FACULTY OF
ENGINEERING
AND TECHNOLOGY

HOCHSCHULE
FURTWANGEN
UNIVERSITY

Master Thesis

Fluid 4.0-Compliant Framework for Digital Representation and Graph-Based Neural Modeling of Hydraulic Systems

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Submitted in partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

Program: Advanced Precision Engineering (APE)
Faculty of Engineering and Technology
Hochschule Furtwangen

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Submission: 26 January 2026, Villingen-Schwenningen

Abstract

The Fluid 4.0 approach was explicitly conceived to go beyond standard IT solutions and static mapping. It directly addresses persistent operational challenges in hydraulic systems, such as productivity, lead time, and quality, thereby confirming its role as a framework that tackles core manufacturing bottlenecks rather than remaining confined to conventional IT.

In this thesis, Fluid 4.0 is established as a standardized, topology-agnostic approach for representing hydraulic systems in a machine-readable and semantically consistent form. This methodology solves the fundamental problem of requiring a unique predictive model for each individual system. Hydraulic circuits are expressed as directed multigraphs encoded in a JSON schema that maps each component to its SAP name, ensuring seamless integration with enterprise asset management and strategic maintenance planning. This representation is fully compatible with the Asset Administration Shell (AAS), ensuring compliance with Industry 4.0 standards and full lifecycle traceability. The graph encapsulates both the physical connections of components and the underlying physical relationships between variables, preserving a baseline description of system dynamics that remains valid across different topologies. Consequently, a single foundational model can be rapidly fine-tuned to new hydraulic configurations, predicting key operational outputs such as pressure, flow, or cylinder position.

Building on this representation, the thesis introduces PhysiGNet (Physical Graph-based Neural Entity), a graph-based neural model that learns physical behavior from normal operational data. By exploiting the inherent graph structure, PhysiGNet provides a powerful and reusable baseline that generalizes across hydraulic systems, eliminating the need for training a completely new model from scratch for each machine. The deviations between its predictions and measured values enable precise anomaly detection and fault localization at the component level. This capability allows for evaluating current system performance and assessing the rationale of planned replacements against actual operational behavior. Furthermore, this methodology naturally extends to predicting the Remaining Useful Life (RUL) of components, providing a data-driven foundation for maintenance strategies.

The framework is grounded in a thorough investigation of real industrial needs and validated through a real-world demonstrator. The results showcase measurable improvements in transparency, predictive maintenance accuracy, and industrial scalability, confirming that Fluid 4.0 bridges the gap between abstract IT infrastructures and tangible day-to-day manufacturing performance.

Core Objectives

- Investigate operational bottlenecks in hydraulic plants and assess how Fluid 4.0 can reduce dependency on extensive fault data, enabling generalizable models and measurable improvements in productivity, lead time, and quality.

- Define a reusable schema for hydraulic diagrams that encodes component topology, fluidic connectivity, and measurement points, enabling semantic consistency and machine-readability.

- Develop PhysiGNet, a graph-based neural model trained on normal data to infer physical behavior, enabling anomaly detection and leakage localization without requiring labeled fault data.

- Validate the proposed framework through a real-world demonstrator, emphasizing gains in predictive capability, lifecycle transparency, and industrial scalability under Fluid 4.0 principles.

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