# Modeling and Evaluation of Maintenance Procedures for Gas Distribution Networks with Time-Dependent Parameters

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**Abstract.** Gas networks comprise a special class of infrastructure, with relevant implications on safety and availability of universal services. In this context, the ongoing deregulation of network operation gives relevance to modeling and evaluation techniques supporting predictability of dependability metrics. We propose a modeling approach that represents maintenance procedures as a multi-phased system, with parameters depending on physical and geographical characteristics of the network, working hours, and evolution of loads over the day. The overall model is cast into a non-Markovian variant of stochastic Petri nets, which allows concurrent execution of multiple generally distributed transitions but maintains a complexity independent of network size and topology. Solution is achieved through an interleaved execution of fluid-dynamic analysis of the network and analytic solution of the stochastic model of the procedure. Solution provides availability measures for individual sections of the network as well as global quality of service parameters.

**Keywords:** gas distribution networks, non time-homogeneous systems, performance evaluation, Markov regenerative processes, transient stochastic state classes

## 1 Introduction

Quantitative evaluation of availability is gaining increasing relevance for the efficient operation of gas distribution networks, led by several causes including competitive challenges raised by re-organization of utilities, issues of homeland security, demand-response control applications, and automation capabilities offered by smart monitoring and actuation devices [22]. This motivates investigation in modeling and solution methods, both in the tactic perspective supporting decision during run-time operation and in the strategic perspective related to planning of topology, localization of sensing/actuation devices and evaluation of sustainable service levels.

The problem has been widely investigated in telecommunication and power systems, yet gas networks are different in notable aspects, such as: localization of failure and network reconfiguration, which may involve much less automation and may result in a large variability of timings; regulation of controllable inputs, which involves processes running on a much slower time scale; a lower level of network redundancy and a different perspective on the criticality of interruptions; flexibility in management of input pressure levels, which allows trading efficiency of operation against resilience to transient faults.

Most of the literature on the analysis and simulation of gas networks focuses on the fluid-dynamics perspective, mainly oriented to assess flow rates and pressures across network elements [14, 11]. Optimization of operations has been addressed in various aspects, notably to favor efficient integration within multi-carrier systems combining provisioning of electric and gas power [19, 17, 16, 18]. In [23] fluid-dynamic analysis of a section of a real gas network is repeated for different configurations of demand reflecting the statistics of usage in different day hours and seasons.

In a previous paper [6], we proposed a method for modeling the availability of middle/low pressure gas networks, which consists in an interleaved execution of *i*) a quasi-static fluid-dynamic analysis of the network and *ii*) a stochastic model of the failure management procedure. The latter uses non-Markovian temporal parameters, thus overcoming the limits of memoryless and unbounded support of exponential distributions. As a distinctive trait, fluid-dynamic calculations are decoupled from the non-Markovian stochastic analysis and the complexity of stochastic analysis is insensitive to topology and size of the gas network.

In this paper, the model of [6] is extended so as to capture non-homogeneous temporal parameters. As a matter of fact, failure management procedures and their impact on network operation may be affected by various time-dependent parameters, including the responsiveness of repair infrastructure and the gas consumption rate, both of which can be modeled through cycles with phases of deterministic duration. In the evaluation stage, the evolution over time of the failure management actions is analysed through transient analysis based on stochastic state classes and generalized Markov renewal equations, as proposed in [15]. Stochastic analysis provides the probability over time of any feasible operating condition of the network after a failure. Transient probabilities are then aggregated on the basis of the results of fluid dynamics analysis, identifying service levels in each operating condition, which enables the derivation of availability measures for each node in the network.

The rest of the paper is organized in four sections. In Section 2, we present both the failure management model (Section 2.1) and the fluid-dynamics model (Section 2.2). In Section 3, we recall the salient aspects of the solution technique of [15] (Section 3.1) and we discuss how the results of stochastic transient analysis are exploited to derive transient and average availability measures (Section 3.2). In Section 4, we exemplify the proposed approach on a small-sized case study of the literature (Section 4.1) and we present the obtained transient and average availability measures (Section 4.2). Finally, conclusions are drawn in Section 5.

## 2 Model

The gas distribution network comprises a kind of hybrid system combining continuous physical variables affecting fluid dynamics (pressure and flow rate) with the temporal behaviour of actions taken to recover from a failure. This duality is coped with by the interaction of two separate models: a stochastic model is used to analyse the timings of the failure management procedure (Section 2.1), whereas a fluid-dynamics simulator is used to quantify the lack of service metrics associated with each possible set of boundary conditions (Section 2.2).

For what concerns the fluid dynamics, gas is supplied to a low-pressure distribution network from a medium-pressure transmission network through a set of regulating stations (input nodes), and it is withdrawn by end-users at a certain number of load nodes. In the perspective of analysis, input nodes have a known pressure, whereas load nodes have a known flow balance, with their pressure depending on topology and flow patterns in the network. As a first approximation, which is valid for most existing distribution networks, the flow balance at load nodes is considered to depend on the time-of-day, whereas pressure at the supply nodes is considered constant. To guarantee correct operation as well as commercial standards, pressure at each load node should exceed a given minimum threshold and should not be greater than a maximum allowed value.

Whenever a network component fails, pressure levels and flow rates may be affected, and a set of maintenance actions is undertaken in order to restore the correct operating mode. These actions usually affect network topology and flow patterns: for instance, if a leaking pipe is detected, the nearest upstream and downstream valves are closed to isolate the faulty section, while other sectioning valves may be opened to minimise the number of end-users affected. The temporal evolution of repair actions and their effects are conditioned by various time-dependent parameters: on the one hand, the duration of some phases depends on the time-of-day, i.e., on the responsiveness of the system (e.g., availability of repair personnel may be lessened or null during nighttime); on the other hand, the degradation of the quality of service perceived by end-users depends on the load level throughout the network, which in turn varies according to a cyclic daily pattern.

Without loss of generality, the failure management procedure can be conveniently abstracted as a phased-mission process [20], consisting of three phases. The first phase includes operations occurring before physical intervention on the network, e.g., organisation of work team, planning and transportation on site. This phase is considered to end when the failed component (e.g., pipe) is excluded from the network, which comprises the first variation of topology. Hence, load nodes are partitioned into three classes:

- *i) offline* nodes, disconnected from any supply node;
- *ii) online served* nodes, connected with sufficient pressure;
- *iii) online not served* nodes, connected but with pressure lower than required.

The second phase represents actions occurring while the network status is in a modified configuration with respect to regular operation. In this phase repair is performed, while pressure is concurrently controlled at some regulating station, so as to restore the correct pressure levels at online load nodes during repair.

The third phase begins when the regular topology is restored, and it includes actions that do not affect user-perceived quality of service but are necessary for the operator to close the maintenance procedure. It is worth noting that the division in three phases has a general character and can be tailored to any specific procedure, as long as there exists a single continuous phase during which the network topology is modified.

The quality of service maintained throughout the procedure is captured by various metrics of performability, including the number of nodes served with an insufficient pressure and the amount of gas requested by users and not delivered.

### 2.1 Stochastic Model

The process of failure management can be represented as a *stochastic Time Petri Net* (sTPN) [24, 5] extended with features such as enabling conditions and update functions, which reproduce modeling mechanisms that are usual in such environments such as SAN networks [12] and do not change the essence of analysis. As regards sTPN syntax and semantics, the reader is referred to [24].

The model is shown in Figure 1. Two looped chains of deterministic (DET) transition are use to model the dependence of repair responsiveness (places *workHour*, *extraHour* and *nightTime*) and load levels (places *highLoad*, *medLoad* and *lowLoad*) on the time-of day. The duration of each transition corresponds

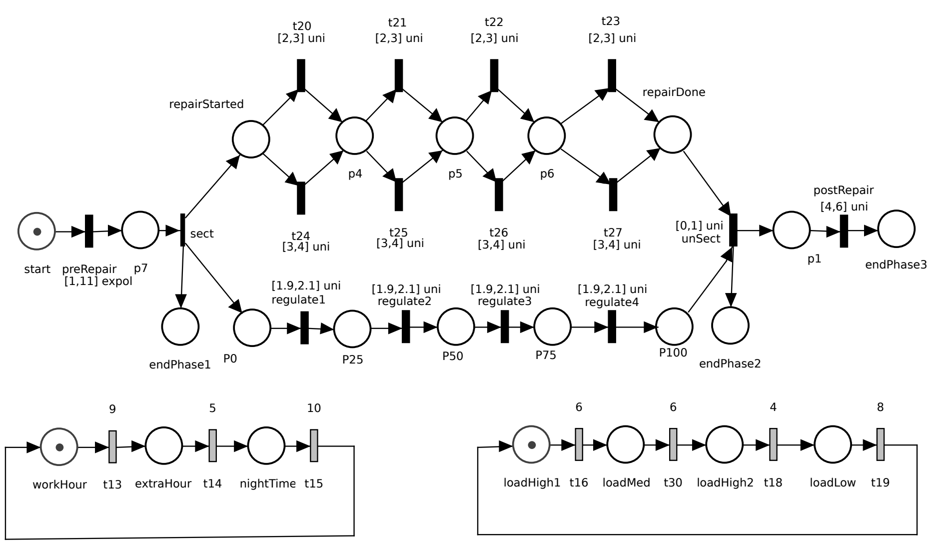


**Fig. 1.** The sTPN specification of the failure management model. IMM, DET and GEN transitions are represented by thin bars, thick gray bars, and thick black bars, respectively. The distributions associated with timed transition refer to the case study analysed in Section 4.

to the duration of the preceding phase, while the sum of the durations of each loop amounts to 24 h, thus modeling in both cases a cyclical daily pattern.

The failure management procedure is divided in three parts. Transition *preRepair* represents actions taken during phase 1 (no network status modification). The time duration of phase 1 activities can have much different characterisation depending on organisational issues or network topology in each specific context. To illustrate the ability of the modeling and analysis technique in accommodating such difference, we use here a general (GEN) transition with an expolynomial (EXPOL) distribution over bounded support, which was derived so as to be bounded over $[1, 11]$ h and have an expected value equal to 3 h, and a variance equal to 2 $h^2$. The immediate (IMM) transition *sect* models the end of phase 1 and the beginning of phase 2.

The dependence of the repair speed on the time-of-day can be modelled by a number of parallel transitions which are alternatively enabled according to the marking of the corresponding DET loop. In doing so, an approximation is introduced following the same approach applied in [20]: when the time-of-day phase changes, two possible modelling strategies lead to different results. In the first case, the previously enabled transition is disabled and one of the mutually exclusive ones is newly enabled (thus disregarding the time elapsed since the enabling of the former, lengthening the total duration and leading to a worst-case approximation). Alternatively, at the time-of-day phase change, the previously enabled transition could be fired, thus shortening the total duration.

To restrain the impact of approximation, the repair activity is partitioned in four steps of equal duration, in a manner somehow similar to what happens in continuous phase approximations, where time advancement is consolidated into discrete markings [2, 21]. This is represented in the model by the chained transitions linking places *repairStarted* and *repairDone*.

Concurrently with the repair procedure, pressure in the system is gradually raised, thus affecting service status of various load nodes. The process, intrinsically continuous, is discretised in four phases of equal duration represented by places *P0* through *P100*.

The final places of the two concurrent processes enable transition *unSect*, which represents the network status being reverted to normal operation as well as the end of phase 2. Since pressure regulation is stopped when the repair phase ends, an update function is associated with transitions *t23* and *t27*, which empties places *P0* through *P75* and puts a token in place *P100*.

Finally, transition *postRepair* models phase 3. Three absorbing places are chained to the output of transitions *sect*, *unSect* and *postRepair* transitions, so as to monitor the time elapsed from the start of the procedure to the end of each of the three main phases.

As previously mentioned, during the repair phase pressure at some input node is regulated (raised) in order to minimise the service impact on end users. The final pressure to be reached after the increase is calculated by means of the fluid-dynamic model as the minimum of two values: the minimum pressure necessary at the supply node so that all connected load nodes experience a pressure higher than the corresponding required pressure threshold, and the maximum pressure at the supply node so that no load node experiences a pressure higher than its maximum tolerated pressure. By means of the exposed modelling, a factual separation between the fluid dynamic model (whose complexity does depend on the complexity of the studied network) and the stochastic model (whose complexity does not) is achieved. In particular, the fluid dynamic model is used for two different purposes:

- to calculate the pressure increase to be imposed at the supply node in order to restore adequate pressure to all online load nodes;
- to evaluate service status at load nodes during each phase of the failure management process.

In the latter case, it is necessary to perform a certain number of analyses depending both on the load values considered (time-dependence of flow balance at load nodes) and on the number of steps representing the pressure increase process (time-dependence of pressure level at supply nodes). For each simulation, various measures representing service levels can be calculated and used as reward rates in the stochastic model.

### 2.2 Fluid-Dynamic Model

Given a set of boundary conditions, fluid-dynamic calculations are performed to assess the network state in terms of pressures at nodes and mass flow rates in pipes. In detail, two sets of equations are written to evaluate the mass balances at nodes and the pressure loss along pipelines, taking pressures at supply nodes and mass flow rates withdrawn at load nodes as inputs.

The first set of equations states that, for each node $n$, the signed sum of flow rates that enter or exit from $n$ must be equal withdrawn flow rate $Q_n^w$, i.e.,:

$$\sum_{i \in I_n^{\mathrm{ent}}} Q_{in} - \sum_{j \in I_n^{\mathrm{ex}}} Q_{nj} = \begin{cases} 0 & \text{if } n \text{ is a passive node} \\ Q_n^w & \text{if } n \text{ is a load node} \end{cases} \tag{1}$$

where $I_n^{\mathrm{ent}}$ and $I_n^{\mathrm{ex}}$ are the sets of indexes of pipelines that enter and exit from node $n$, respectively.

The second set of equations is used to calculate the pressure loss for each pipeline $m$, according to the Darcy-Weisbach formulation:

$$\delta P_m = f \cdot \frac{\delta L}{D_m} \cdot \frac{\rho V^2}{2} \tag{2}$$

where $\rho$ is the gas density, $V$ is the average gas velocity, $D_m$ is the pipeline diameter, and $f$ is the Darcy friction factor calculated by means of the Colebrook equation [10] for turbulent flows and the Poiseuille formula for laminar flows.

Combining Equations 1 and 2, a non-linear system is written and solved through an iterative procedure based on the Newton-Raphson method.

# 3 Evaluation

The model of Section 2.1 is evaluated through regenerative transient analysis based on stochastic state classes [15, 24] using the Oris tool [7, 4, 1].

## 3.1 Quantitative Transient Analysis

The solution technique of [15] supports the transient analysis of models with multiple concurrent GEN transitions that underlie a Generalized Semi-Markov Process (GSMP) with equal-speed timers [13, 9]. The state of the underlying GSMP is sampled after each transition firing and an additional timer called $\tau_{age}$ is maintained to account for the absolute elapsed time. This identifies a *transient stochastic graph* whose states are named *transient stochastic state classes* (transient classes for short), each made of a marking plus the joint support and PDF of $\tau_{age}$ and the times-to-fire of the enabled transitions. The marginal PDF of $\tau_{age}$ permits to derive the PDF of the absolute time at which a transient class can be entered, enabling the evaluation of continuous-time transient probabilities of reachable markings within a given time horizon, provided that the number of transient classes that can be reached within that time interval is either bounded or can be truncated under the assumption of some approximation threshold on the total unallocated probability.

The complexity of the solution technique can be reduced in the case that the model underlies a Markov Regenerative Process (MRP) that always reaches a regeneration point, i.e., a state where the future behavior is independent from the past behavior through which it has been reached. In this case, transient analysis is limited to the first regeneration epoch and repeated from every regenerative point, supporting the derivation of the local and global kernels that characterize the MRP behavior [8, 9, 3] and enabling the evaluation of the transient probabilities of reachable markings at any time through the numerical integration of generalized Markov renewal equations.

## 3.2 Evaluated Measures

Each marking in the stochastic model can be associated with a reward rate corresponding to the relevant metrics of performability. Since lack of service experienced by end-users is determined on the basis of pressure regulation status (places *P0* through *P100*) and load level (places *highLoad*, *medLoad*, *lowLoad*), reward rates are associated to the twelve reachable combinations. In particular, performability is measured through the number of non-served nodes (either offline or online with insufficient pressure) and non-served gas demand corresponding to such nodes.

Moreover, the absorbing places in the failure management model are used to evaluate the Cumulative Distribution Function (CDF) of the completion time of any of the three phases, allowing the derivation of average measures.

## 4 A Case Study

We illustrate here the gas distribution network considered in the experimental validation (Section 4.1) and we discuss the obtained results (Section 4.2).

### 4.1 Experimental Setting

Figure 2 shows a topological representation of the sample gas distribution network analysed in the experiments. The network has a double-loop topology and is made of a supply node marked as A, six load nodes marked as B through G, and fifteen pipelines.

Operating parameters of the network components have been chosen so as to experience different degrees of network unavailability following different pipeline failures. In detail, three load levels are considered, and the correponding withdrawal rates at load nodes are reported in Table 1. Moreover, each load node is supposed to have a minimum required pressure of 20 mbar. During the regular operation of the network, the pressure in each load node is greater than the corresponding pressure threshold, so that all nodes are properly served.

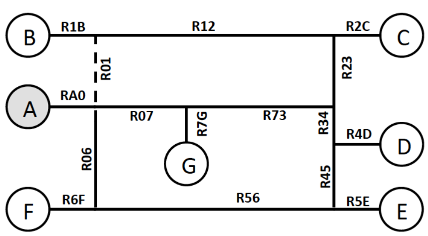


**Fig. 2.** Sample gas distribution network. The shaded nodes are supply nodes, while the others are load nodes. The dashed pipe is the one whose failure is considered.

| **Node** | **maxLoad** ($Sm^3/h$) | **medLoad** ($Sm^3/h$) | **minLoad** ($Sm^3/h$) |
|---|---|---|---|
| B | 200 | 150 | 100 |
| C | 200 | 150 | 100 |
| D | 150 | 113 | 75 |
| E | 200 | 150 | 100 |
| F | 200 | 150 | 100 |
| G | 100 | 75 | 50 |

**Table 1.** Mass flow rates of the nodes of the gas distribution network shown in Figure 2 for three different load scenarios.

Once a failure is detected and located, the corresponding pipe is excluded from the network and the load nodes are divided into online and offline nodes. If the failed pipe does belong to one of the main loops, no load node will be offline, whereas if the failed pipe is one of the radial connections from the main loops to a load node, one ore more of such nodes will.

For failures of pipes belonging to the ring, the pressure regulation time is characterized by assuming a pressure increase rate of 2 mbar/h and using the results of the fluid-dynamic analysis which provides the minimum pressure increase $\Delta P$ to be actuated at the supply node so that all online nodes are served.

### 4.2 Experimental Results

Without loss of generality, we illustrate the process of analysis with reference to a failure occurring at pipe *R12* as an example for discussion. Note that we deliberately focus on a failure of a pipeline that belongs to the network ring, as such failures will leave more load nodes not served than failures of radial pipelines and make pressure regulation a sensible choice.

**Fluid-Dynamic Analysis** As a first step, a calculation is performed by excluding the failed pipe from the network and leaving every other parameter unchanged. The pressure at each node is shown in the third column of Table 2 in the *highLoad* scenario. Comparing the pressure values with those in the first column (regular operation), it can be noted that the nodes originally downstream of the failed pipe (B and C) experience a great pressure loss due to the change in flow patterns, whereas other load nodes suffer smaller decreases.

| node | regular | P0 | P25 | P50 | P75 |
|---|---|---|---|---|---|
| A | 40.0 | 40.0 | 46.0 | 52.0 | 58.0 |
| B | 38.8 | 0.0 | 0.0 | 2.8 | 9.1 |
| C | 31.1 | 3.6 | 5.5 | 9.4 | 15.6 |
| D | 21.4 | 6.8 | 11.3 | 16.5 | 22.7 |
| E | 28.1 | 18.1 | 22.9 | 28.3 | 34.5 |
| F | 31.7 | 22.8 | 27.7 | 33.2 | 39.3 |
| G | 29.7 | 8.1 | 11.0 | 15.5 | 21.7 |

**Table 2.** Pressures at nodes during the different steps of pressure regulation and regular operation in the highLoad scenario. Shaded cells correspond to nodes not served.

From the values in Table 2, global metrics can be derived. Table 3 shows the reward rates as calculated by aggregating the results of the fluid-dynamic analysis in terms of nodes not served and demand not served.

| scenario | P0 | P25 | P50 | P75 |
|---|---|---|---|---|
| number of nodes not served | | | | |
| highLoad | 5 | 4 | 4 | 2 |
| medLoad | 4 | 2 | - | - |
| lowLoad | - | - | - | - |
| demand not served (Sm2/h) | | | | |
| highLoad | 850 | 650 | 650 | 400 |
| medLoad | 650 | 400 | - | - |
| lowLoad | - | - | - | - |

**Table 3.** Reward rates from fluid-dynamic calculations.

**Stochastic Analysis** As a first step, the probability of having completed each phase of the procedure at time $t$ (given that procedure is started at 10 a.m.) is calculated and reported in Figure 3(a). Figure 3(b) shows the probability of being in each of the markings corresponding to a degradation of the perceived service quality at time $t$.

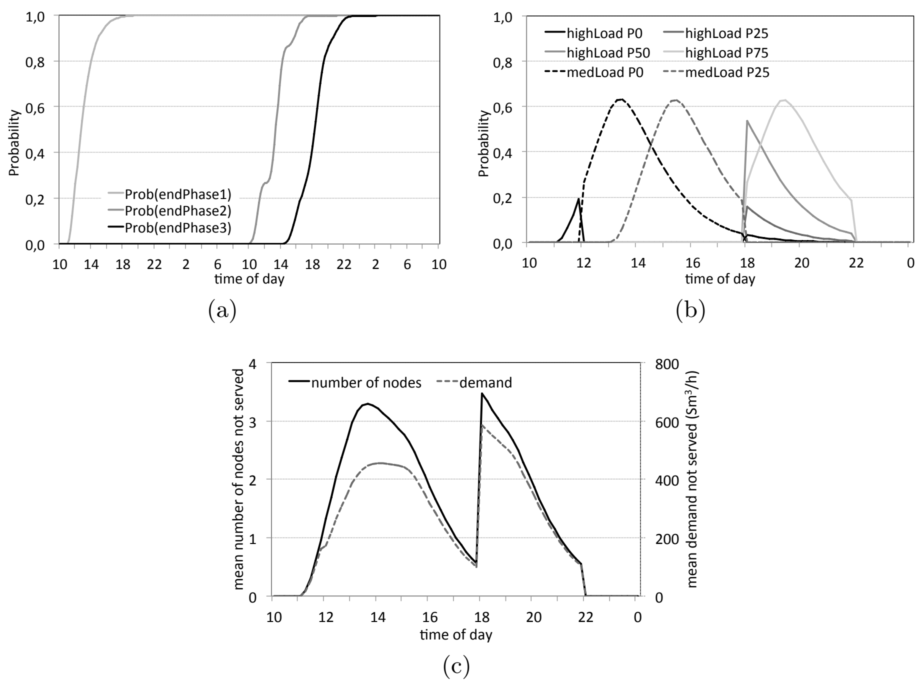


**Fig. 3.** Results of the stochastic analysis: (a) probability of completion of each phase by time $t$, (b) transient probability of being in a marking with lack of service at time $t$ and (c) expected value of nodes not served and demand not served at time $t$

Each peak refers to a different pressure level, solid lines representing highLoad scenario and dashed lines corresponding to medLoad. The four peaks lie at approximately equal distances from each other, corresponding to the duration of the regulation step (note that the "medLoad P50" line is not shown, as it brings no service disruption, but it can be inferred from the "highLoad P50" line). Figure 3(c) shows the expected values of the two lack of service measures, calculated using values in Table 3 as reward rates. Thus, considerations arise on the critical time-of-day in terms of service disruption and on the global impact of the failure, e.g., the discontinuity at 18 h corresponds to increased lack of service due to rising load in the network, which leads to lower pressure especially for nodes farther away from the supply station, while the area below the dashed curve represents the expected gas amount not sold due to the maintenance procedure.

## 5 Conclusions

Being a universal service, gas distribution networks represent a critical infrastructure with notable safety and availability issues. Their operation is cyber-physical, as the intrinsically physical infrastructure (which is geographically extended and follows deterministic laws) interacts with remote control strategies and operational and maintenance procedure in determining the temporal evolution of service status. Therefore, modelling and evaluation shall couple hybrid behaviour of continuous physical variables and stochastic timing, usually in non-Markovian classes, with parameters depending on time-of-day such as repair organisation responsiveness and level of gas consumption in the network. The proposed modelling and solution approach decouples these complexities, making stochastic timed analysis independent of the size and topology of the network and, vice versa, allows fluid-dynamic analysis to be carried out on a finite number of configurations. Results support evaluation of performability measures that answer relevant needs for ongoing deregulation of markets for distribution utilities.

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