Simulation of Protective Mechanisms in District Heating Systems

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ABSTRACT

This paper presents a hybrid automata-based framework for simulating protective mechanisms in district heating systems under emergency conditions. District heating networks exhibit complex dynamics combining continuous thermo-hydraulic processes with discrete control actions triggered by accidents such as pipeline ruptures, pump failures, or valve malfunctions. Traditional modeling approaches struggle to capture this hybrid behavior. To address this, we develop a formal model where the physical system is represented as a hybrid automaton with discrete operational modes (normal, accident, recovery) and continuous state variables (pressures, flows, temperatures). Protective devices—such as pressure relief valves, pump trip logic, and emergency shutdown systems—are encoded as control automata with thresholds, time delays, hysteresis, and logical dependencies. These controllers interact with the plant automaton in a closed-loop configuration, enabling realistic simulation of accident evolution and protection responses. The framework is applied to representative failure scenarios, including pipe breaks and pump outages, demonstrating its ability to evaluate the correctness, robustness, and coordination of safety mechanisms. Results highlight the value of automata-based modeling for identifying design weaknesses, tuning protection parameters, and supporting safety verification in thermal energy infrastructure.

Keywords: district heating systems, hybrid automata, protective mechanisms, safety systems, thermo-hydraulic simulation, discrete-event modeling, emergency shutdown, process safety, fault scenarios, control logic

Introduction

Ensuring the reliability and safety of district heating systems is a critical task for modern urban infrastructure. Heat supply networks serve large numbers of consumers, and serious failures may lead to long outages, equipment damage, and substantial economic losses.

Accidents in such systems are inevitable over long lifetimes; therefore, systematic analysis of possible accident scenarios and the effectiveness of protective mechanisms is required.

However, predicting the evolution of accident scenarios and assessing the performance of protections is challenging. The behaviour of a district heating system during emergencies is governed by nonlinear thermo-hydraulic dynamics coupled with discrete events such as equipment trips, valve actions, and operator interventions. Traditional steady-state or purely continuous models are insufficient to capture these discrete aspects. Conversely, pure discrete-event models cannot represent pressure surges, flow transients, and thermal dynamics with sufficient fidelity.

A promising approach is to use automata-based models, and in particular hybrid automata, which combine finite-state machines with continuous dynamics. In this framework, the heating network is represented by a set of discrete modes (normal operation, various accident states, recovery) and continuous state variables (pressures, flows, temperatures). Protective devices and control logic are formalised as interacting automata that observe system variables and issue control commands. This provides a rigorous way to simulate accident development and to evaluate whether protections maintain safety.

The aim of this study is to develop an automata-based simulation framework for a district heating system under emergency conditions, focusing on the operation and coordination of protective mechanisms. The study describes a typical district heating system and justifies the need for hybrid discrete–continuous modelling. It classifies major accident types and represents them as input events of an automaton. It also constructs a hybrid automaton model of the heating network with explicitly defined discrete states and a transition function. In addition, protective mechanisms are represented as control automata with thresholds, delays, and logical dependencies. The plant and control automata are integrated into a closed-loop model for simulating representative accident scenarios, after which the correctness and robustness of protective functioning are evaluated and possible weaknesses are identified.

Object of Study and Model Requirements

A typical district heating system (DHS) consists of one or more heat sources, such as boilers or combined heat and power plants, a supply and return pipeline network, pumping stations, regulation nodes, including valves, pressure regulators and heat exchangers, and consumers connected through substations. The physical process is thermo-hydraulic: hot water or steam flows through the network, transfers heat to consumers, and returns to the source for reheating.

Key operational parameters include pressure at characteristic nodes, supply and return temperature, and flow rates in pipelines. Safe operation requires that these variables remain within prescribed limits determined by design codes and equipment ratings. Exceeding these limits may lead to pipeline rupture, cavitation, boiling, thermal shock, or other forms of damage.

The system is equipped with various protective mechanisms. These include pressure relief valves, which open when pressure exceeds a setpoint; low-pressure protections for pumps, which trip the pump on insufficient suction head; over-temperature protections in boilers and heat exchangers; automatic and manual shut-off valves for isolating network segments; and emergency shutdown (ESD) functions at sources and pumping stations.

These protective devices typically implement threshold-based logic, often with intentional time delays and hysteresis to avoid spurious actions. Their activation changes the network topology or operating mode, for example by closing a valve or stopping a pump, and thus modifies the continuous dynamics.

The nature of accident evolution in district heating—continuous propagation of pressure and temperature waves combined with discrete switching of equipment—implies that the system must be modelled as a hybrid discrete–continuous process. Continuous models alone cannot represent trip logic or valve sequencing; discrete models alone cannot predict the magnitude and duration of overpressure or temperature excursions. Therefore, we adopt a hybrid automaton framework in which each discrete mode corresponds to a particular configuration of the network and protective devices, and continuous dynamics are represented by differential-algebraic equations (DAEs) associated with that mode.

The modelling requirements include the representation of normal, pre-fault, accident and recovery modes of the system. Accident events must be represented as inputs causing transitions between modes. The model must include protective logic with thresholds, delays, hysteresis and logical dependencies. It must also couple discrete control decisions with thermo-hydraulic continuous dynamics and provide the ability to simulate accident scenarios as sequences of discrete transitions and continuous evolution.

Classification of Accident Situations and Risk Factors

Major classes of accidents in district heating systems include pipeline ruptures and large leaks, which may be caused by corrosion, fatigue, water hammer or external impact and lead to rapid pressure drops and large mass discharge. Another important class is pressure surges and drops without physical rupture, which are associated with pump trips, rapid valve movements, or abrupt demand changes. Pump station failures caused by power loss or mechanical failure may result in loss of circulation in parts of the network. Failure of regulating equipment, such as stuck or misoperating valves and pressure regulators, may lead to overpressure, underpressure, or loss of supply in certain branches. Finally, reduction of heat source performance, including boiler or CHP trips or fuel supply interruption, primarily leads to loss of heat supply.

In the automaton framework, these accidents are represented as external input events. Let Σ denote the alphabet of input symbols, for example

$$\Sigma = \{\text{PipeBreak}(i), \text{PumpStationOut}(j), \text{ValveStuck}(k, \text{state}), \text{SourceDrop}, \dots\},$$

where the indices may indicate locations or components.

Each event $\sigma \in \Sigma$ causes an abrupt change of network configuration or boundary conditions and triggers protective responses. Primary events can also lead to secondary events: for example, a pipeline rupture causes a pressure drop that may trigger pump low-pressure trips; a pump station outage may lead to local boiling and subsequent overpressure.

The goal of scenario analysis is to consider a representative subset $\Sigma_{\text{init}}^{*} \subset \Sigma$ of initiating events and to study the resulting chains of state transitions in the closed-loop hybrid system.

Methodological Approach: Automata Representation of the Thermal Network

We denote the automaton model of the heating network by $H = (S, \Sigma, \delta)$, where S is the state space, Σ is the set of input events defined above, and δ is the transition function. The automaton is hybrid: states have both discrete and continuous components.

Discrete States of the System

We decompose the state space as $S = S_d \times \mathbb{R}^n$, where S_d is a finite set of discrete modes and $\mathbb{R}^n$ is the space of continuous variables, including pressures, flows and temperatures at selected nodes.

Typical discrete modes include normal operation, where all equipment functions within permissible limits and no protections are active. They also include pre-alarm states, where deviations exceed alarm thresholds but remain below trip thresholds, allowing operator intervention. Accident states of varying severity may include modes such as PipeBreak, PumpStationOut, and OverpressureRelief, which may be further refined by location and component. Post-accident recovery states describe reconfigured operation after isolation of damaged segments or activation of backup equipment.

Each discrete mode $q \in S_d$ corresponds to a given combination of equipment status, such as pumps on or off, valves open or closed, and relief valves open or closed. Therefore, each mode defines a specific network topology and a corresponding set of boundary conditions.

Transition Function

The transition function $\delta: S \times \Sigma \to S$ governs discrete changes of mode. For clarity, we distinguish transitions caused by external accident events $\sigma \in \Sigma$ and internal transitions caused by protective actions or by crossing continuous thresholds.

Examples of transition rules include the transition from Normal to Accident: if a primary event $\sigma = \text{PipeBreak}$ occurs in mode Normal, then $\delta\big((\text{Normal}, x), \sigma\big) = (\text{PipeBreak}, x')$, where x' accounts for the instant effect of a leak, such as the initial pressure drop at the break. Another example is the transition from Pre-alarm to Accident: if a monitored variable $y(t)$ crosses a trip threshold for longer than a specified delay, the crossing is abstracted as an internal event and causes a transition to an accident state. A transition from Accident to Recovery occurs once isolation valves report closed and protective actions complete. Finally, a transition from Recovery to Normal occurs after reconfiguration or repair, and when variables return to permissible ranges.

Realistic modelling requires explicit incorporation of delays, hysteresis and nonlinearities. Delays are needed because trip logic typically requires that conditions persist for a minimum time to avoid spurious trips. In timed automata terms, clocks and timing guards can be used to ensure that transitions are enabled only when, for example, $y(t) < y_{\min}$ holds for more than τ_{trip} seconds. Hysteresis is required because different thresholds for activation and reset prevent chattering. For instance, a relief valve may open at P_{set} and close only after pressure falls below $P_{\text{set}} - \Delta P$; this can be implemented as distinct guards for forward and reverse transitions . Nonlinear conditions, including composite logical conditions such as low pressure *and* pump running, as well as rate-of-change constraints, can also be encoded as guards.

Formally, the model can be viewed as a possibly timed hybrid automaton in which time elapses in each mode subject to invariants, and transitions are guarded by predicates over both continuous variables and clocks.

Hybridisation of the Model

For each discrete mode $q \in S_d$ we associate a system of DAEs

$$f_q(x, \dot{x}) = 0,$$

describing thermo-hydraulic dynamics in that mode. These equations include continuity and momentum relations for flow in pipes, energy balance for heat transport and losses, and component-specific relations such as pump head–flow curves, valve characteristics and heat exchanger performance.

When a mode transition occurs, for example due to valve closure or pump trip, the structure of the DAEs and/or parameters change, reflecting the new topology or equipment states.

The hybrid system evolves through continuous evolution $x(t)$ satisfying $f_q(x, \dot{x}) = 0$ in mode q, and through discrete jumps $(q, x) \to (q', x')$ governed by δ, with x' determined by appropriate reset maps or continuity conditions.

Continuous variables influence discrete transitions via guard conditions. Conversely, discrete transitions modify continuous dynamics through changes to q and possibly x'. This coupling is characteristic of hybrid automata and underlies many embedded control systems.

Formation of Accident Development Scenarios

Given the hybrid automaton model, an accident scenario is represented as a trajectory in state space

$$(q_0, x_0) \overset{\sigma_0}{\to} (q_1, x_1) \overset{\sigma_1}{\to} \cdots \overset{\sigma_k}{\to} (q_{k+1}, x_{k+1}),$$

where σ_i denote exogenous accident events or internally generated events, such as threshold crossings or controller commands.

Scenario construction begins with initialization of the system in a nominal steady state (q_0, x_0), where $q_0 =$ Normal. Then a primary initiating event $\sigma_0 \in \Sigma$, such as a pipe rupture or pump station outage, is applied, and the resulting state $(q_1, x_1) = \delta\big((q_0, x_0), \sigma_0\big)$ is computed. After that, continuous dynamics are integrated in mode q_1 until a guard condition is satisfied or a new event occurs. The corresponding transition is then triggered, updating the system to (q_2, x_2), and the evolution–transition cycle is repeated. The process terminates when a recovery mode is reached or when an unsafe absorbing state is encountered, for example uncontrolled overpressure.

Examples of trajectories include a pipeline break and isolation scenario, where the sequence may be represented as Normal → PipeBreak → pump low-pressure trip → PipeBreak_PumpOff → isolation valves closed → IsolatedRecovery. In a pump station blackout and backup scenario, the sequence may be represented as Normal → PumpStationOut → LowPressureAlarm → BackupPumpStart → DegradedRecovery. In a control valve failure and relief scenario, the sequence may be represented as Normal → ValveStuckClosed → OverpressureAlarm → ReliefOpen → OverpressureControlled.

Scenarios can be documented as chains of transitions or visualised as paths in the state-transition graph. They provide a structured means of exploring accident development and assessing whether protective mechanisms prevent the system from entering dangerous regions of state space.

Simulation of Protective Mechanisms

This section focuses on the automata-based representation of protective mechanisms and their integration with the plant model.

Structure and Algorithms of Protections

Protective functions may be simple mechanical devices or complex logic implemented in safety PLCs or DCS-based ESD systems. Common features include threshold mechanisms, time delays, logical dependencies and coordination.

Threshold mechanisms are used in pressure relief valves opening at $P \geq P_{\mathrm{set}}$, in low-pressure trips for pumps if $P_{\mathrm{in}} \leq P_{\min}$, and in over-temperature trips for boilers if $T \geq T_{\max}$. The basic algorithm is of the form

$$\text{if } y(t) \geq y_{\mathrm{trip}} \text{ then trip; if } y(t) \leq y_{\mathrm{reset}} \text{ then reset,}$$

possibly with separate alarm thresholds.

Time delays are added to avoid nuisance trips caused by short disturbances or measurement noise: conditions must persist for a minimum duration τ_{trip} before a trip is issued. A small intentional delay significantly reduces spurious trips while still maintaining safety margins defined by the process safety time.

Logical dependencies and coordination are also important. Protective logic often includes interlocks based on equipment state, for example when a pump trip is enabled only if the pump is commanded to run. It may also use voting logic across redundant sensors, such as 2-out-of-3 voting for critical trips, to improve reliability. In addition, coordination between protections may be required, for example blocking automatic pump start if an upstream relief valve is open, or enforcing a specific sequence of actions. These behaviours can be naturally encoded in finite-state automata representing each protective function.

Automaton Representation of Protections

We represent each protection as a control automaton with transition function $\delta_{\mathrm{ctrl}}(s,x) \to u$, where $s \in S_d$ denotes the current discrete mode of the plant, $x \in \mathbb{R}^n$ the vector of measured process variables, and u a set of control commands, such as “trip pump”, “close valve”, or “open relief”. Many protections also have internal states, such as Idle, Arming, and Tripped, so a more complete description is

$$\delta_{\mathrm{ctrl}} : Q_{\mathrm{ctrl}} \times S_d \times R^n \to Q_{\mathrm{ctrl}} \times U,$$

where Q_{ctrl} is the controller state space and U the set of possible command outputs.

For example, a low-pressure pump protection can be described as an automaton with the states Idle, TripDelay, and Tripped. Its input is the suction pressure $P_{\mathrm{in}}(t)$ together with the pump run command, and its output is a pump trip command when the automaton enters the Tripped state. The transition from Idle to TripDelay occurs if $P_{\mathrm{in}} < P_{\min}$ and the pump is commanded to run. The transition from TripDelay to Tripped occurs if $P_{\mathrm{in}} < P_{\min}$ persists for $t > \tau_{\mathrm{trip}}$. If $P_{\mathrm{in}} \geq P_{\min}$ before the delay expires, the automaton returns from TripDelay to Idle. The transition from Tripped to Idle is allowed only after manual reset and when $P_{\mathrm{in}} \geq P_{\mathrm{reset}}$.

Similarly, a relief valve can be modelled as a two-state automaton with states Closed and Open, where transitions are guarded by pressure thresholds with hysteresis and optional delay.

These automata are typically Mealy-type, where outputs are associated with transitions, or Moore-type, where outputs are associated with states. They operate concurrently with the plant, reading measured variables and issuing discrete control actions.

Coupling of Control Automata with the Plant Automaton

The plant automaton H and the set of control automata $\{C_i\}$ are coupled via feedback. The plant provides sensor values $x(t)$ and mode information $s(t)$ to the controllers. The controllers produce control commands $u_i(t)$ that trigger mode transitions in the plant.

This can be formalised either as a network of interacting hybrid automata or as a single augmented automaton with composite state $(q, x, q_{\mathrm{ctrl},1}, \dots, q_{\mathrm{ctrl},m})$. Practically, the interface is implemented by treating controller outputs as events in the plant automaton:

$$\delta\big((s,x), \sigma_{\mathrm{ctrl}}\big) = (s', x'),$$

where σ_{ctrl} encodes commands such as “PumpTrip” or “ValveClose”. The transition changes the discrete configuration, for example pump status or valve position, and thus the continuous dynamics $f_{s'}$.

The resulting closed-loop system is itself a hybrid automaton, for which safety properties can in principle be analysed using hybrid systems techniques such as reachability analysis and model checking.

Evaluation of Protective Functioning

The correctness and robustness of the protective mechanisms are assessed by analysing simulation trajectories according to several criteria. Threshold sufficiency means that trip thresholds must be low or high enough to prevent equipment damage, but not so conservative as to cause unnecessary trips. Simulation reveals whether, for example, relief valves open before pressure approaches design limits and whether pump trips occur early enough to avoid cavitation.

Robustness to transients means that intended delay and hysteresis should suppress nuisance trips caused by short disturbances or noise. In scenarios with transient dips or spikes, the automata should remain in normal states; chattering, understood as rapid switching, indicates insufficient hysteresis or overly short delays.

The model also allows identification of false and missed trips. False positives correspond to protective actions without true need, whereas false negatives correspond to failure to act under hazardous conditions. Both are undesirable and suggest adjustments to thresholds, delays or logic.

Coordination is another criterion, since multiple protections must not interact adversely. Oscillatory behaviour, for example cycles of relief valve opening and pump ramping, or conflicting commands indicate coordination issues that can be resolved by interlocks or revised logic.

Finally, stability and recovery are assessed by verifying that after protective actions the system converges to a stable safe state, that is, to a recovery mode. Continued divergence or oscillation indicates that protections are insufficient or that additional control strategies are required. These criteria provide a structured basis for tuning protection parameters and revising logic using the automata-based simulation framework.

Numerical Modelling and Results

A prototype implementation of the described framework was developed using a hybrid simulation environment combining thermo-hydraulic modelling with state-chart based discrete logic. For example, the continuous network dynamics can be implemented in MATLAB/Simulink with fluid libraries, while discrete automata are implemented using Stateflow or equivalent tools.

The test system is a simplified looped district heating network with a single heat source, two main pump stations and several consumer branches. Nominal conditions include a supply pressure of about 1.0 MPa and return pressure of 0.6 MPa, with design flow rates chosen to yield realistic pressure drops. Protective elements modelled as automata include low-pressure trips for each main pump, isolation valves around selected pipeline segments, a pressure relief valve at the source, and an over-temperature cutout at the boiler.

Representative accident scenarios were simulated. These scenarios included a full-bore pipeline rupture mid-way along a main line, an outage of a main pump station caused, for example, by power loss, a control valve stuck nearly closed in a consumer branch, and a heat source trip corresponding to loss of heat input.

For each scenario, simulation produced time histories of pressures, flows, temperatures and discrete states, as well as state-transition logs.

In the pipeline rupture scenario, the local pressure plunged rapidly and a major leak flow was observed. Isolation valve controllers detected abnormal conditions and commanded closure within a few seconds. The hybrid automaton trajectory followed the expected sequence: Normal → PipeBreak → PipeBreak_PumpOff due to low-pressure pump trip → IsolatedRecovery. After isolation, pressures in intact parts of the network recovered and flow losses ceased. Relief valves did not open unnecessarily, indicating appropriate setpoints and coordination.

In the pump station outage scenario, pressures in the affected region decayed; backup supply via an alternate pump was configured to start after a delay when pressure remained low. The automaton transitions captured this sequence and showed that pressure stayed within acceptable bounds once backup activated. Without backup, extended underpressure would have resulted, but still without additional mechanical damage, illustrating a reliability rather than a safety issue.

In the valve-stuck scenario, the stuck valve caused local loss of supply and upstream overpressure. The relief valve automaton opened when pressure exceeded its setpoint, limiting pressure to a safe level but at the cost of periodic venting. This revealed a potential weakness: relying solely on relief action leads to sustained inefficiencies and cyclic behaviour. Coordinated logic to throttle pumps or adjust network configuration based on relief valve status would improve performance.

The heat source trip scenario mainly resulted in gradual temperature decline; safety thresholds were not violated. No protective actions were triggered, which is appropriate: this is an availability issue, not a mechanical safety threat.

Parametric studies showed the effect of varying protection thresholds and delays. Lowering a relief setpoint increased frequency of operation and energy loss but reduced peak pressures; raising it reduced operations but increased margin utilisation. Varying pump low-pressure trip thresholds altered the balance between avoiding cavitation and preventing nuisance trips. These trade-offs can be quantitatively explored within the automata-based model.

Overall, the numerical experiments confirmed that the proposed hybrid automaton model reproduces expected system behaviour and provides a detailed view of protective mechanism operation.

Discussion

The results demonstrate that the automata-based model provides a transparent and rigorous representation of accident development and protective responses in district heating systems.

First, the explicit state-transition representation clarifies causal chains: which event triggered which protection, and at what time. This is valuable for post-incident analysis, for training, and for designing protection coordination. The concept of first-out logic, widely used in ESD systems, is naturally represented in the automaton by the sequence of transitions.

Second, the simulations revealed subtle interactions among protections. In particular, cases where relief valves and pumps could interact in a cyclic fashion suggest the need for improved coordination, such as interlocks or supervisory logic. Such issues are difficult to detect with purely steady-state analyses but become evident in hybrid simulations.

Third, the closed-loop hybrid automaton exhibited desirable stability properties in the considered scenarios: trajectories remained within safe bounds, and post-accident states settled to new equilibria rather than diverging. Although a formal proof of safety for all possible disturbances was not attempted here, the results support the conclusion that the current protection design is adequate for the examined cases.

At the same time, several limitations and sources of uncertainty must be acknowledged. The physical models are simplified, for example by assuming single-phase flow and approximate water hammer effects; phenomena such as flashing and two-phase flow during major leaks are not captured. Only single-fault scenarios were considered, whereas simultaneous faults or common-cause failures may stress protections beyond design assumptions. Sensor failures and human factors were not included, although real systems rely on redundant sensing and operator intervention, which could be represented by additional automata or stochastic models. Finally, computational complexity may limit the size and detail of networks that can be modelled with full hybrid dynamics.

Despite these limitations, the study supports the conclusion that automata-based hybrid modelling is a powerful tool for safety and reliability analysis of district heating systems. It complements traditional steady-state and probabilistic methods by providing time-resolved insight into accident dynamics and protection performance.

Conclusion

This work presented a hybrid automaton based approach for modelling the operation of protective mechanisms in district heating systems under accident conditions. The main contributions include the formulation of a hybrid automaton model of a district heating network, with discrete modes representing normal, pre-fault, accident and recovery regimes and continuous thermo-hydraulic dynamics associated with each mode. Another contribution is the representation of protective devices as control automata with thresholds, delays, hysteresis and logical dependencies, as well as the integration of these controllers with the plant automaton via feedback. The work also demonstrates, through numerical simulation of representative accident scenarios, that the model can reproduce realistic accident development and protective responses and can be used to evaluate the adequacy and robustness of protections.

The results show that the automata-based model can identify weaknesses in protection logic, support tuning of thresholds and delays, and provide insight into coordination among heterogeneous protective mechanisms. It thus offers a rigorous framework for scenario-based safety analysis and can enhance the design and verification of protective systems in district heating.

Future work directions include extension to probabilistic or stochastic hybrid automata to account for random failures of equipment and sensors, enabling quantitative risk assessment. Further development may also involve hierarchical or descriptive automata for large-scale networks, improving modularity and scalability. Another important direction is the application of formal verification techniques, such as model checking of timed and hybrid automata, to prove safety properties including non-reachability of unacceptable states. Finally, the proposed framework can be integrated into digital twin architectures for real-time monitoring and decision support.

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