systems, based on their expertise, ad hoc methods and heuristic rules. Often, however, there is not only any strong evidence on optimality of their choices they make, but also, "they are open to serious errors and biased decisions because they use "rules of thumb" or heuristics for decision making" ([10], as quoted in [11]). This reported deficiency in fair architectural and engineering decision making methods application have led one of the leading management journals –Omega, The International Journal of Management Science, of Elsevier– to devote its latest (at this time) issue to "Multiple criteria decision making for engineering" (Omega, Vol. 36, 2008).

## 1.2 Literature review

A considerable research has been performed on the technical side of utility IT system development; however, less attention has been paid to provide the utility company decision-makers with systematic methods for proper selection of their IT facilities, which meet performance and cost requirements of the utility IT system. Furthermore, the new liberalized power system market has reduced the profit margin of electric utility companies. Consequently, the utilities should ensure that their decisions are optimum, or at least "good enough" [12], to cope with the decreased economic safety margins and the new challenging competitive environment.

Almost the largest portion of the papers on IT in power systems literature report practical implementations of some IT in distribution system and DA functions, discussing their advantages (mostly) and disadvantages, as well as hinting some experienced pitfalls and

drawbacks of DA [13-21]; moreover, the other popular topic in DA and IT in power research papers includes development reports of software (like: object oriented, agent oriented, component based, unified modeling language (UML)), hardware and communication techniques [21-31], as well as special algorithms and software, developed for DA functions [32-36].

Marihart [37] wrote an excellent comprehensive paper on various methods and media of power systems IT infrastructures; however, it was a qualitative description of the methods that was interesting enough, but no quantitative figure was given there. Design reports of DA sub-systems and components has been the subject of a great deal of papers presented in power systems literature [38-42], all of them focusing on the technical facet of electrical and information engineering issues; though some of them develop mathematical models, they, however, work within the electrical or information technology dilemma, not on its systems approach.

Another considerable category of research papers in IT in power and DA field devote their effort on theoretical evaluation (albeit, utilizing empirical data) of DA functions feasibility [24,43-50]. The latter category of the surveyed research papers, share the most common points with the approach taken in our manuscript. They have mostly calculated the costs and benefits of DA functions, and consequently by calculating the cost to benefit ratio (or subtract, in the case of homo-unit cost and benefit values), and then concluding a proposed methodology of DA feasibility study, or presenting empirically practical conclusions on the feasibility of a specific DA function, like restoration or loss reduction.

In the most of the feasibility study methods of DA function in literature, the financially benefits of DA function are calculated in terms of the money (or energy) gained by the implementation of those DA function, e.g. the re-gained energy not-supplied (ENS). However, since most of these papers are written to show the extent of feasibility and profitability of DA functions implementation, there exist still considerable needs for methods, considering the performance and other intangible (or quality) gains of DA implementations. More importantly, severe needs exist for the cost-performance tradeoff analysis methodologies, which are necessary parts of the architectural design phase of UMA and DA projects. Many tradeoff analysis methodologies are already developed in SE field [51-58], suitable to be applied to the above mentioned problems of tradeoff analysis.

## 1.3 This paper

Systems approach can be instrumental in aiding the power and information systems decision-makers in the above-mentioned methodological shortages for adopting the best possible IT solution for UMA systems; and this paper is aimed to participate in filling the gap for a SE

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<sup>1</sup> ICT is the European Union equivalent of the American IT -conveying the same meaning- "to recognize the convergence of traditional information technology and telecommunications, which were once seen as distinct areas." [3, p.3].

approach to IT-enabling electric utilities<sup>1</sup>. The purpose

**Table 1** Conceptual outline of this paper.

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of this paper is to present a design decision-model to aid the utility company enterprise architects and managers on their IT-based UMA system.

We have adopted the feeder reconfiguration function (FRF) of UMA as an implementation<sup>2</sup> case study; although another functions of UMA could be implemented, certain reasons led us to select FRF: FRF is a sub-sub-function of UMA (according to CIRED DA taxonomy [59]), which consists almost all of the above-mentioned sub-systems of the UMA system in a vertical manner: power distribution system, IT infrastructure, and people. Another reason is our personal interest in it, because of our previous practical and academic experience in FRF. Other characteristic of FRF – comparing to other UMA sub-systems like CIS/CRM<sup>3</sup> or AM<sup>4</sup>– is that there exist strong and long technical power engineering tradition of research and practice in literature; consequently, its performance measures can be defined and computed easier.

FRF can be defined as topology-change in distribution system, by closing or opening network switches. Feeder reconfiguration of DSs can be utilized for different operational goals like: loss reduction (i.e. to reduce the resistive  $R \cdot I^2$  line losses [33-35,60-64]), load balancing (i.e. to balance lines loadings  $S_j/S_{j\max}$  [33,34,65]), and service restoration (i.e. to restore the faulted network, and minimize the affected area after a fault [14-17,34,66,67-74]). The UMA-FRF system

which is designed in this paper as a case study stands for the latter goal of feeder reconfiguration, that is, *service restoration*.

This paper is the continuation and completion of the ideas presented in [73,74]. To the best of our knowledge, this research is the first implementation of the established –yet young<sup>5</sup> and important [75]– discipline of Systems Engineering (SE) methodology in power distribution automation (DA) systems, according to the Science Citation Index® and the IEEEExplore®.

Consequently, we might claim that one of the novelties (and contributions) of this research work lays in its very first stages, i.e. the problem definition stage; since – again, to the best of our knowledge, according to timely searches in various scientific databases<sup>6</sup>– we could not find similar research works in the literature, which share our approach to the architectural design of IT in power distribution engineering<sup>7</sup>. Introducing, defining, or formulating a new problem (or a new approach to an old problem, or even a new paradigm) could be very advantageous and important for scientific progress, as it inspires the other researchers to continue the work and improve the primitive solution, proposed by the first introducer of the problem [76-79]. A good example for the importance of introducing a new problem could be the introduction of FRF problem by Merlin and Back in 1975 [61] using a simple solution, and improved solutions of Shirmohammadi and Hong [62], Civanlar, Grainger, Yin and Lee [60], and Baran and Wu [63], continued by hundreds of papers presented on this topic. Shortly, the presented paper contributes to the scientific literature as follows: Apart from formulating a new problem in power systems engineering, the presented paper includes two sets of findings: firstly, the architectural design methodology as design problem formulation and a decision model; and secondly, some facts found when experiencing tradeoff analysis on the nature of the different design concepts in industrial IT systems. The first series of findings are general Systems Engineering issues, while the second series of findings are domain specific in the energy system IT application area.

The Wymorian FoMs and SFs [51] have been used in this paper to cope with two major problems face ahead; quantifying the quality requirements of the UMA system, and for tradeoff between contradicting multiple criteria of the decision-making problem for system

1 We pay the readers' kind attention to the following two different meanings of utility in this paper: first, as an enterprise that functions in public services, and second, as a mathematical function indicating the preferences or interests of players of a game, in game theory and decision-making literature. The exact intention of the word could be derived from the context.

2 As this paper has declared systems approach as its methodological base, thus the term "implementation" will mean in systems level, in this context.

3 CIS/CRM: customer information systems / customer relation management, the 121 system in TREC.

4 AM: asset management.

5 Compare 1995 of INCOSE establishment (about 22 years ago) for systems engineering to the more than a century of IEEE for electrical engineering.

6 As the reference list shows, our searches spans a vast diversity of scientific resources, from professional institution publications (like the IEEE, IET, CIGRE, CIRED, INCOSE and SIAM) to well-known research periodical journals publishing companies (like the Elsevier and the Taylor and Francis).

7 Surely, the doors are open to scientific criticism; thus the authors will definitely be grateful to the reviewers or readers who happen to find and introduce research works on systems engineering approach (this model-based, Wymorian approach) to power distribution systems automation design.

design. The rigorous mathematic, parametric and traceable nature of the presented design-decision method makes it possible for the utility policy-makers to affect the decision-making process by their preferences; and consequently, to investigate the effect of different policies on the decision made by the method, i.e. the final design concept.

In the presented paper, the above-mentioned design-decision model, the UMA design procedure and design concepts are introduced briefly; subsequently, the results of the modeling are presented, and finally a comparative discussion on the results regarding the design concepts is offered. Table 1 shows the conceptual outline of this paper.

## 2 Method

### 2.1 Systems approach

Formal presence of systems science may root back to the 1930s (or even earlier) –by the introduction of Cybernetic approach to the self-control systems– as a unifying theory of science, based on the notion that all of the purposeful sets of entities share common attributes, upon the works of von Bertalanffy [80,81].

This idea of unifying theory of systems science emerged through the works of designers –in various fields of architecture, computer and information systems, electrical engineering, civil engineering, linguistics, psychology, organizational management, environmental and urban planning– to this hypothesis that design projects in all fields share common methodologies and features; consequently, bearing the new fields of "general systems design theory" [81,82] and "systems engineering (SE)".

INCOSE<sup>1</sup> Handbook of SE, which itself defines SE as "Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems" [83], regards "Rocket locomotive; progenitor of main-line railway motive power" in 1829 as the first origin of SE as a discipline, however, launching the "British multi-disciplinary team to analyze the air defense system" in 1937, sounds more relevant.

The first academic degree-granting SE department was founded and chaired by A.W. Wymore –who established a complete framework for SE as an academic discipline– at the University of Arizona in early 1960s [51,84-86].

Though the SE task used to be performed by other engineering professionals with a wider knowledge and experience of their field, formal presence of the SE as a discipline in industry could be traced back to a general meeting hosted by General Dynamics Company in 1989, declaring "the apparent shortage of qualified engineers, those who could think in terms of a total system—rather than just a specific discipline—and could implement the systems engineering process.", and the latter meeting held by Boeing in 1990. They subsequently made consensus on forming the

NCOSE<sup>2</sup>, which officially changed its name to the INCOSE in 1995 [87]. By the internationally release and recognition of the ISO/IEC 15288 standard in 2002, "the discipline of systems engineering was formally recognized as a preferred mechanism to establish agreement for the creation of products and services to be traded between two enterprises - the acquirer and supplier" [83].

Nevertheless, the deficiency of systems approach still exists in engineering projects, as R.W. Lucky –the IEEE Fellow– regrettably declares: "academic prestige is based on expertise and reputation in narrow disciplines." [24]; yet, there is a considerable need for systems approach –a big picture view– to complex, large and adaptive systems development projects, like power systems and information systems. Lucky subsequently concludes: "In recent years, a number of well-known universities have begun new programs in systems engineering." [75].

### 2.2 The proposed methodology

This paper uses the Model-Based Tricotyledon Theory of A. W. Wymore [51] as a base for its presented design methodology, as it is shown in Fig. 1.

The model-based approach uses the figures of merit (FoMs) as measures for merit of the architectural design concepts, by which the system architect can gain a quantitative sense to evaluate and compare different design concepts. Figures of merit –that are also called evaluation measures, measures of effectiveness, attributes, performance measures, or metrics [54]– are almost always defined as statistically expected values, objectively (formally) or subjectively; objectively in the sense that the figure of merit is defined as the expected value of a random variable, or subjectively in the sense that the system architect might select and assert at the early stages of the design procedure [51]. Andrews et al. [88,89] have also used the Wymorian methodology to quantify the qualitative assessment of soil.

Wymorian standard scoring functions (SSFs) are used to grade the FoMs and to establish a unified scaling system for FoMs as:

$$SSF(L, B, S, FoM) = 1 / \left[ 1 + \left( \frac{B - L}{FoM - L} \right)^{2 \cdot S \cdot (B + FoM - 2 \cdot L)} \right] \quad (1)$$

where, L, B and S denote lower value of FoM, baseline (expected) value of FoM and slope of the SSF curve at the baseline point [51].

The system FoMs are classified into two categories of performance FoM and cost FoM, where performance FoM represents the merit for system functional requirements; while cost FoM represents the merit for system technology requirements, i.e. the merit of the design concepts for utilization of the resources. Both, system functional requirements and system technology

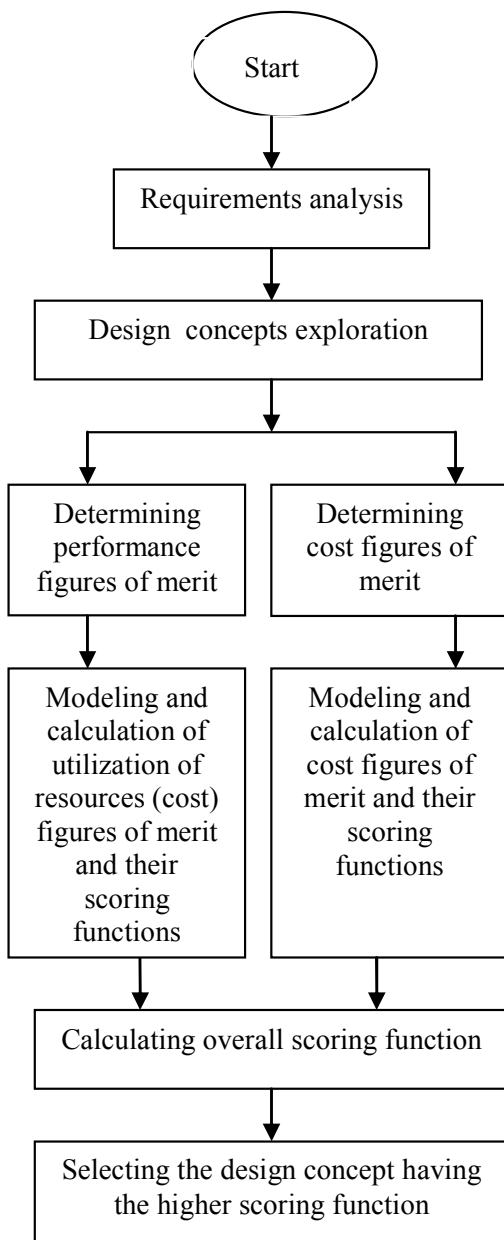
<sup>1</sup> INCOSE: International Council on Systems Engineering.

<sup>2</sup> NCOSE: National Council on Systems Engineering

requirements should have been explored and determined in the “system requirement analysis” phase of the system design procedure. The performance FoMs (PFoMs) and cost FoMs (CFoMs) are calculated as weighted summation of their relevant scoring functions, as follows in Eq.s (2) and (3):

$$PFoM = W_p^t \bullet PFoMSF \quad (2)$$

$$CFoM = W_c^t \bullet CFoMSF \quad (3)$$



**Fig. 1** UMA-FRF model-based system design decision methodology.

The performance FoM and cost FoM are combined together in overall FoM function, based on designer's (decision-maker's) preferences, by a weighting formulation, as shown in Eq. (4):

$$OFoM = W_o^t \bullet OFoMSF \quad (4)$$

where, P, C, O, FoM and SF denote: performance, cost, overall, figure of merit and scoring function, respectively; and the "t" superscript indicates the transposed of a vector or matrix. Bold symbols indicate matrices (or vector). Hence PFoM, CFoM and OFoM are performance, cost and overall figures of merit;  $W_p$ ,  $W_c$  and  $W_o$  indicate weighting vectors for performance, cost and overall; and PFoMSF, CFoMSF and OFoMSF delegate performance, cost and overall figures of merit scoring functions vectors, respectively. Equations (1)-(4) are taken from [51].

The finally achieved overall FoMs (OFoM) represent the overall FoM for each of the alternative design concepts, by which, the systems architect can make decision, and select the best design concept, according to the system requirements.

Weighted summation (linear) formulation for data or decision fusion is one of the possible choices at our disposal, out of many decision fusion formulations like: powered product fusion, sum-minus-product fusion, exponential fusion, certainty factor fusion and compromise (l-p norm) fusion [54,55]. In fact, the weighted summation fusion method is probably the oldest and the simplest one, which is backed to a letter from B. Franklin to J. Priestley in 1772 [55], however, using simple methods grants the users (and the readers of their works) the advantages of traceability and understandability. According to us, when a problem can be solved by a simple method –without losing preciseness and correctness– the simple method could be the first wise choice to solve the problem; and the more sophisticated method can be left for future research, for prospective incremental and gradual improvements in design and solution methodologies [78,79]. The weights are derived from interviews with the stakeholders of the system (customer, owner and user), since they shall be content with the finally designed system [55-58].

### 3 Implementation

#### 3.1 Top-level function definition (UMA-FRF)

In this paper, the feeder reconfiguration function (FRF) of utility management automation (UMA) system is considered as an example to be designed, in order to show the implementation of the proposed architectural design method.

The open/close status of switches in electricity distribution network determines the topology of the network. This topology-change can be utilized to achieve operational goals in utility management. The

feeder reconfiguration function of utility management automation system is used to perform this duty, in collaboration between hardware, software and bio-ware (human).

When a fault occurs in power distribution network, the protection relays must act in order to prevent the system collapse, which causes outage for some of the electric energy consumers. Complete recovery of the faulted network may take a considerable time, and the affected customers can not buy and use the electric energy from the network, during this outage time. The normally open switches in the network can be operated to minimize the affected area, and feed maximum connected customers. This, in turn, will improve the distribution system reliability, and reduce the undelivered energy. The goal of feeder reconfiguration function for restoration is to restore the faulted network, and minimize the affected area after a fault [14-17, 67-74].

### 3.2 Test system

The UMA-RFR system is architecturally designed here, however, to maintain the abstraction level of the results in the presented paper; the design methodology is implemented to the well-known test power distribution network of Fig. 2. It includes 16 switches and 13 line sections, introduced first by Civanlar et al. [60], which has been used as a benchmark in many distribution systems reconfiguration and restoration analyses [34,35,68-72]. The network parameters can be found in [60], as well as in [68-72].

### 3.3 Design concepts

As an architectural design project in systems level, this paper focuses its attention on the IT infrastructure for the UMA-FRF system which communication sub-system is a part of that. There are many available communication system design concepts, for instance, Marihart [37] introduces and classifies a fourteen-itemed list of communication methods for power systems. According to Marihart's recommendations [37], as well as Monenco Consulting Engineers' report [90] and personal engineering judgment, we consider Spread Spectrum, distribution line carrier (DLC), and Leased Line in this research paper as its three alternative design concepts.

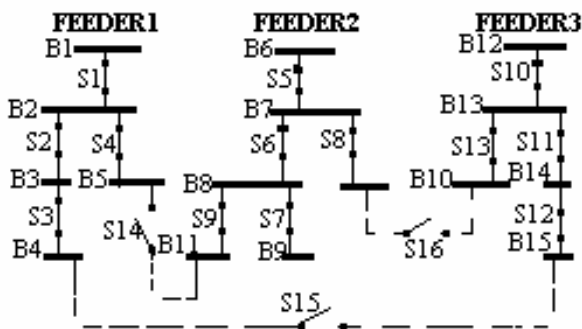


Fig. 2 Three Feeder Network as a Test System.

### 3.4 Functional (performance) requirements figures of merit

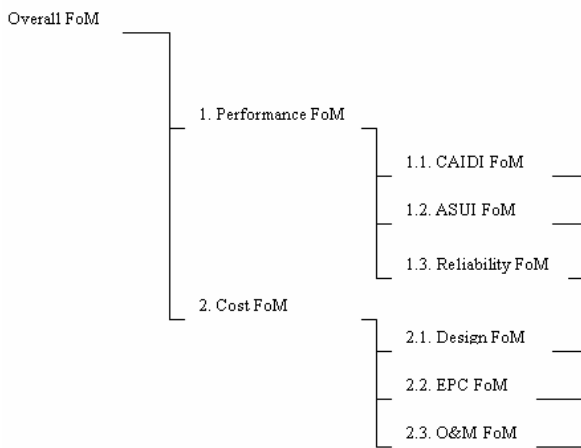
Three main requirements are defined as system performance or functional requirements, where two of them indicate the power distribution system reliability (in fact, availability) and the other one points to the UMA-FRF system reliability. Generally, we can write:

$$\text{SystemAvailability} = f(\lambda, \mu) \quad (5)$$

where  $\lambda$  denotes the *failure rate* and  $\mu$  indicates the *repair rate*. Frequency reliability indices are influenced by  $\lambda$ , which indicate the reliability of the components and structure of the system; while duration indices are functions of  $\mu$ , that those indices denote the capability of the system management and operation team to repair or restore the failed system [91,92]. The mission of the UMA-FRF system –as mentioned as the top-level system function– is to restore the failed network; consequently, the duration system reliability indices should be adopted rather than the frequency indices. Momentary faults constitute a major part of distribution system faults; according to a survey in Finland, about 90% of the distribution system faults are momentary. Another survey in Tehran Regional Electric Company (TREC) shows similar percentage, as well. Installing reclosers, auto-sectionalizers, and changeovers can be regarded as the best solution for momentary faults, as called local distribution automation [49]; however, the extra almost 10% of the faults in DS cause sustained outages which need to be removed (or fixed). Consequently the DS practitioners devote their effort to minimize the faulted (disconnected) area, because of the sustained faults, by DS restoration (which is known within the Iranian electricity distribution practitioners as network maneuver). Therefore, the performance of the UMA-FRF system is defined by sustained reliability indices [91-93].

Three following main requirements were defined as system functional or performance cost requirements:

1. Minimum Number of Faulted (Disconnected) Customers: The customer average interruption duration index (CAIDI) seems to be the best representation for the number of faulted customers, in power system reliability terminology [91-93].
2. Minimum Restoration (Recovery) Time: The average service un-availability index (ASUI) seems to be the best representation for the restoration time, in power system reliability terminology [91-93].
3. UMA-FRF system Reliability: In the case of digital communication system, reliability is commonly expressed in terms of bit error rate (BER) or probability of bit error measured at the receiver output [94,95].



**Fig. 3** Hierarchy of performance, cost, and overall FoMs and their scoring functions.

### 3.5 Technology (cost) requirements figures of merit

Three following main requirements were defined as system technology or cost requirements:

1. Cost of System Design: At this stage, there will be no cost for the system design because it has been done in another sub-project.

2. Cost of System Engineering, Procurement and Construction (EPC): This is the amount of money spent on the engineering design, subsystems procurement, and construction of the system. The prices are calculated based on the individual prices. Then the prices are normalized, as the relative prices are important for this study.

3. Cost of Operating and Maintenance (O&M): This is the amount of money spent on the operation and maintenance of the system. The prices are calculated based on the individual prices. Then the prices are normalized, as the relative prices are important for this study.

Reference [90] – a feasibility study report, performed by Monenco Consulting Engineers (for Central Tehran Distribution Co.) – may be used as a source for single prices for those readers who want to calculate the EPC and O&M costs for DA. Price changes due to inflation or financial policies of different vendor companies produce small changes in the cost studies; in fact, it does slightly matter which source (or at which time) we use for the prices, since the relative prices are important in our cost study, rather than the absolute prices.

## 4 Results and Discussions

Two computer programs were developed to model the performance and cost FoMs and calculate their respective scoring functions, and also to model tradeoff analysis between the performance and cost for three design concepts, i.e. Spread Spectrum, DLC, and Leased Line, based on the methodology presented in Fig. 1.

Figure 3 shows the hierarchy of performance, cost, and overall FoMs and their scoring functions.

The FoM modeling program calculated the performance FoMs, i.e. CAIDI, ASUI, and Reliability values, and their Wymorian scoring function as well, for the three design concepts. This program also plotted the performance FoMs scoring functions of the three design concepts versus the types of performance figures of merit in Fig. 4. Square, triangle, and pentagram signs represent Spread Spectrum, DLC, and Leased Line, respectively, in all of the figures. The CAIDI and ASUI FoMs took the same value for the three design concepts; however, the Reliability FoM of the DLC design concept drops significantly. As can be seen in Fig. 4, the overall performance FoM of the Spread Spectrum and the Leased Line systems are the same, with a considerably higher value than DLC overall performance.

CAIDI and ASUI FoMs of the UMA-FRF system take the same value for the three design concepts; however, the Reliability FoM of the DLC design concept drops significantly, because of its dependence on power systems networks, as shown in Fig. 4. As a result, the overall performance of the Spread Spectrum and the Leased Line systems are the same, with a considerably higher value than DLC overall performance.

The cost FoMs were calculated and plotted by the FoM modeling program, as well. The design, EPC, O&M, and overall cost were calculated for the three design concepts. Subsequently, the Wymorian scoring functions of the cost FoMs were calculated and plotted versus the types of cost FoMs for three design concepts, as can be seen in Fig. 5.

The design cost has been assumed near zero, since it has been performed in another project. As shown in Fig. 5, the EPC cost FoM score for the Leased Line is 83%, where the cost FoM score of the DLC and Spread Spectrum are 29% and 28%, respectively. On the other hand, the Spread Spectrum and DLC systems showed O&M cost FoM scores of 38% and 39%, respectively, where the corresponding FoM score for the Leased Lines is 22%. The overall FoM score for Spread Spectrum and DLC is 15%, while the overall FoM score for Leased Lines is 13%.

Spread Spectrum and DLC follow almost the same cost curves, whereas this cost characteristics differ for the Leased Lines, as shown in Fig. 5. That is, the EPC cost FoM of the Leased Line is almost three times the cost FoM of the two other design concepts. The reason for higher EPC cost FoM of Leased Lines is that Leased Lines are rented from other companies (the communication companies) legacy systems, while the utility companies themselves should build Spread Spectrums and DLC systems. On the other hand, the O&M cost FoM for the Spread Spectrum and DLC systems are twice that of FoM for the Leased Lines, as our assumed utility company should pay monthly rent to the owner of the Leased Lines.

The tradeoff-modeling program calculated the overall FoM score for the three design concepts, and plotted the

scores versus overall performance, overall cost, and overall FoMs in Fig. 6, which displays the results for the overall FoM scores of the three design concepts, i.e. Spread Spectrum, Leased Line, and DLC, respectively as 34%, 33%, and 22%.

In this case study, it has been assumed that the utility company decision-makers (stakeholders) prefer to pay the most of the money in the system building phase. This assumption logically makes sense, since during the building phase of the UMA system, a budget have been specified for establishment of the UMA system.

Conversely, the utility decision-makers are less interested in paying endless monthly rent bills that will be issued by the communication companies, after starting the operating phase of the UMA system life cycle.

According to this policy, EPC cost FoM takes 2.5 times more weight compared to O&M cost FoM in the overall cost FoM. As a result, overall cost FoM of the Spread Spectrum and DLC systems are slightly more than the

overall cost FoM of the Leased Lines, as it can be seen in Figs 5 and 6.

Spread Spectrum and Leased Line systems outperformed the performance FoM competition, while the Spread Spectrum and DLC systems qualified the competition for the cost FoM, as depicted in Fig. 6. Finally, as Fig. 6 indicated, the Wymorian scoring functions method select the Spread Spectrum, as the final design concept due to the overall FoM, with a minor superiority to the Leased Lines alternative. Of course, this selection is due to the policies and preferences of the utility company decision-makers (stakeholders), while this policies and preferences show themselves in the weights and scoring function parameters of the Wymorian design decision-making method (Equations (1)-(4)). For instance, if the weights of performance and cost FoMs change, the results of the overall FoM change, i.e. the Leased Line, might be selected instead of the Spread Spectrum.

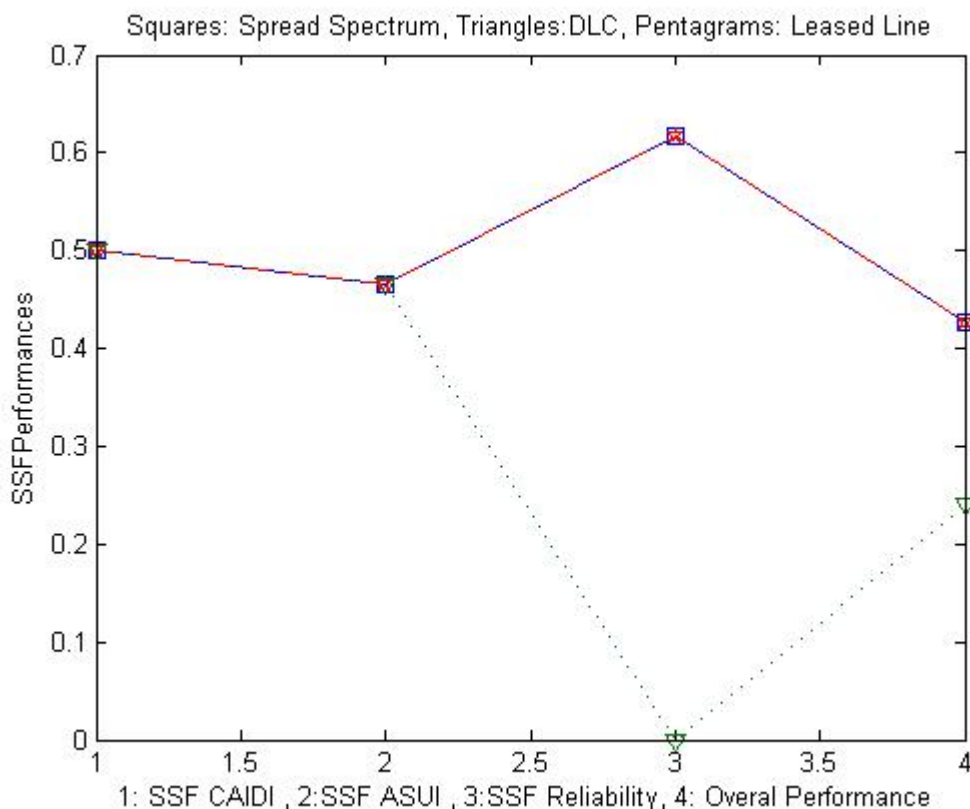


Fig. 4 Scoring functions for performance FoMs versus three design concepts.



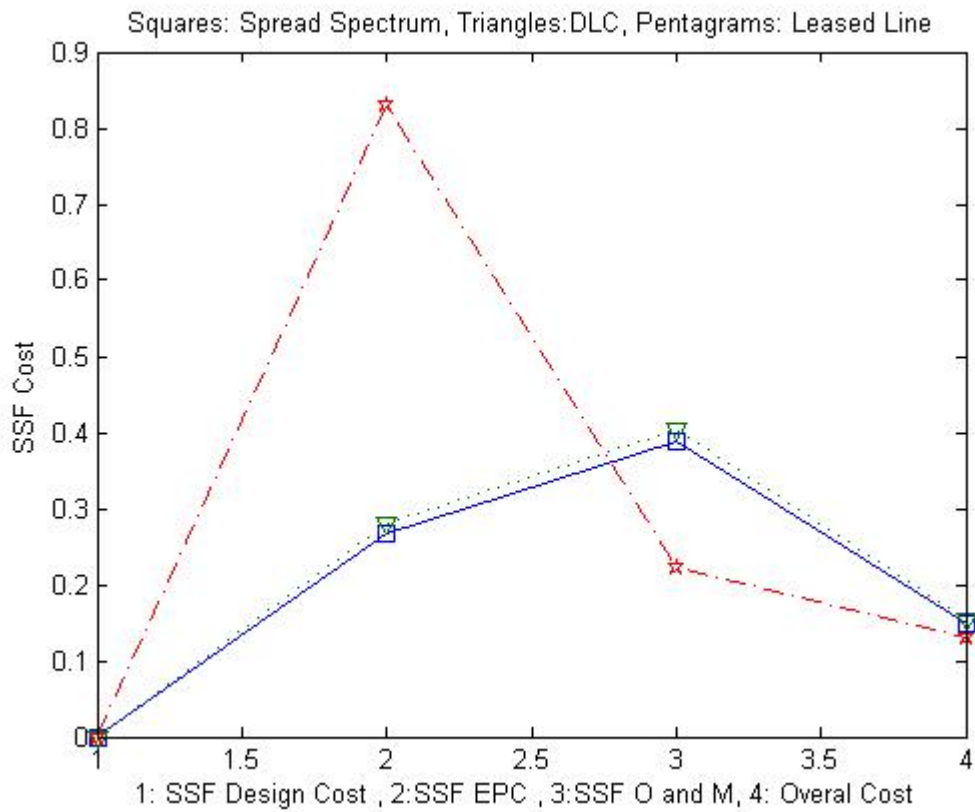


Fig. 5 Scoring functions for cost FoMs versus three design concepts.

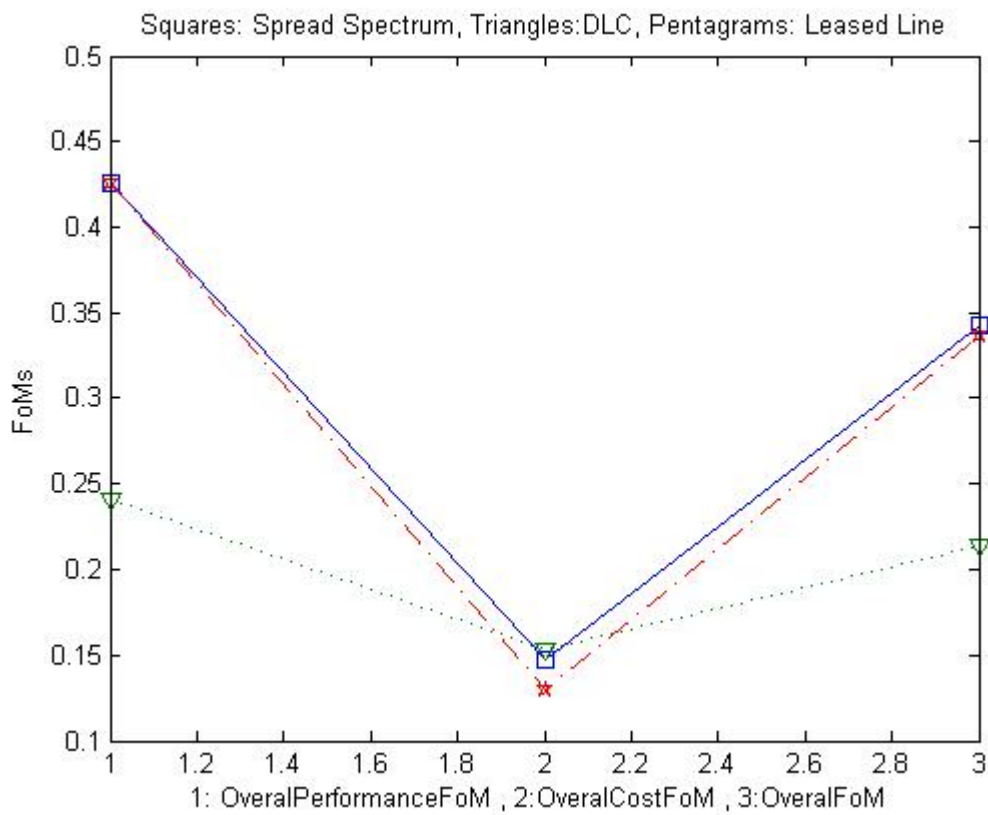


Fig. 6 Scoring functions for overall performance and cost FOMs versus three design concepts.

## 5 Conclusions

A novel<sup>12</sup> Systems Engineering (SE) approach to architectural design problem –as well as its multiple criteria decision making– of IT infrastructure for UMA systems was introduced, defined and formulated; then, a model-based design methodology was presented, based on the A. W. Wymore's Tricotyledon general systems design theory. The proposed design methodology was implemented to the IT infrastructure of electric power utility management systems, where the feeder reconfiguration function (FRF) of the UMA system was considered as an implementation example.

Two challenges of quantification of qualitative attributes and multiple (mostly contradicting) attributes of such a complex socio-technical systems were raised, and Wymorian FoMs and scoring functions were devised to cope with those challenges.

The ability to manipulate the decision results by the changing policies and preferences of the decision-maker can be regarded as a major advantage of proposed method, which lets the decision-makers make the mathematical models work for them to take their policies and preferences into account in the decision-making and decision-support process.

The top-level functional need was considered as managing open/close status of the network switches in order to restore the faulted network, which implemented on a well-known test distribution system, to maintain a certain level of abstraction.

Subsequently, the UMA-FRF system functional (performance) and technology (cost) requirements and figures of merit (FoM) were discovered in the requirement discovery phase at the early stage of the systems design. Minimum faulted energy consumers, minimum recovery time, and reliability were selected as performance requirements; while, cost of system design, cost of EPC (engineering, procurement, and construction), and cost of O&M (operation & maintenance) were discovered as cost requirements. Various alternatives for communication systems as the IT infrastructure were investigated, and three concepts of Spread Spectrum, Distribution Line Carrier (DLC), and Leased Lines were finally adopted, as alternative design concepts.

The FoM modeling program calculated the performance FoMs, i.e. CAIDI (customer average interruption duration index), ASUI (average service un-availability index), and Reliability values, and their Wymorian scoring function as well, for the three design concepts. It was concluded that the overall performance of the Spread Spectrum and the Leased Line systems are the same, with a considerably higher value than DLC overall performance.

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<sup>12</sup> The novelty of the presented approach is to the best of our knowledge, according to timely searches in various scientific databases, as described in details, in the Introduction section of the paper.

The cost FoMs were calculated and plotted by the FoM modeling program. The design, EPC (engineering, procurement and construction), O&M (operation and maintenance), and overall cost were calculated for the three design concepts. Subsequently, the Wymorian scoring functions of the cost FoMs were calculated and plotted versus the types of cost FoMs for three design concepts. The resulting simulation showed that the EPC cost FoM of the Leased Line was almost three times the cost FoM of the two other design concepts, because Leased Lines are rented from other companies legacy systems, while the utility companies themselves should build Spread Spectrums and DLC systems. On the other hand, as the utility companies should pay monthly rents to the owner of the Leased Lines, the O&M cost FoM for the Spread Spectrum and DLC systems were twice that of FoM for the Leased Lines.

The overall cost FoM of the Spread Spectrum and DLC systems were slightly more than the overall cost FoM of the Leased Lines, according to the assumed policy of the utility company decision-makers. The tradeoff-modeling program calculated the overall FoM score for the three design concepts, and plotted the scores versus overall performance, overall cost, and overall FoMs.

Finally, the proposed design decision method selected the Spread Spectrum, as the final design concept due to the overall FoM, with a minor superiority to the Leased Lines alternative.

The following further works are under our study or are already studied and are under review for publication, as the continuation and improvement of this present paper:

- The concept of policy-driven decision-making, for scenario-based design-decision practices,
- Implementation of other sorts of decision fusion for tradeoff studies of MCDM,
- Mathematical considerations of the proposed decision design methodology,
- Implementation of the proposed design methodology to other sub-functions of UMA,
- Architectural design of UMA under different IT investment policies and socio-economical situations,
- Implementation of the proposed design methodology to a local distribution system of TREC, considering the effects of regional (customized) pre-assumptions and conditions on the design processes and products.

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#### Appendix: Nomenclature

IT: information technology  
 IS: information system  
 ICT: information and communication technology  
 UMA: utility management automation  
 FRF: feeder reconfiguration function  
 MCDM: multi (multiple)-criteria decision-making  
 DA: distribution automation  
 DS: distribution system  
 DG: distributed (or dispersed) generation  
 IED: intelligent electronic device  
 SCADA: supervisory control and data acquisition  
 TREC: Tehran regional electric company  
 SE: systems engineering  
 FoM: figure of merit  
 SF: scoring function  
 DLC: distribution line carrier  
 $\lambda$ : failure rate  
 $\mu$ : repair rate  
 CAIDI: customer average interruption duration index  
 ASUI: average service un-availability index  
 BER: bit error rate  
 EPC: engineering, procurement, and construction  
 O&M: operation and maintenance

Wymorian: related to A.W. Wymore's theory of SE  
 SSF parameters: L, B and S denote lower value of FoM, baseline (expected) value of FoM and slope of the SSF curve at the baseline point.

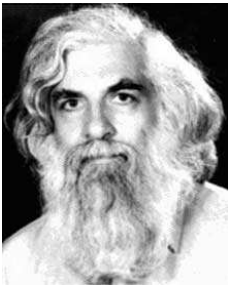
P: performance  
 C: cost  
 O: overall  
 PFoM: performance figure of merit  
 CFoM: cost figure of merit  
 OFoM: overall figure of merit  
 $W_p$ : weighting vector for performance  
 $W_c$ : weighting vector for cost  
 $W_o$ : weighting vector for overall  
 PFoMSF: performance figure of merit scoring function vector  
 CFoMSF: cost figure of merit scoring function vector  
 OFoMSF: overall figure of merit scoring function vector



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