A Petri Net-T3SD Policy Driven Method for IT Infrastructure Selection in Smart Grid

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Abstract—**this paper presents a novel expert system referred as Petri Net equipped Tricotyledon Theory of System Design (PN-T3SD) to select a proper IT infrastructure for smart grid. The proposed PN-T3SD is a policy-driven decision making method – combining the ideas from Petri nets and Wymorian T3SD- that can change the result of decision making according to the utility's policy. The PN-T3SD is applied to the practical data of the Greater Tehran Electrical Distribution Company (GTEDC). Three Alternatives of Spread Spectrum (SS), Distribution Line Carrier (DLC) and Leased Line (LL) are selected as proposed IT infrastructure. The implemented results are examined by developed policies scenarios.**

I. INTRODUCTION

Electric power smart grid is a stellar example of a system of systems (SoS) and a typical example of a complex adaptive systems (CAS), consisting electric power system, automation and control system, IT system and human (bio-ware) system.

Smart grid as future vision of power system extensively relies on its information technology (IT) infrastructure [1], [2]. Since this migration in the technology needs a reliable and optimized IT infrastructure, and given the fact that the most challenging part of the smart grid is distribution automation systems which extensively depends on IT systems; it is readily understood that the selection of an efficient, optimized and reliable IT infrastructure can be regarded as one of the core issues in the smart grid.

Annually, almost over US$10 trillion is spent on IT-enabling projects for different enterprises around the world, which shows the significance of research of IT systems development [3]. Although great improvements are seen, more than half of these IT projects fail to meet functional requirements, cost estimations, or schedule estimations [4]. This clarifies the necessity of reliable and efficient IT infrastructure selection in the smart grid as a complex enterprise. However, many failures in the IT systems of energy utilities are resulted from unsystematic design, ad hoc designs and heuristic rules [5]-[12]. These methods not only are highly suspected of not being optimal, but also "*are open to serious errors and biased decisions because they use "rules of thumb" or heuristics for decision making*" [9].

Since in a utility company, the operational and functional needs of the utility sub-systems are dictated by the utility corporate policy, stakeholders must ensure that the developed IT systems are aligned with those policies. Reference [10] report that alignment of the IT system with the enterprise corporate policy reduces the IT projects failure risk. Therefore, the design decision method is highly sensitive to the enterprise corporate policy, thus being Policy-Driven [1].

Despite the considerable number of publications on the optimization of financial cost functions, [13-18], there is little literature considering quantitative approach of performance in IT systems and power system, especially in a tradeoff with cost. A. W. Wymore introduced the Figures of merit (FoM) and scoring functions (SF) to quantify the system quality attributes (T3SD) [19]; subsequently, reference [1] successfully applied Wymorian Figures of merit (FoM) and scoring functions (SF) to the IT infrastructure selection problem. Furthermore, there is still a considerable research space in implementations of performance/cost tradeoff studies in both power and IT systems design literature.

This paper, as a continuum of IT infrastructure design research [1], [5], [19], introduces a PN-T3SD policy-driven design decision for the selection of IT infrastructure, implemented to the smart grid. The fundamentals of this research are presented in [1], [5] and [21]. To the best our knowledge, these series of papers [1], [5] and [20] are the first implementation of the established - yet young and important- general systems design methodology to the smart grid systems, according to the Science Citation Index® and IEEEXplore®. Furthermore, this study is more suitable to implement various policies in comparison with its ancestors [1]. The PN-T3SD method also, facilitates to capture the human expert judgments for decision making. Moreover, the nature of T3SD theory which unifies different FoMs, simplifies Petri net modeling process, as expressed in this paper.

The remainder of this paper is organized as: a background on Petri nets is presented, succeeded by Methodology, Implementation, Results and Discussions, and Conclusions sections.

II. BACKGROUND

This section is intended to briefly introduce the main concepts of Petri net, in order to make this paper self-explanatory. We use notation, definition, and properties of Petri nets as given in [21].

A. Petri net definition

A Petri net is a particular kind of bipartite directed graph including *places*, *transitions*, and *directed arcs*. Directed arcs

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connect places to transitions or transitions to places. The dynamic behavior of a Petri net is shown by flow of *tokens* from some places to others by firing transitions.

A Petri net is formally defined as a 5-tuple $N = (P, T, I, O, M_0)$, where

(1) $P = \{p_1, p_2, \dots, p_m\}$ is a finite set of places;
(2) $T = \{t_1, t_2, \dots, t_n\}$ is a finite set of transitions, $P \cup T \neq \emptyset, P \cap T = \emptyset$;
(3) $I: P \times T \to N$ is an *input function* that defines directed arcs from places to transitions, where N is a set of nonnegative integers;
(4) $O: T \times P \to N$ is an *output function* that defines directed arcs from transitions to places;
(5) $M: P \to N$ is a *marking* describing the distribution of tokens in places. The initial marking of net is indicated by M_0. The marking of net changes during the execution of Petri net.

B. Petri net graph

A Petri net graph has two types of nodes, *circles* and *bars (boxes)* representing places and transitions, respectively. *Directed arcs (arrows)*, labeled with their multiplicity (weight), connect places and transitions. *Dots* resided in the circles represent tokens in places (see Fig. 1). For Petri net of Fig. 1:

$$\begin{aligned} &P = \{p_1, p_2, p_3\};\ T = \{t_1, t_2\};\ I(p_1, t_1) = 1\,, \\ &I(p_2, t_1) = 0\,, I(p_1, t_2) = 1\,, I(p_2, t_2) = 2\,, \\ &I(p_3, t_i) = 0\,; O(t_1, p_3) = 1\,, O(t_2, p_3) = 1\,, \\ &O(t_i, p_j) = 0\,; M_0 = (3, 2, 0)^T\,; (i, j = 1, 2) \end{aligned} \tag{1}$$

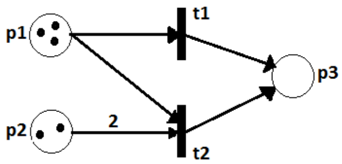


Fig. 1. A simple Petri net graph

C. Transition Firing

The execution of a Petri net is controlled by the number and distribution of tokens. Followings are *enabling rule* and *firing rule* of a transition, which control the flow of tokens in places:

(1) Enabling rule: A transition t is enabled if $\forall p \in P: M(p) \geq I(p, t)$.
(2) Firing rule: The firing of an enabled transition t removes from each input place p the Number of Tokens (NOT) equal to the Weight of Arc (WOA) connecting p to t; and, deposits in each output place the NOT equal to the WOA connecting t to p.

Mathematically, firing t at M yields a new marking M' determined by Eq. 2.

$$\forall p \in P: M'(p) = M(p) - I(p, t) + O(t, p) \tag{2}$$

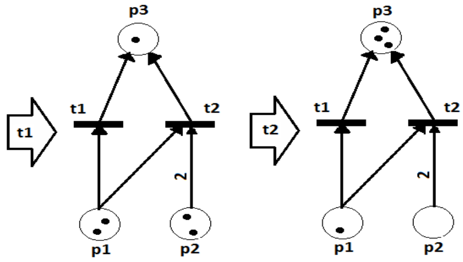


Fig. 2. Transition firing and new markings

D. Reachability

A marking M_1 is said to be *immediately reachable* from M_0 if firing an enabled transition in M_0 results in M_1. Reachability is generalized in the way that a marking M_2 is said to be reachable from M_0 if firing a sequence of transitions in T, starting from M_0, results in M_2. The set of all reachable markings of a graph G from initial marking M_0 is denoted by $R(G, M_0)$ [22].

E. Incidence matrix and state equation

The incidence matrix of a Petri net with m places and n transitions is $A = [a_{ij}]_{n \times m}$ with typical entry $a_{ij} = a_{ij}^+ - a_{ij}^-$ where $a_{ij}^+ = O(t_i, p_j)$ and $a_{ij}^- = I(p_j, t_i)$. According to firing rule, a_{ij} represents change in number of tokens (NOT) in place p_j when transition t_i fires once.

Suppose M_k as a $m \times 1$ column vector which jth entry denotes the NOT in place j immediately after the kth firing in some firing sequence, and u_k as the kth firing vector with only one nonzero entry, a 1 in the ith position for the ith transition to be fired at the kth firing. The state equation for the Petri net is as given by Eq. 3.

$$M_k = M_{k-1} + A^T . u_k\ ;\ k = 1, 2, \dots \tag{3}$$

Now, suppose that destination marking M_d is reachable from M_0 through a firing sequence $\{u_1, u_2, \dots, u_d\}$. The state equation can be generalized as Eq. 4.

$$M_d = M_0 + A^T . \sum_{k=1}^{d} u_k \tag{4}$$

F. Inhibitor arc

An *inhibitor arc* connects an input place to a transition and changes the transition enabling condition in the way that there should be no tokens in each input place connected to the transition by an inhibitor arc.

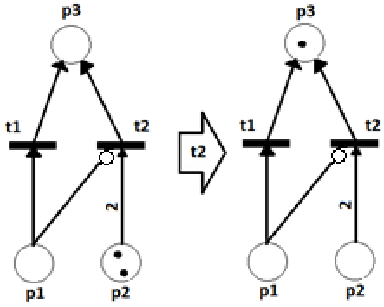


Fig. 3. Inhibitor arc in Petri net graph

G. Deterministic timed Petri net(DTPN)

Deterministic timed Petri net is 6-tuple (P, T, I, O, M_0, τ), where (P, T, I, O, M_0) is a Petri net, and $\tau: T \to \mathcal{R}^+$ is a function that associates transitions with deterministic time delays.

A transition t_i in a DTPN can fire at time τ if and only if for any input place p of this transition, there have been the NOT equal to the WOA connecting p to t_i continuously for the time interval $[\tau - \tau_i, \tau]$, where τ_i is the associated firing time of transition t_i. After the transition fires, each of its output places, p, will receive the NOT equal to the WOA connecting t_i to p at time τ [21].

H. Petri net modeling of IF-THEN rules

An IF-THEN rule can be modeled as a transition which input places and output places represent antecedent portion and consequence portion of the rule, respectively, in a way that each proposition in antecedent portion is modeled as an input place and each proposition in consequence portion is modeled as an output place [23].

III. METHODOLOGY

A. problem statement: IT selection decisions as sub-problems of smart grid

The main problem is to select an IT infrastructure or one of the smart grid's functions, here referred to as Feeder Reconfiguration Function of Utility Management Automation System [24].

As shown in Fig. 4, the complete solution includes an IT infrastructure which, if selected correctly, can complete the architecture of smart grid to implement feeder reconfiguration function system.

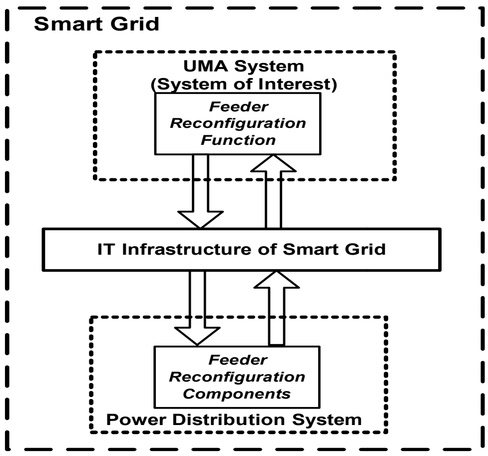


Fig. 4. Architecture of IT Infrastructure in Smart Grid for Feeder Reconfiguration Function

To solve the problem, this paper introduces a design decision model for selecting an efficient IT infrastructure for a smart grid according to the policy of the utility. Fig. 5 illustrates our presented design decision model, in which design inputs and design concepts can be introduced by requirement analysis [1]. A simple classification of system requirements include: performance requirements, cost requirement and trade-off (policy) requirements [1], [19].

B. PN-T3SD System Design Method

The design decision model which is proposed is based on the model-based Tricotyledon of system design (T3SD). In Fig. 5, the PN-T3SD design decision model that this paper proposes is shown. The Fig. shows that, after the analysis of the requirements, two sets of Figures of merit (FoMs) and their scoring functions are determined for the performance and cost requirements of the system. Same as [1], the system design concepts (the IT infrastructure alternatives) are explored by investigating the technologies that are available to build the system [1]. The standard scoring functions (SSFs) are used to grade the FoMs and to build a unified scaling system for FoMs, thus mapping the FoMs space to a normalized space of [0 1]; consequently, this method leads to different sort of FoMs with different dimension. This nature of the T3SD theory that unifies and normalizes the FoMs, simplifies Petri net modeling of system (for more information on selection of the best SSFs see [19], [25], [26]).

In this paper, Petri net is proposed as an expert system to select the proper IT infrastructure. Since T3SD theory applies normalization and unification pre-processing on the inputs, Petri net modeling techniques can be simply applied; however, these scored inputs need to be quantized – for our approach three levels of quantization are considered, Unusable (U), Moderate (M), and Excellent (E). Afterwards, the IF-THEN rules, extracted from judgment of the Greater Tehran Electrical Distribution Company's (GTEDC) Experts, are modeled by Petri nets. In order to execute the nets, based on the modeling method, the quantized scored inputs are transformed to initial markings. In the process of transforming, *Unusable*, *Moderate*, and *Excellent* values are modeled by one, two and three number of tokens, respectively.

The mathematical foundations of this method allow design decision parameter to be changed to gain specific operational or organizational goals. This interesting feature of the PN-T3SD method allows the design decision makers to change the PN-T3SD parameters to influence the results of the design decision by their preference and values. The proposed design decision model is called "Policy-Driven", because the policies of the design decision act as drivers for the design decision process.

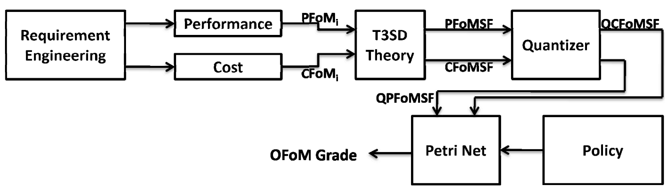


Fig. 5. The Proposed PN-T3SD Method for selection of IT Infrastructure

IV. IMPLEMENTATION

This paper focuses on the IT infrastructure selection for the Feeder Reconfiguration Function (FRF) of utility management automation (UMA) system, as one of the functions of the smart grid [27]-[29].

Marihart has enumerated 14 different design concepts for the IT infrastructures [30]. In this paper, due to the engineering practice of the GTEDC, we have considered three different design concepts of: Spread Spectrum (SS), Distribution Line Carrier (DLC) and Leased Line (LL) [1], [5], [20].

A. Fig.s of Merits

These three design concepts are being evaluated form the cost and performance perspectives as follows:

1) Performance Fig. of Merits (PFoM)

According to the functional requirements of the UMA-FRF system, three PFoMs are considered:

A) Minimum number of disconnected costumers which is best modeled with the customer average interruption duration index (CAIDI) [1], [5], [20] [31], [32].

B) Minimum recovery time which is best modeled with the average service unavailability index (ASUI) [1], [5], [20], [31], [32].

C) System reliability in the sense of digital communication which is best modeled with the Bit Error Rate (Rel.) [1], [5], [20], [33].

Fig. 6 shows the SSFs calculated for the aforementioned PFoMs which are later quantized and applied to Petri nets.

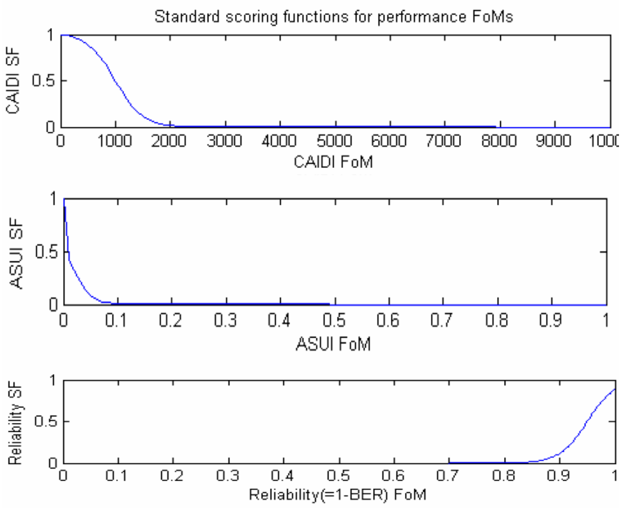


Fig. 6. PFOMs' SSFs

2) Cost Fig. of Merits (CFoM)

As the functional requirements of the system led into defining the PFoMs, the technological requirements are the reason for the cost. In other words, the technological requirements specified for the system of interest will lead to defining the CFoMs. We have considered three CFoMs in our evaluations:

A) The cost of system design: In this particular case study, there is no cost since it has been considered in another sub-project.

B) Cost due to the system engineering, procurement and construction (EPC): This is the amount of money spent on the construction stage and subsystems procurement which are calculated separately and then normalized due to the fact that the relative costs are of importance in this study [1], [5], [20] and [34].

C) Cost of operation and maintenance (O&M): This is the amount of money spent due to the maintenance cost, and is then rescaled due to the fact that the relative cost is of importance in this study [1], [5], [20] and [34].

Fig. 7 shows the SSFs calculated for the aforementioned CFoMs.

B. Policy for Tradeoff Analysis

We develop three polices (two of them are new polices) for design decision method. These policies are: payment method, possession, cost-performance trend.

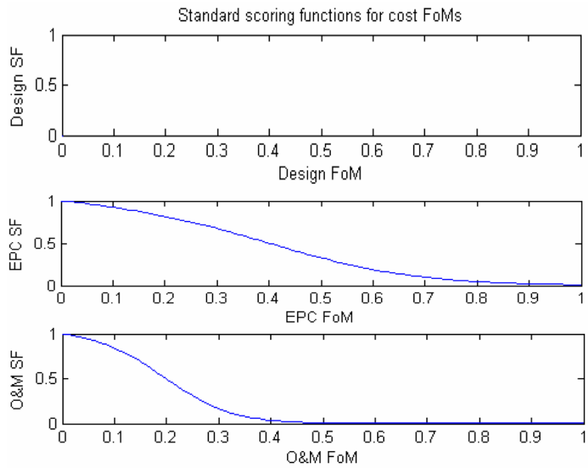


Fig. 7. CFoMs' SSFs

The utility may have different payment strategies for its new IT infrastructure. For example, the utility may prefer to pay once or over time. This policy is represented by a variable with three linguistic values, namely, pay-once-policy (OP), moderate-payment-policy (MP), and pay-gradually-policy (GP).

New IT infrastructure's possession is an important policy for the utility because it expresses how the IT infrastructure can be controlled by the utility. This policy is illustrated by a variable with three linguistic values: low possession (LP), moderate possession (MP), and full possession (FP).

The utility's policy about trend toward performance or cost shows the importance of cost and performance compared to each other. This policy is illustrated by a variable with three express values: cost oriented, cost-performance equilibrium and performance oriented.

C. Petri Net Modeling

The proposed modeling method includes two steps: first, the overall performance and cost of each IT infrastructure is determined based on scored performance and cost FoMs; then, it is determined that how much the suggested IT infrastructures satisfy and adapt to the given policy.

Fig. 8 shows the designed Petri net for determining each alternative's performance based on its PFoMs (CAIDI, ASUI, and Rel.). As mentioned earlier, to be able to apply scored FoMs to the net as inputs, they should be quantized. In our application, there are three levels of quantization including *Unusable (U)*, *Moderate (M)*, and *Excellent (E)*. These quantized scored FoMs form initial marking in a way that Unusable, Moderate, and Excellent values are modeled by one, two, and three number of tokens in corresponding places, respectively. The output of the net is the overall performance of the alternative which can be one of the three values of *Poor*, *Moderate*, or *Excellent* corresponding to places P_a, M_a, and E_a, respectively.

As shown, we used a hierarchical algorithm in our modeling method, i.e. the input tokens in initial marking propagate in the net from left to right filling output places hierarchically until the net reaches its dead-end. To illustrate, the proposed net is the implementation of the look-up table of Table I extracted from experts' judgments; for instance, when the IT infrastructure in Unusable regarding one (or more) PFoM, disregarding values of other PFoMs, the overall performance of alternative is *Poor*. The modeling method is in a way that when the net reaches its dead-end, there is one token in only one of the output places P_a, M_a, or E_a determining the ovarall performance of alternative. We can simply say, using experts' judgments, we designed a Petri net that combines the scored PFoMs and gives the overall performance of the alternatives.

TABLE I. LOOK-UP TABLE FOR PETRI NET OF FIG. 8

Quantized Scored PFoMs			Overall Performance
CAIDI	ASUI	Rel.	
U	X	X	P
X	U	X	P
X	X	U	P
M	M	M	M
M	M	E	M
M	E	M	M
E	M	M	M
M	E	E	E
E	M	E	E
E	E	M	E
E	E	E	E

Levels of PFoMs: U, M, E for Unusable, Moderate, and Excellent, respectively.
Levels of Performance: P, M, E for Poor, Moderate, and Excellent, respectively.

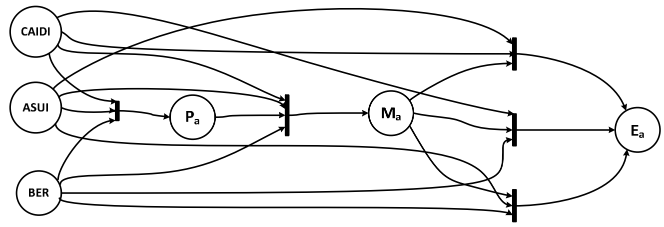


Fig. 8. Petri net model for determining overall performance of IT Infrastructure; *P*, *M*, and *E* represent *Poor*, *Moderate*, and *Excellent*, respectively; the index of *a* stands for *Alternative* performance of system.

The same procedure stays for determining the overall cost of each alternative based on its scored CFoMs (EPC and O&M); except for overall cost, since the effects of EPC and O&M are significantly different in high values for different possession and payment policies, the output values for overall cost of each alternative is determined by two letters which correspond to EPC and O&M, respectively. Note that quantization levels for CFoMs are the same as that of performance FoMs, that is, *Unusable*, *Moderate*, and *Excellent*. Therefore, the overall cost of each alternative is U, MM, ME, EM, or EE (for *Unusable* values of CFoMs, we used only one output). Fig. 9 shows the designed Petri net for determining the overall cost of alternatives.

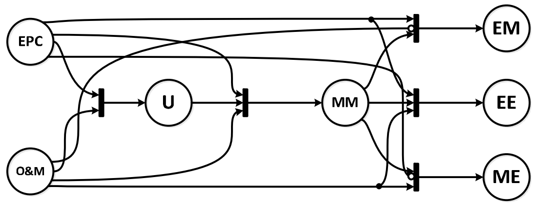


Fig. 9. Petri net model for determining the cost of IT Infrastructure; *U*, *M*, and *E* represent *Unusable*, *Moderate*, and *Excellent*, respectively.

Now that we have the overall performance and cost characteristics of suggested IT infrastructures, we can compare each of them with the characteristics of the given policies. To do so, first, we consider the performance of the alternatives. Fig. 10 shows the proposed Petri net model that determines how much each alternative satisfies the wanted performance in given policy. As shown, based on the cost-performance trend, three levels are considered for wanted performance, namely, *Not Considered (NC)* for cost-oriented policy, *Moderate (M)* for cost-performance equilibrium policy, and *Excellent (E)* for performance-oriented policy. In modeling method, one place is considered for each of these values; thus, based on what value is wanted in the given policy, the corresponding place gets one token and the other two places remain empty in initial marking. Outputs of the net of Fig. 9 (P_a, M_a, and E_a) are also inputs of this net. Using the rule that the suggested IT infrastructure should satisfy the wanted performance given by policy, we designed the Petri net of Fig. 9 for determining the level of satisfaction of given policy regarding performance characteristics by each IT infrastructure (for example, an IT infrastructure with Excellent performance satisfies all levels of wanted performance in an Excellent way). As shown, three levels of satisfaction are considered, *Poor (P)*, *Moderate (M)*, and *Excellent (E)*, each one modeled by a place in the net.

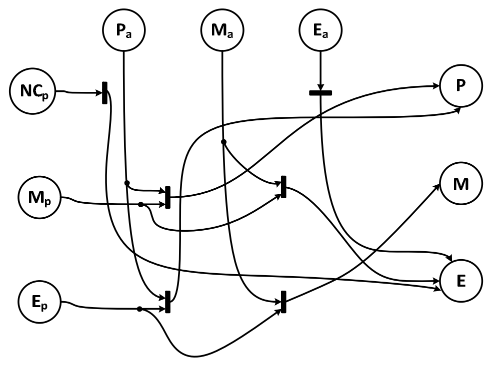


Fig. 10. Petri net model for applying policy regarding performance; *NC*, *M*, and *E* represent *Not Considered*, *Moderate*, and *Excellent*, respectively; the index of *p* stands for *Policy*.

Fig. 11 shows the designed Petri net that determines the level of adaptation of each alternative with the type of possession given in policy. Left-hand side places are the outputs of the net of Fig. 10 showing the cost characteristics of the alternative, and upper places are considered for the possession policy, i.e. *FP*, *MP*, and *LP* correspond to full possession, moderate possession, and low possession, respectively (possession policy determines which place gets a token in initial marking). As shown, the outputs of the net are the right-hand side places showing the level of adaptation between alternative's cost characteristics and possession policy (*P*, *M*, and *E* stand for *Poor*, *Moderate* and *Excellent* adaptation, respectively).

Petri net of Fig. 12 determines the level of adaptation between each alternative and payment policy. It uses the same modeling method as that of Fig. 11 for possession policy; except, the upper places are for payment policy in a way that *OP*, *MP*, and *GP* correspond to pay-once-policy, moderate-payment-policy, and pay-gradually-payment, respectively.

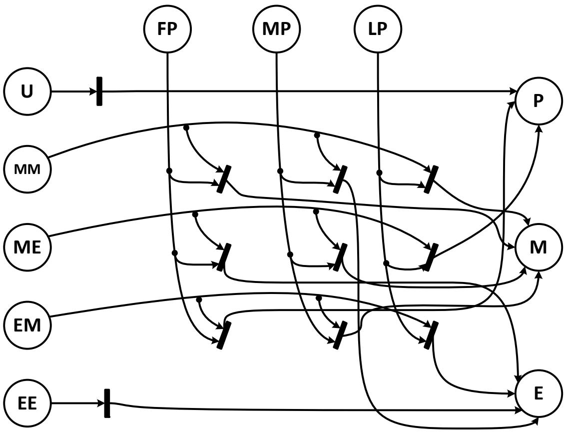


Fig. 11. Petri net model for applying policy regarding type of possession; *FP*, *MP*, and *LP* represent *Full*, *Moderate*, and *Low* possession, respectively.

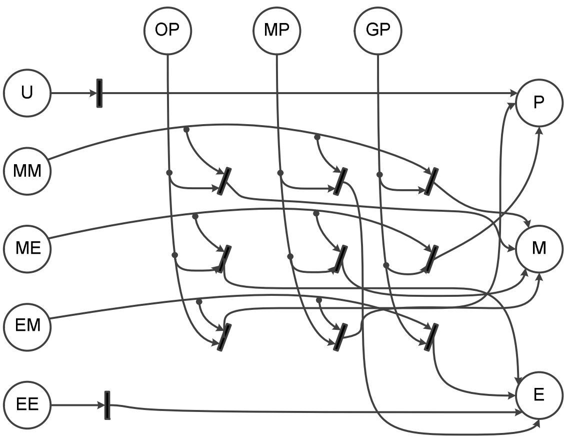


Fig. 12. Petri net model for applying policy regarding type of payment; *OP*, *MP*, and *GP* represent *at once*, *moderate*, and *gradual* payments, respectively.

V. Results and Discussions

Three scenarios are developed to examine policy driven feature of the proposed PN-T3SD design method. The developed scenarios reflected prospective policy of the company:

1. The utility prefers moderate payment, moderate possession of technology and cost-performance equilibrium: unbiased policy.
2. The utility prefers moderate payment, full possession of technology and cost-performance equilibrium: full possession policy.
3. The utility prefers pay-once-policy, full possession of technology and cost-performance equilibrium: pay-once and full possession policy.

The presented three scenarios are implemented in PN-T3SD method.

Table I shows the quantized scored FoMs for each IT Infrastructure. These values are transformed to initial marking and applied to first and second Petri nets in order to determine the overall performance and cost of each IT infrastructure. Outputs of these nets along with level of performance, type of possession, and type of payment of different policies specified in scenarios, given in Table III, are then applied to Petri nets of Figs. 10, 11, and 12 to determine the level of adaptation of each IT Infrastructure to given policies in scenarios. Table IV shows the results PN-T3SD for each alternative.

TABLE II. Quantized Scored FoMs of IT Infrastuctures

Alternative	CAIDI	ASUI	BER	EPC	O&M
DLC	M	M	U	M	E
LL	M	M	E	E	E
SS	M	M	E	M	E
NA	U	M	U	E	E

U, M, and E represent Unusable, Moderate, and Excellent, respectively.

TABLE III. Characteristics of Policies

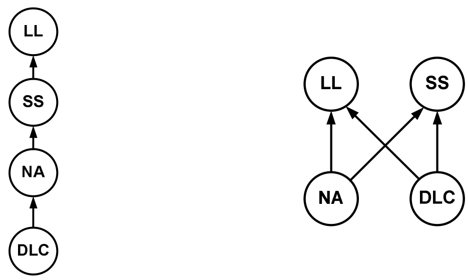
Policy	Performance	Type of Possession	Type of Payment
1	M	MP	OP
2	M	MP	MP
3	M	FP	GP

Levels of Performance: Poor, Moderate, and Excellent;
Types of Possession: Full, Moderate, and Low;
Types of Payment: At once, Moderate, and Gradually.

TABLE IV. Results of PN-T3SD for Each IT Infrastructure Regarding Each Scenario

Alt.	Scenario #1			Scenario #2			Scenario #3		
	Per.	Pos.	Pay.	Per.	Pos.	Pay.	Per.	Pos.	Pay.
DLC	P	M	M	P	E	M	P	E	E
LL	E	E	E	E	E	E	E	E	E
SS	E	M	M	E	E	M	E	E	E
NA	P	E	E	P	E	E	P	E	E

Hasse diagrams [35] of Fig. 13 shows the overall result for different given policies. As shown, for first and second policies, LL is the best option; and, for third policy, PN-T3SD method implies that LL and SS are more matched to the policy than DLC.



(a) (b)

Fig. 13. Overall results of PN-T3SD System in form of Hasse Diagram: (a) for first and second scenarios (b) for third scenario

VI. Conclusions

The PN-T3SD expert system was presented to policy-driven decision making. This expert system selects IT infrastructure for one of the smart grid functions, referred as

Feeder Reconfiguration Function. Three scenarios are presented to examine the PN-T3SD expert system. These scenarios expressed that the result of the expert system can change toward to the utility's policy.

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