Development of a Feedback Based Data Driven Fault Detection and Diagnosis Framework for Residential Heat Pump Systems

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Motivation

The building sector makes up about 35% of total German energy consumption[1]. Most of this energy is used for space and water heating predominantly reliant on burning fossil fuels[2]. To meet the federal climate goals, the heat pump (HP) technology is a promising solution, and the HP market is therefore greatly increasing. However, operational quality needs to be assured to increase the tolerance for this shift in heat generation; efficient Fault Detection and Diagnosis (FDD) is needed. Data driven methods show great potential in research, although they are no standard in industrial systems.

Challenges

- Residential Heating Systems are basically unique in topology and control concept
- Data situation is bad, since faults are undetected or unwanted and hard to emulate
- Faults are manifold in type and symptoms and there can be simultaneous or novel faults
- Reacting to faults conditions high interpretability and a human intervention

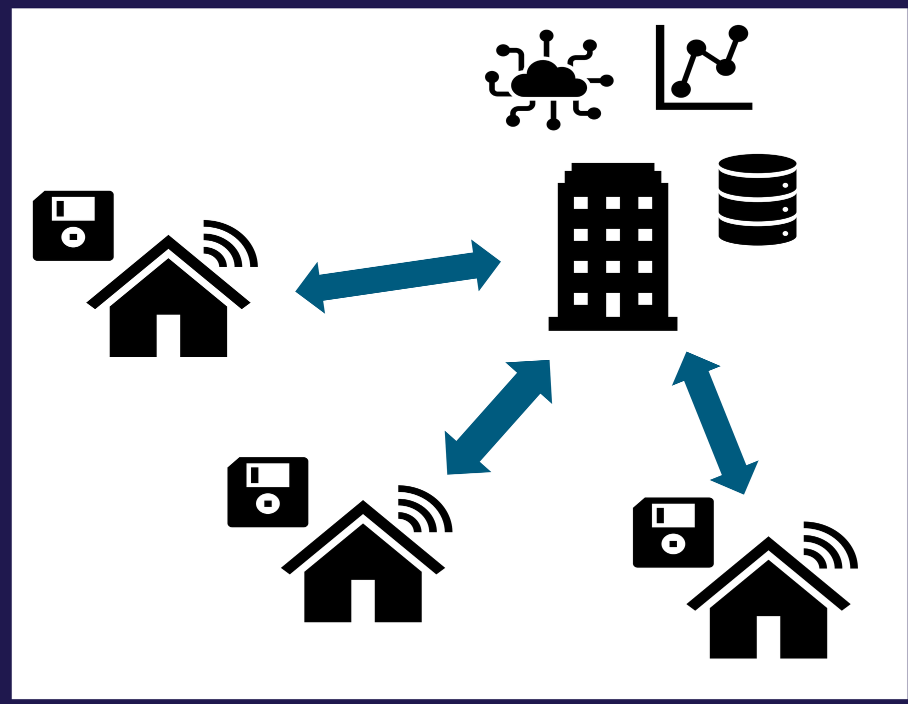
Current Standard

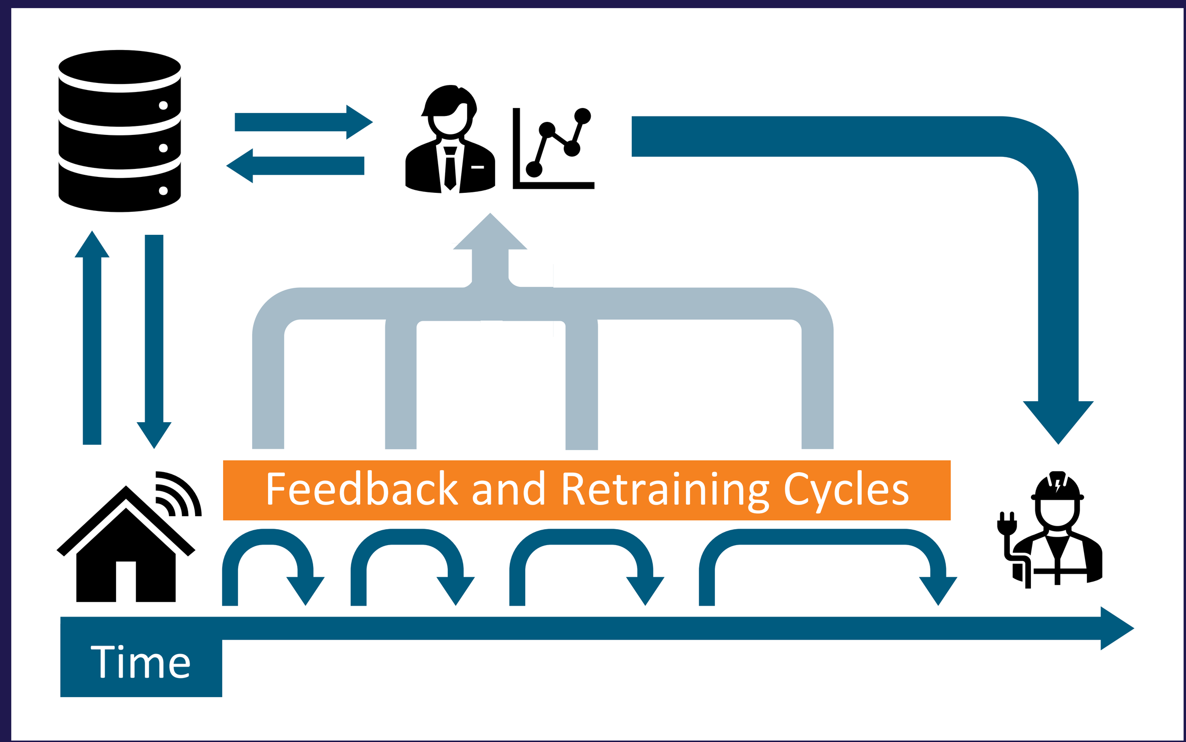
Most FDD methods work on component level. An HP for example has internal rules to capture faulty behavior from simple symptoms like an unmet set value in the supply temperature. Possible causes are listed, and error codes are generated. Maintenance is scheduled and an expert checks different system parts that could have caused the detected fault. There are many problems with this approach. System level faults and performance degrading soft faults are often overlooked, despite their relevance[3]. There is no shared analysis between systems, making the fault diagnosis and removal unnecessarily costly and time consuming. Simple rule-based systems tend to miss novel faults and often generate too many error messages, therefore being ignored by the workmen.

Proposed Fault Detection and Diagnosis Framework

Application Concept

An FDD company does centralized fault analysis of multiple systems and stores reusable information about known faults and pretrained detection methods. Experts answer feedback requests, oversee retraining cycles and schedule maintenance. Suitable ML-modules are stored and operated on the monitoring data decentral at the heating systems and generate emergency warnings.





Application Timeline

On initialization, the heating system components and topology are integrated into the database and suitable ML-modules are selected. In increasingly rare feedback cycles the ML-modules are retrained and adapt to the specific system. In case of faults, maintenance can be scheduled.

Relational Database

To benefit from shared analysis, the database contains information about the studied heating system and the available datapoints. ML-modules trained to e.g. detect a specific faulty operation mode in a single component can then be transferred to other systems sharing this component. Semantic fault information (like characteristic symptoms) as well as time series examples of connected datapoints are integrated into the database to support the expert feedback process. The integration of novel faults and new detection methods during application of the FDD framework enhance the database and consequently the analysis of other monitored heating systems.

Feedback System

Every analyzed system zone or component is assumed to be in one or more faulty or nominal state, associated with an ML-module. Only when no ML-module can make a reliable prediction, feedback is requested. The predictions aid the expert in the labelling process as state suggestions. Feedback is used to retrain the supervised ML-modules with unsure prediction. False predictions indicate novel behavior and new ML-modules are initialized.

Nominal State 1	Nominal State 2	Faulty State 1	Faulty State 2	...	Feed back
True	False	False	False	...	No
Unsure	True	False	False	...	No
False	Unsure	True	True	...	No
False	Unsure	False	Unsure	...	Yes
False	False	False	False	...	Yes

COMETH Principle[4]

An ML-module consists of two supervised ML-Methods with different sensitivity and specificity goals. They optimize a weighted f_β-score and converge to their maximum performance from complementary directions. When the models disagree, feedback is requested, if not the result is assumed to be reliable. The methods can be chosen freely but should be retrainable and contain hyperparameters with influence on sensitivity.

ML-Module		Sensitive Method	
		True	False
Specific Method	True	True	Unsure
	False	Unsure	False

$$SP = \frac{TN}{TN + FP}$$

$$SE = \frac{TP}{TP + FN}$$

$$f_\beta = \frac{(1+\beta^2)\cdot SP \cdot SE}{(\beta^2 \cdot SP) + SE}$$

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zee Zentrum für Erneuerbare Energien Centre for Renewable Energy

Fraunhofer ISE

INATECH Institut für Nachhaltige Technische Systeme

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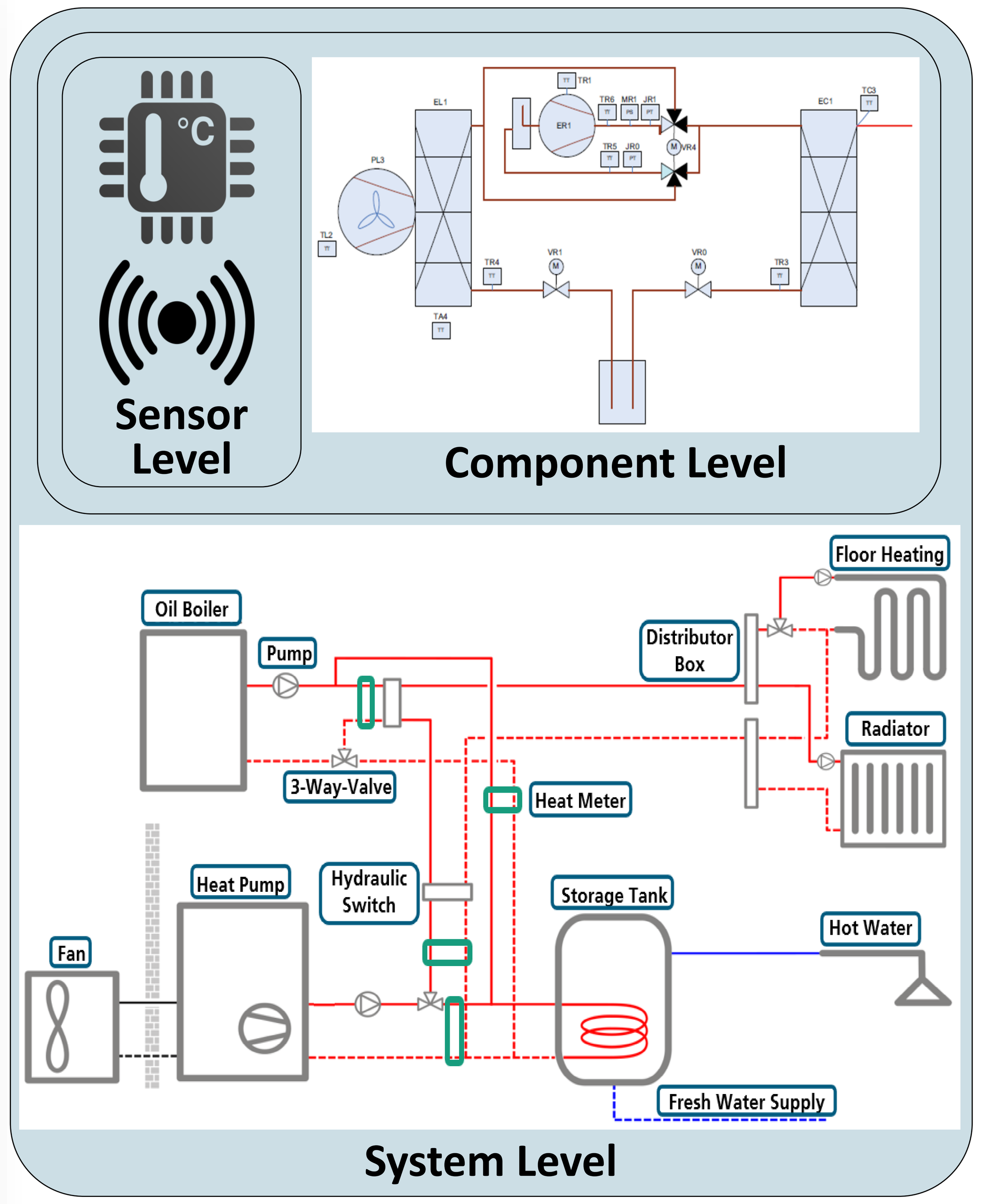
Fault Levels



Systems

Most existing residential heating systems have a boiler and can utilize an HP in a hybrid approach. Modern buildings integrate PV collectors and drop the boiler in favor of electrical backup heaters. The resulting systems have varying topologies and control concepts based on cost, load, T_{amb} or share of renewable energies.

Data

Fault data can be generated from labelling monitoring data of existing buildings (tedious and erroneous), emulating faults in test labs (involves great effort) and simulations (which need validation). We focus on system temperatures, pressures, mass flows and electrical power consumption and control signals of components.

Sources

1. AG Energiebilanzen e.V. Energy Consumption in Germany in 2022 URL https://ag-energiebilanzen.de/wp-content/uploads/2023/07/AGEB_Jahresbericht2022_20230630_engl.pdf
2. Agora Energiewende Die Energiewende in Deutschland: Stand der Dinge 2023. Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2024 URL https://www.agora-energiewende.de/fileadmin/Projekte/2023/2023-35_DE_JAW23/A-EW_317_JAW23_WEB.pdf
3. Madani H 2014 The Common and Costly Faults in Heat Pump Systems *Energy Procedia* **61** 1803-6
4. Benndorf G A, Wystrcil D and Réhault N 2018 A fault detection system based on two complementary methods and continuous updates *IFAC-PapersOnLine* **51** (24) 353-358

Associated Projects

- LCR290 - Development of heat pump solutions with propane for the replacement of gas and oil appliances. The research work is supported by funds from the Federal Ministry for Economic Affairs and Energy (BMWK.IIB5) under grant numbers 03EN4046. Project management is undertaken by the Project Management Agency Jülich (PT-J.ESN4). The authors express their sincere gratitude for the funding, support, and collaboration
- Joint project: Future-Hybrid - Complexity reduction for heat pump hybrid systems of the future; sub-project: Complexity reduction and autoparameterization. The research work is supported by funds from the Federal Ministry for Economic Affairs and Energy (BMWK.IIB5) under grant numbers 03EN4052B. Project management is undertaken by the Project Management Agency Jülich (PT-J.ESN4). The authors express their sincere gratitude for the funding, support, and collaboration