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Integrating artificial intelligence in the lifecycle evolution of district heating networks: challenges and opportunities

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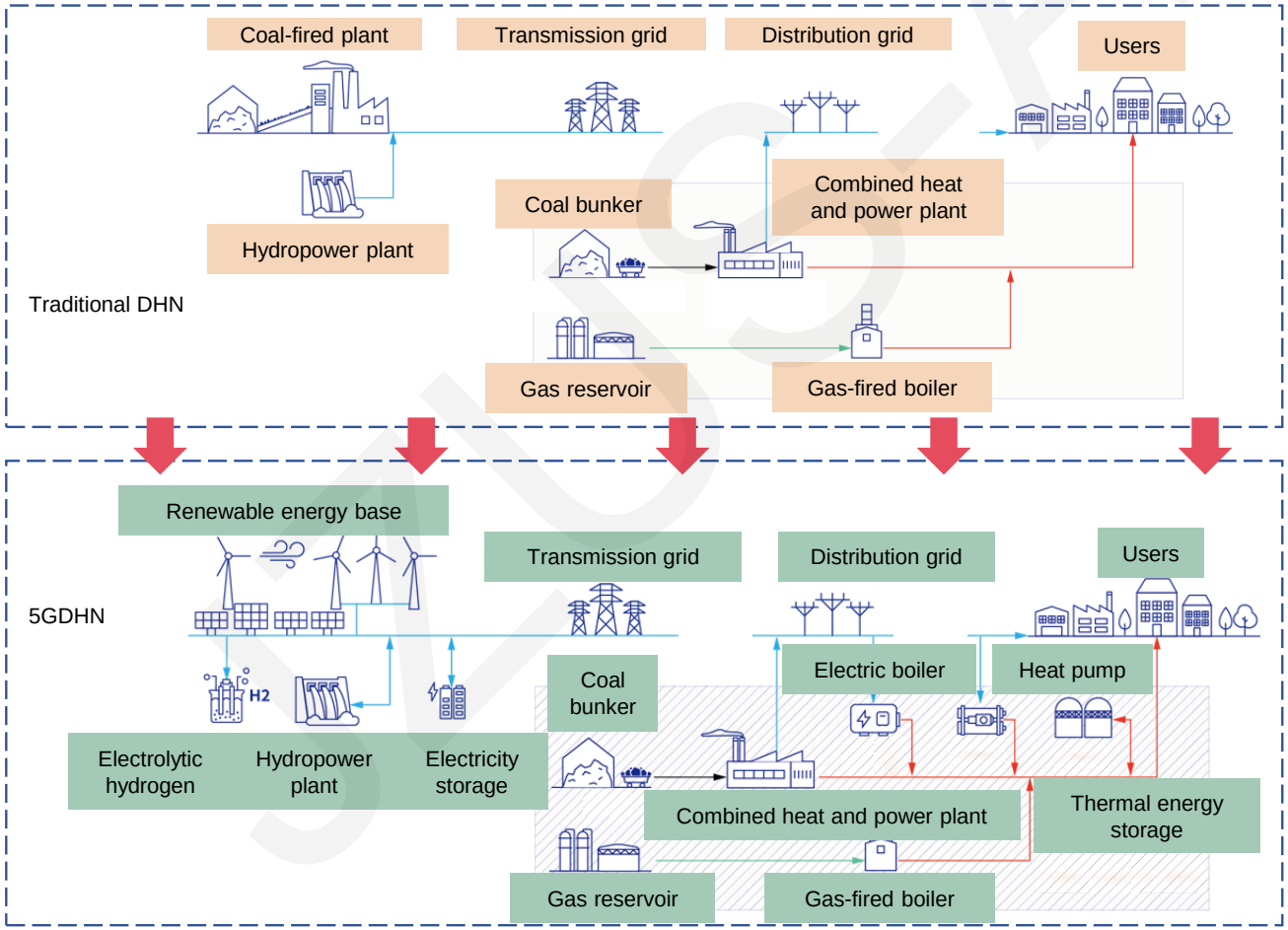
A collaborative research between Zhejiang University and Zhejiang Engipower Technology Co., Ltd.

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Background: from traditional DHNs to 5G DHNs

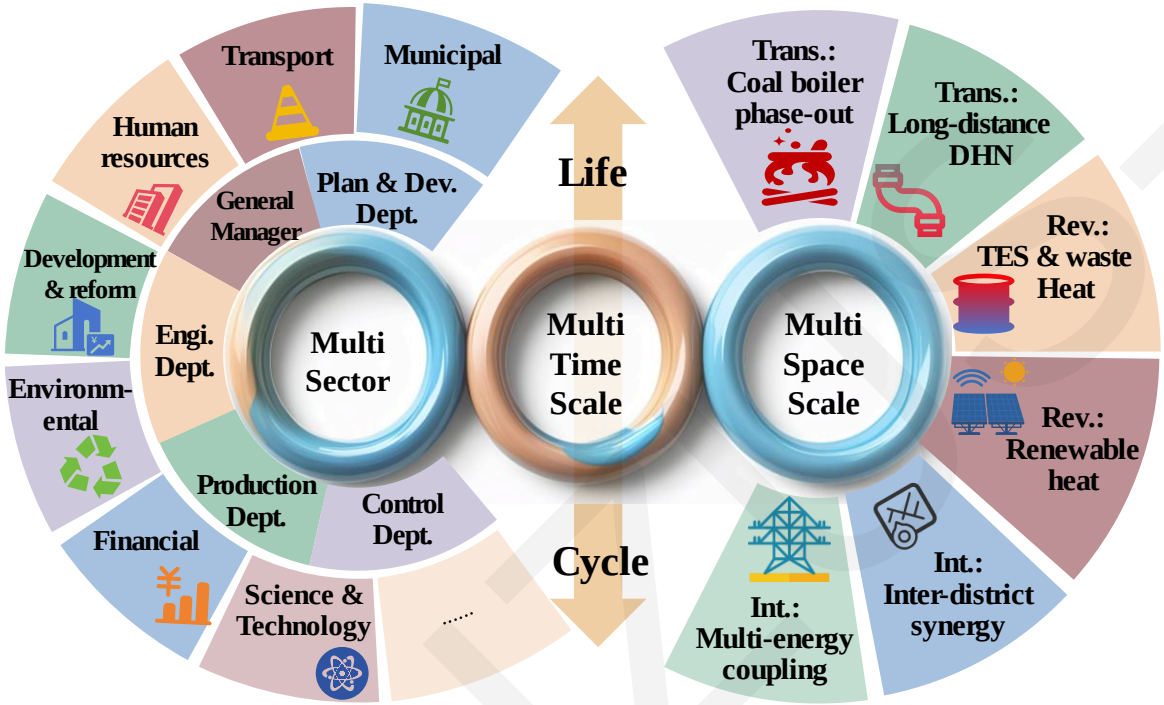
- Heating accounts for about 50% of global energy use; District heating networks (DHNs) must shift from fossil-fuel, high-temperature operation to low-carbon, multi-source coordination.
- 5G DHNs keywords: near-ambient temperature, bidirectional energy flow, decentralized heat sources, thermal storage, and renewable heat.



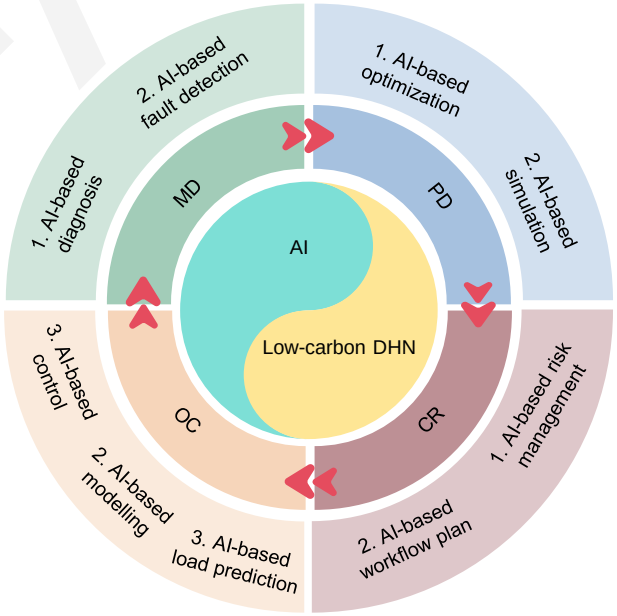
Transformation from traditional DHN to 5G DHN

AI across the DHNs lifecycle

- Full lifecycle: Planning & design (PD) → Construction & renewal (CR) → Operation & control (OC) → Maintenance & diagnosis (MD).
- The AI toolbox spans machine learning, reinforcement learning, evolutionary algorithms, multi-agent systems, expert systems, and natural language processing (NLP).

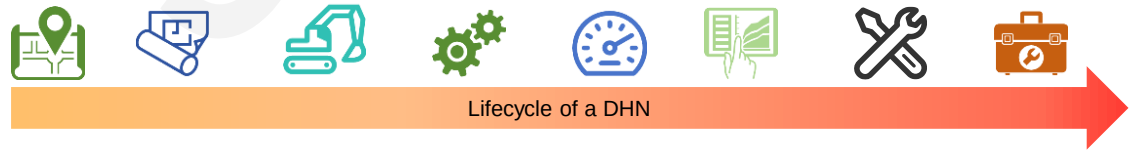


Abbreviations: Dept.=Department; Dev.=Development; DHN = District heating network; Engi. =Engineering; Trans. = Transformation; Rev. = Revolution; Int. = Integration; TES = Thermal energy storage.



Overview of AI in the lifecycle of a DHN

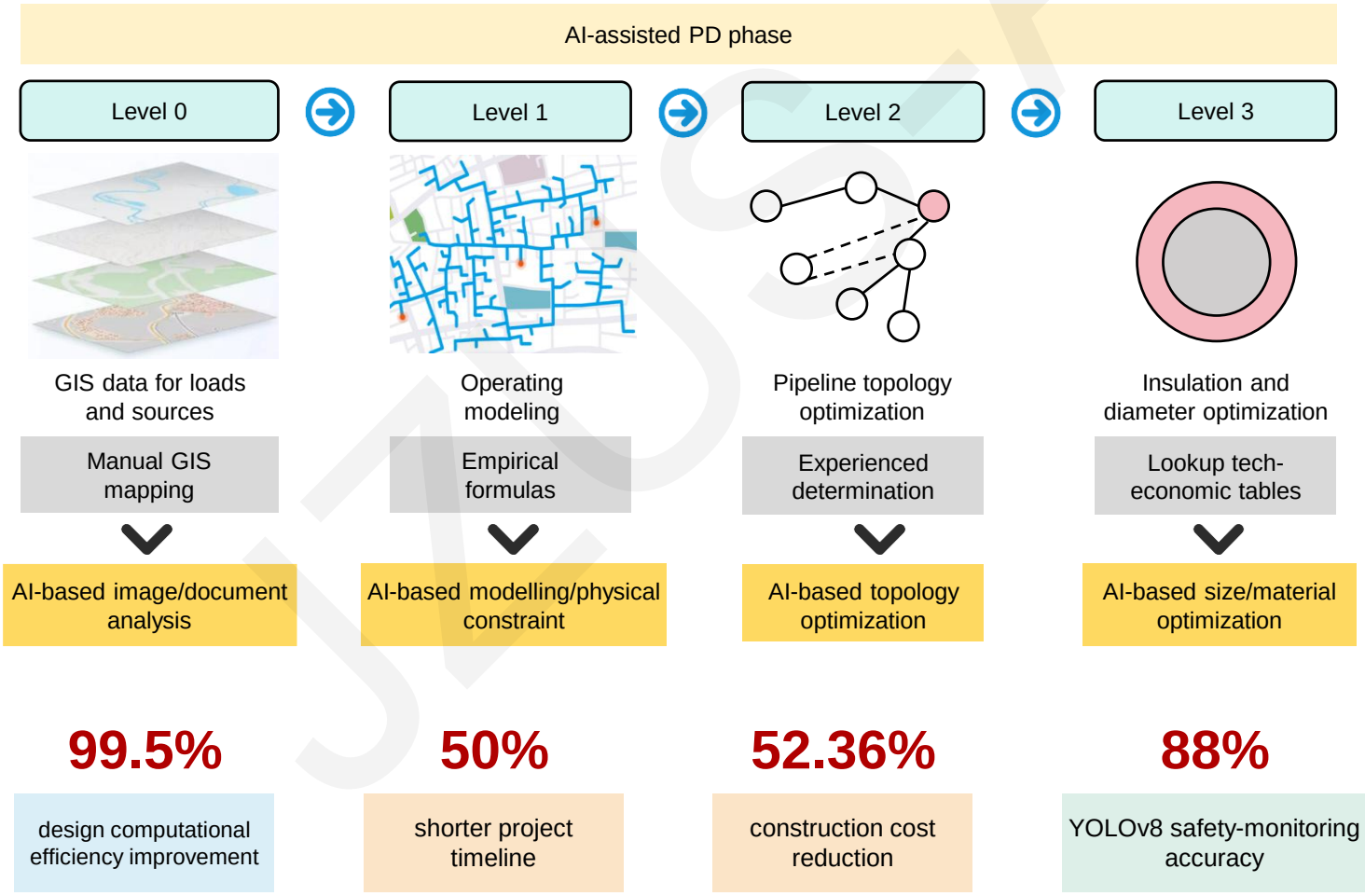
Three core characteristics for the transformation of 5G DHN



Lifecycle of a DHN

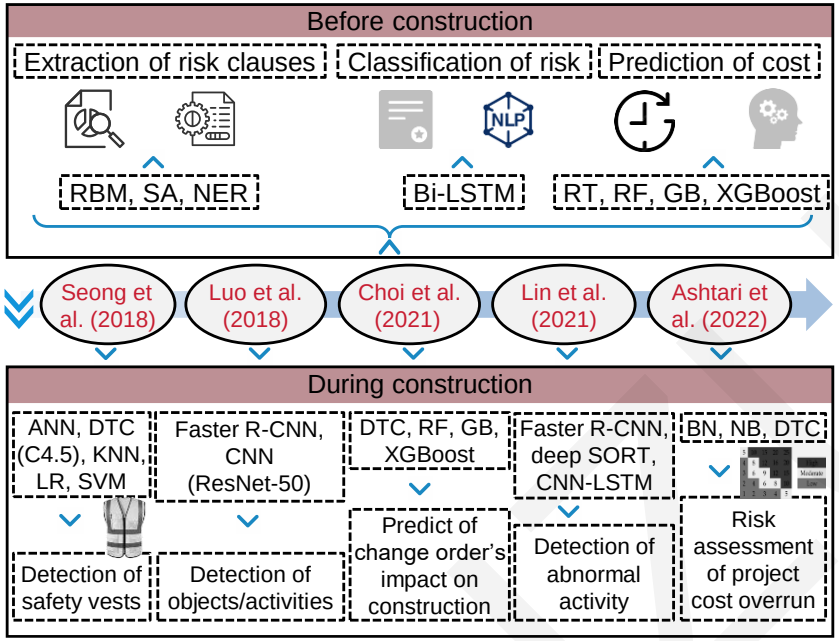
Planning and design

- The Planning and design (PD) phase of DHNs is a complex and multistage optimization problem that is fundamentally concerned with the configuration of pipelines, heat substations, and related components.
- PD: GIS data, operational modeling, network topology, and insulation/pipe-diameter optimization move from experience-driven to AI-assisted workflows.

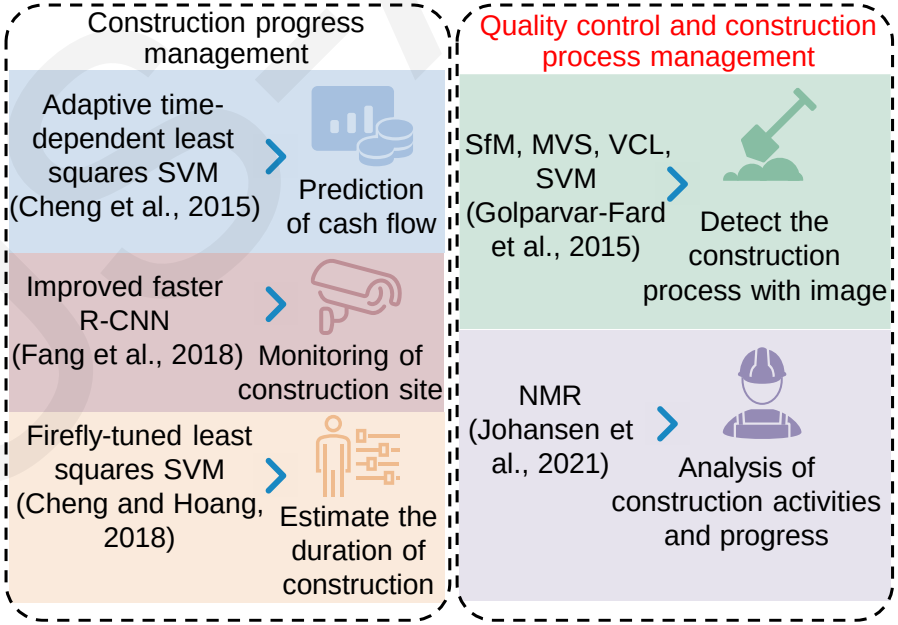


Construction and renewal

- DHN construction features long duration, extended routes, high cost exposure, safety risk, and coordination with municipal utilities.
- Before construction, NLP and ML support contract-risk extraction, risk classification, cost prediction, and drawing-error checks.
- During construction, computer vision and sensing support site safety, progress tracking, workflow planning, and quality control.



AI techniques applied to construction risk assessment.



AI techniques applied to construction workflow planning

50%
faster completion in BIM-enabled construction case studies

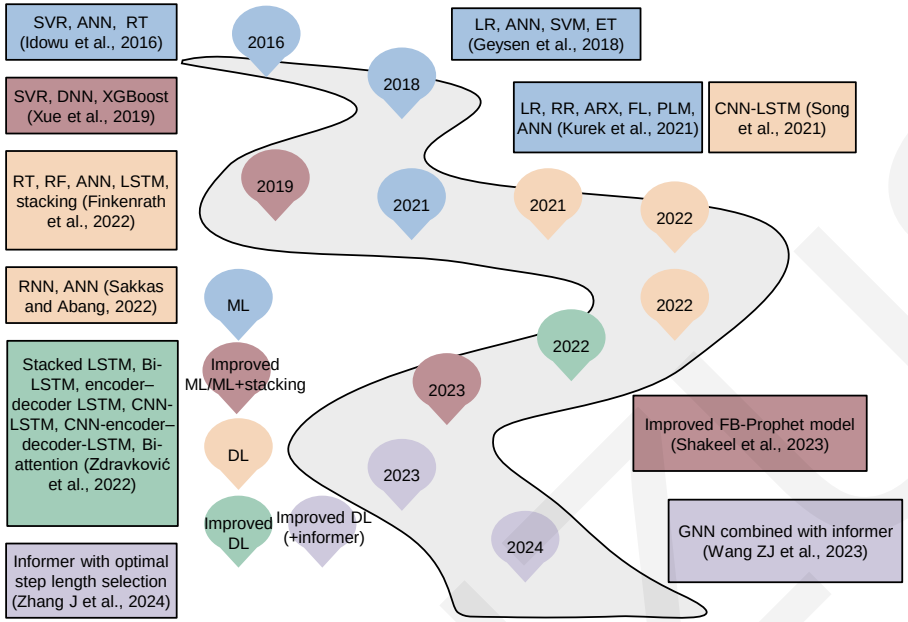
52.36%
reported construction cost reduction

88%
YOLOv8 hardhat/safety monitoring accuracy

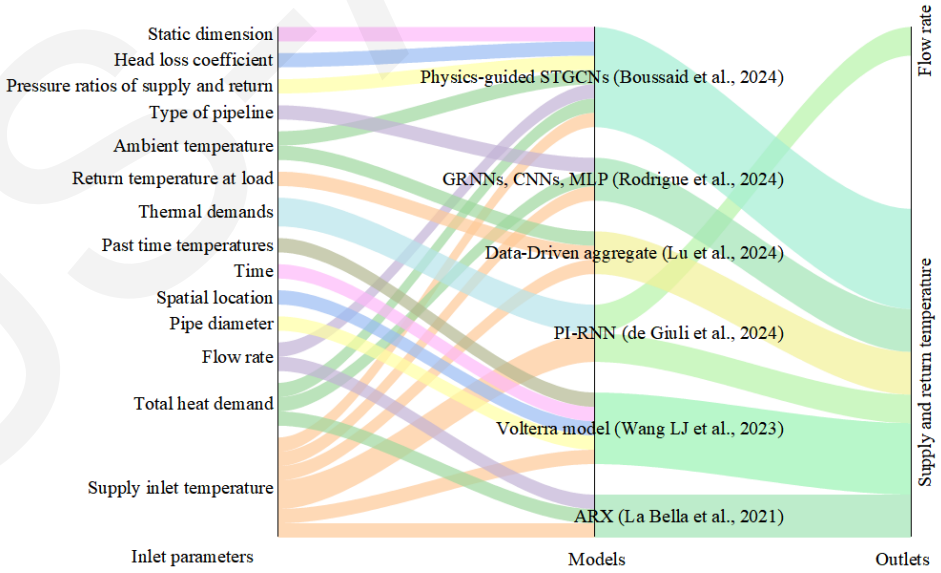
30%
better progress reporting accuracy

Operation and control

- Operation and control (OC) follows a forecast–model–optimize loop: thermal-load forecasting, hydraulic-thermal modeling, and optimal dispatch.
- AI models improve load forecasting; physics-informed and graph-based models accelerate digital-twin simulation; MPC, MAS, MILP and RL support control.



AI techniques applied to thermal load prediction.



AI techniques applied to hydraulic and thermal modeling.

59.4%

forecasting error reduction in noisy IoT settings

21.2→8.6%

MAPE reduction

99%

less dynamic calculation time with physics-guided STGCN

12.5%

operational cost reduction with MPC in a representative week

Maintenance and fault diagnosis

- Maintenance and fault diagnosis (MD) covers monitoring/metering, fault detection and diagnosis, leak localization, predictive maintenance, and remaining useful life assessment.
- AI can learn patterns from sensor streams and simulation data, but real fault data scarcity and transferability remain critical bottlenecks.

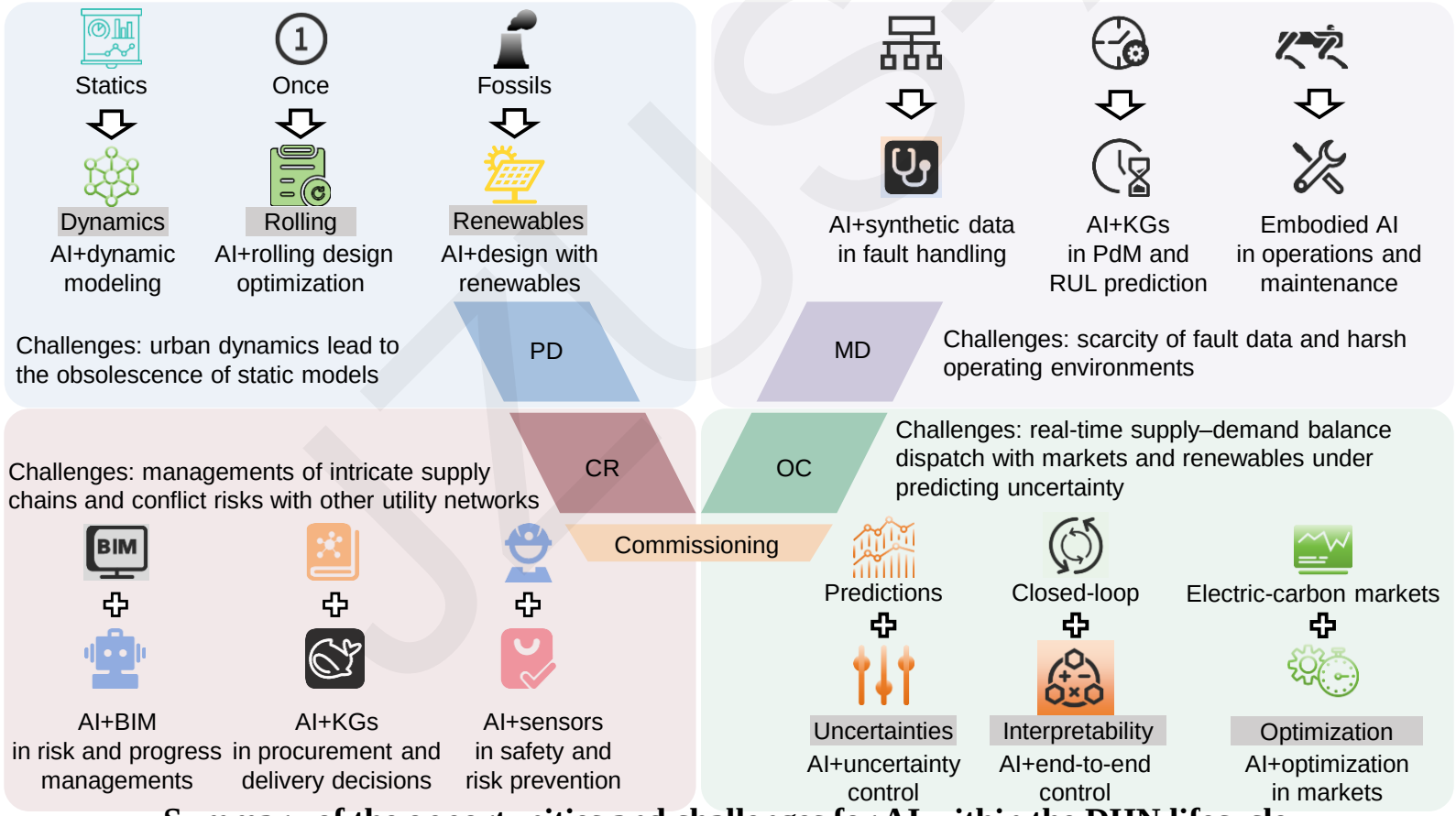
AI techniques applied to fault detection and metering

Detection task	AI technology	Reference
Failure of component	CNN	Li et al. (2020)
	SVM, ANN, bagging DTC	Pałasz and Przysowa (2019)
	XGBoost	Xue et al. (2020)
Pipeline leakage detection and localization	Contextual bandit	Shen et al. (2021)
	ANN	Liu et al. (2023)
	Cuckoo search algorithm and clustering	Xi et al. (2024)
Pipeline pressure and heat loss	Nonlinear ARX neural network	Losi et al. (2024)

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Opportunities and challenges

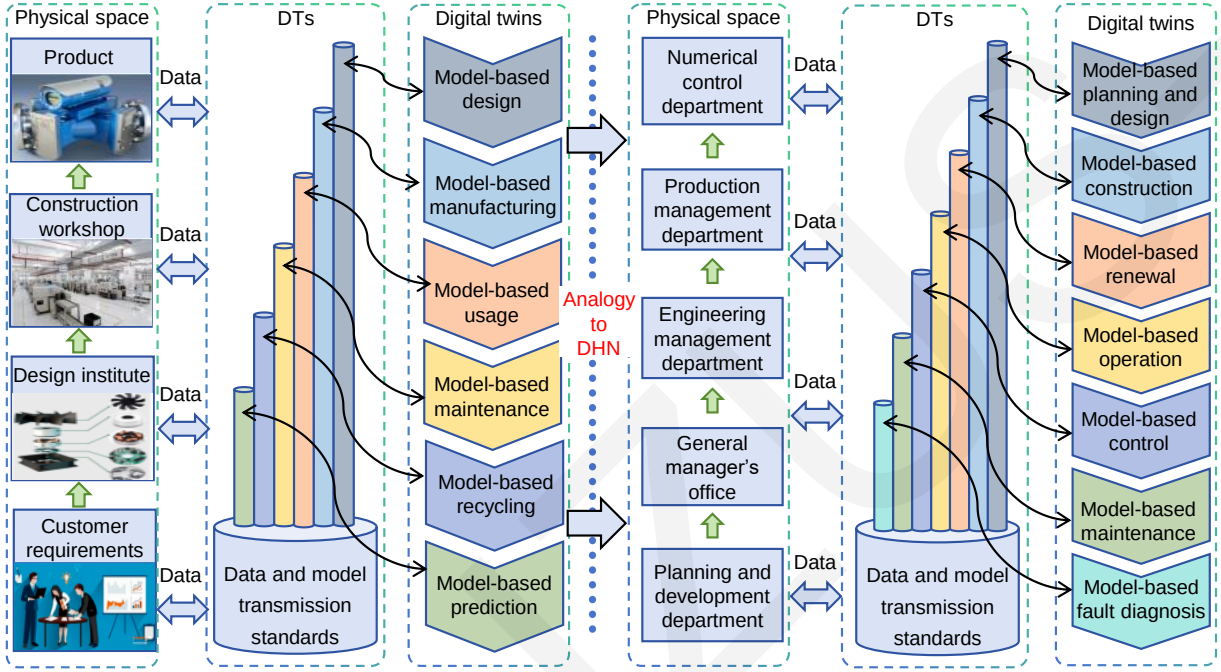
- PD challenge: static models become obsolete as cities evolve; opportunity: dynamic modeling, rolling design optimization, and renewables-aware planning.
- CR challenge: supply chains and utility conflicts; opportunity: AI+BIM, knowledge graphs for procurement, and sensor-based safety systems.
- OC challenge: uncertain supply–demand balance with markets and renewables; opportunity: uncertainty-aware, interpretable, end-to-end control.
- MD challenge: scarce fault data and harsh environments; opportunity: synthetic data, PdM/RUL prediction, and embodied AI inspection.



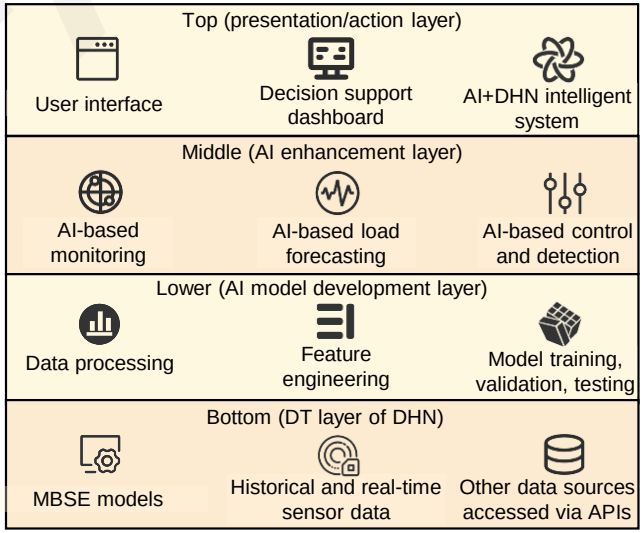
Summary of the opportunities and challenges for AI within the DHN lifecycle

Conclusions

- AI has measurable value across the DHN lifecycle: faster design, safer construction, better forecasting/control, and earlier fault warnings.
- Fragmented applications, data silos, and black-box trust barriers limit full lifecycle optimization.
- The proposed digital thread integrates MBSE models, BIM/GIS/SCADA/maintenance data, and AI services into a unified closed-loop architecture.



Conceptual architecture of the DT paradigm of the DHN, showcasing the central thread integrating all lifecycle



Four-layer architecture of a typical AI-assisted DT platform of the DHN

Future directions

- Adaptive cross-stage semantic interfaces
- Proactive data augmentation
- Distributed collaborative AI-agent networks

Acknowledgments

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