

Probabilistic Estimation of Health Indicators of Complex Systems

Lucas THIL^{1,2}, Pr. Jesse READ², Dr. Rim KADDAH¹

1: IRT SystemX, 2: École Polytechnique

1. Scientific Context

Estimating the health of complex industrial systems with Digital Twins (DT)

- Utilizing sensor data to monitor industrial systems
- Probabilistic estimation of health indicators (HI)
- Combining invariant characteristics and learned information from measured data

Considering the physics governing system operation

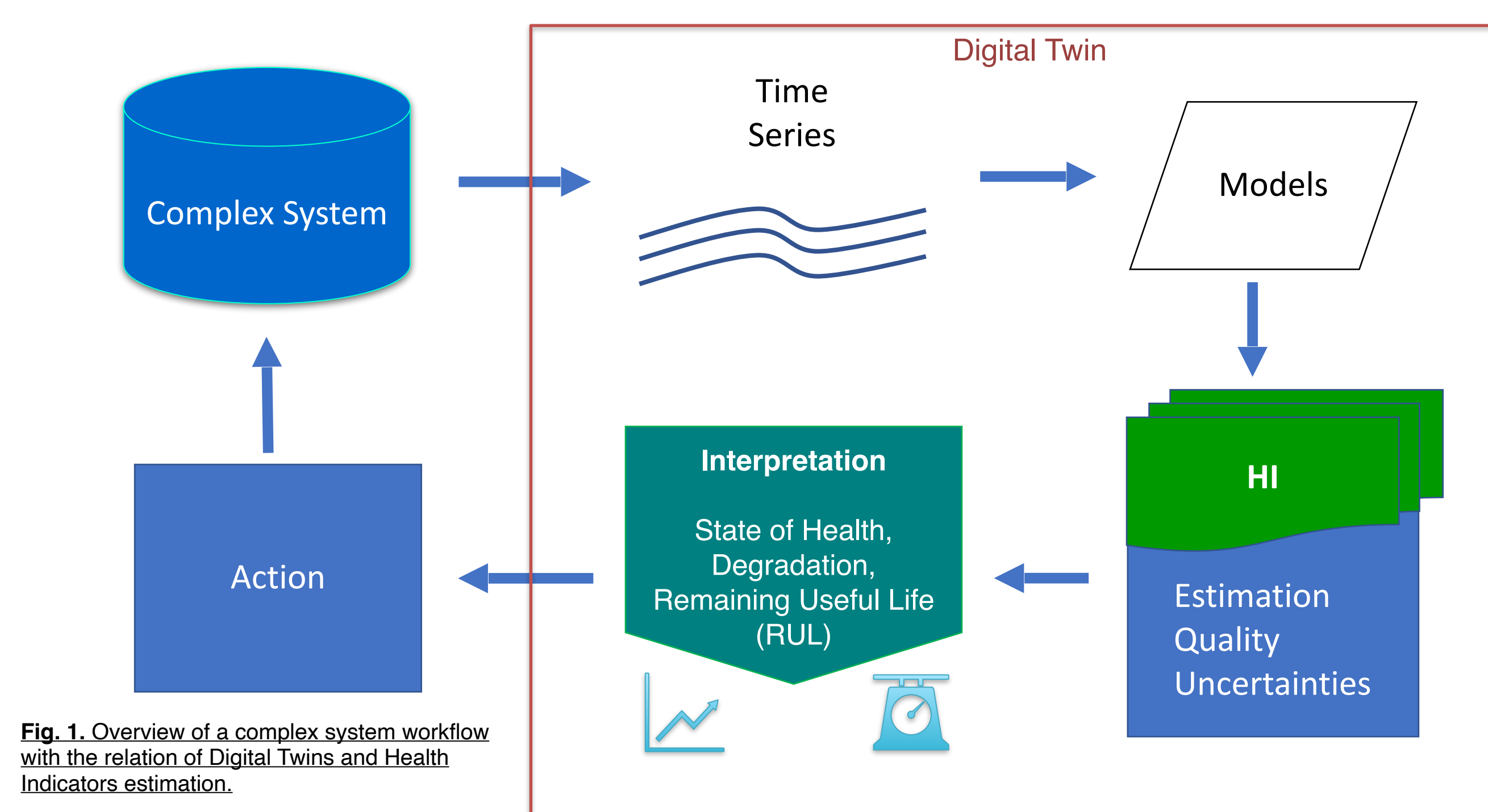


Fig. 1. Overview of a complex system workflow with the relation of Digital Twins and Health Indicators estimation.

2. Challenges and objectives

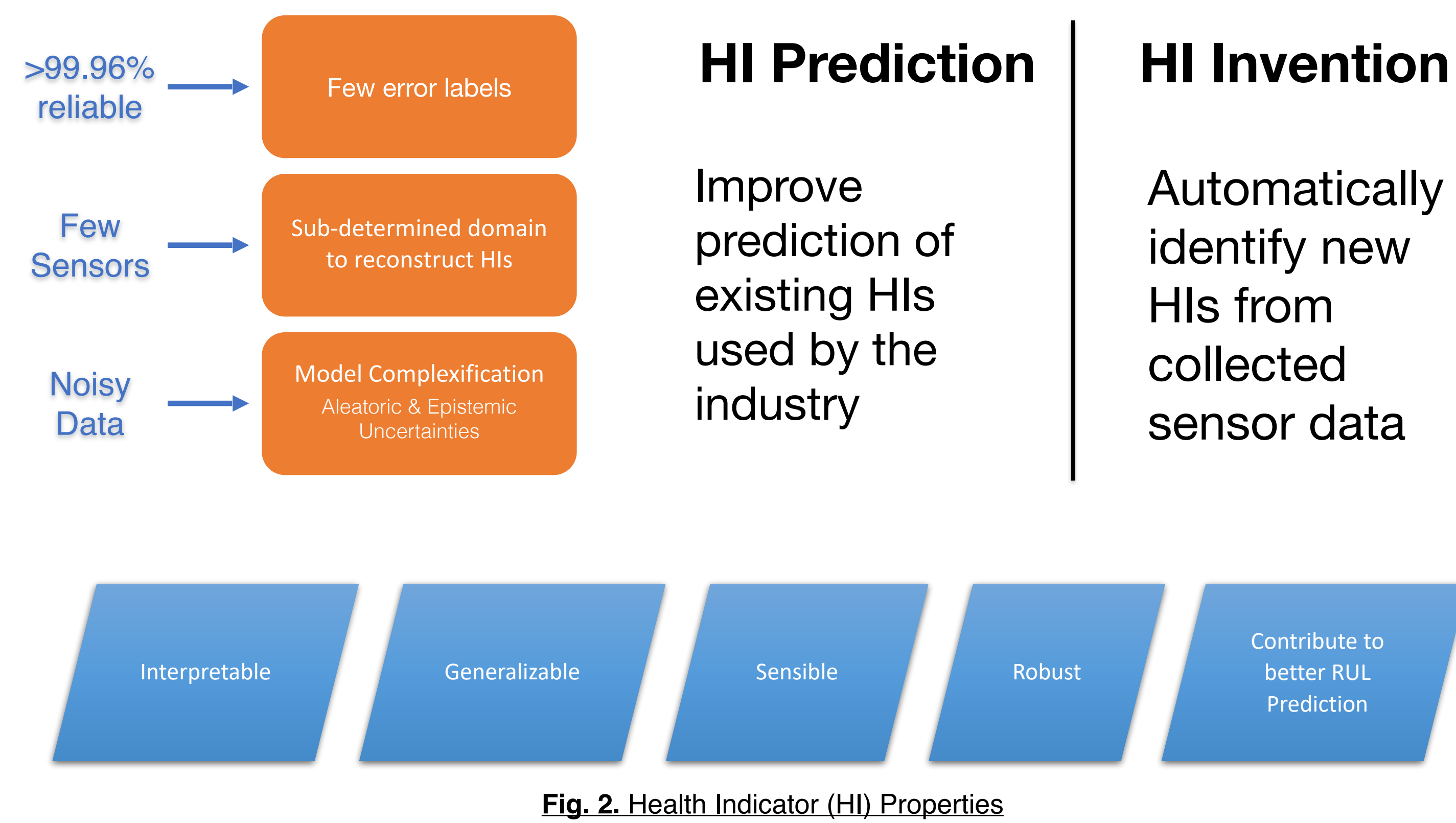
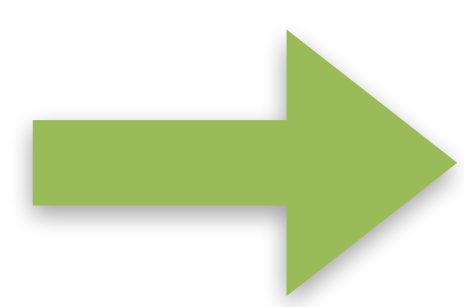


Fig. 2. Health Indicator (HI) Properties



Evaluate Health Indicators on RUL precision

3. Proposed research method

- Identify current challenges in the literature and the industry
- Explore HIs created by data-driven methods
- Propose an AI pipeline architecture to model both HIs with uncertainties: aleatoric and epistemic
- Investigate learning methods: supervised, unsupervised, reinforcement
- Incorporate physics-informed methods

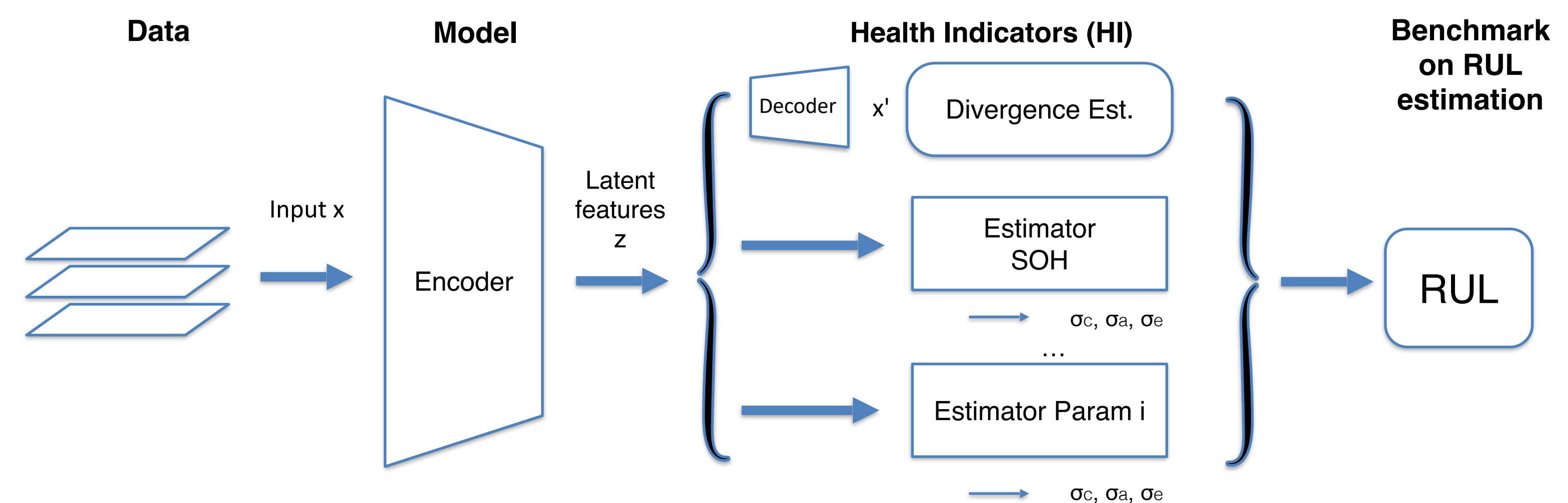
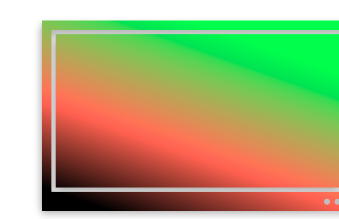
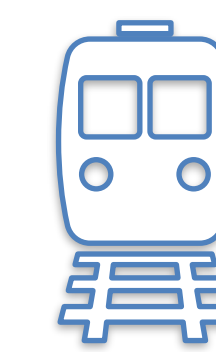


Fig. 3. Overview of the Expected Architecture

4. Case study



CX2 Battery Degradation & PyBaMM Simulator [9-10]



Railroad degradation



Safran Turbofan engine

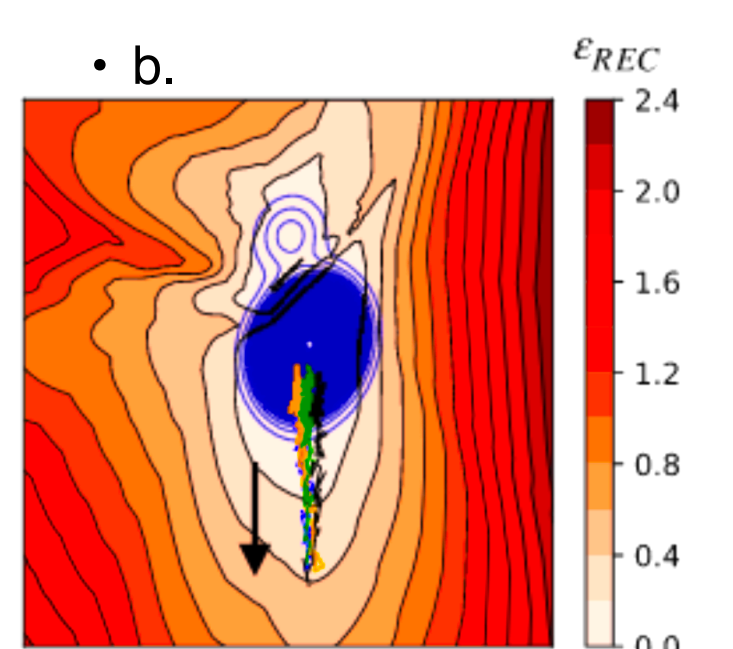
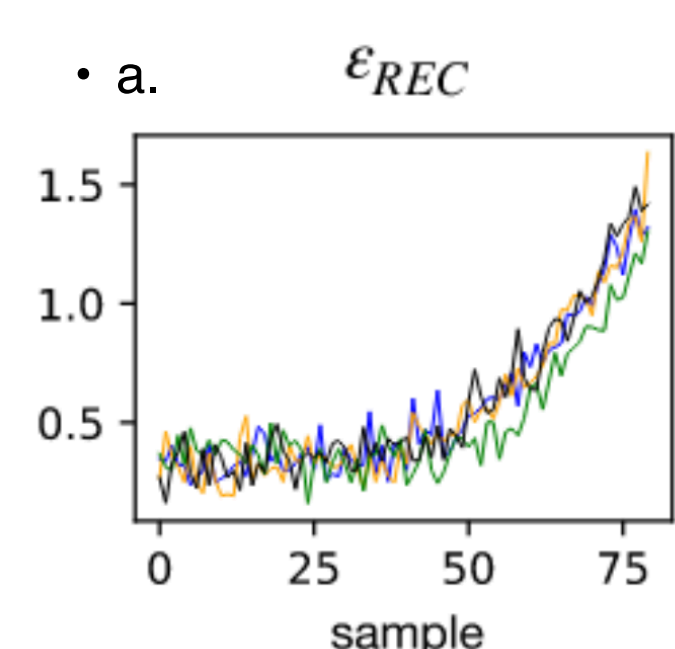
- Assessing real-world applicability
- Managing intricate, real-world scenarios
- Pinpointing and mitigating uncertainty sources
- Evaluating and enhancing performance

5. Expected results

- Unified domain agnostic framework to predict and create HIs
- Gaussian approximation for quantification in aleatoric & epistemic uncertainties
- Benchmarked on RUL estimation
- Interpretable degradation maps

Fig. 5.a. HIs built on deep auto encoder residuals for a degradation profile belonging to FD001 dataset. [1]

Fig. 5.b. Health Indicator representation in the latent space of the deep auto encoder for the FD001 dataset. [1]



6. Future work

- Physics Informed Neural Networks (PINNs)
- Domain adaptation between simulation and real datasets
- Feature selection for HI creation
- Reinforcement learning approaches

7. References

- González-Muñiz, Ana, Ignacio Díaz, Abel A. Cuadrado, et Diego García-Pérez. « Health Indicator for Machine Condition Monitoring Built in the Latent Space of a Deep Autoencoder ». *Reliability Engineering & System Safety* 224 (août 2022): 108482. <https://doi.org/10.1016/j.res.2022.108482>.
- Akbari, A., & Jafari, R. (2020). Personalizing Activity Recognition Models Through Quantifying Different Types of Uncertainty Using Wearable Sensors. *IEEE Transactions on Biomedical Engineering*, 67(9), 2530–2541. <https://doi.org/10.1109/TBME.2019.2963816>
- Abdar, M., Pourpanah, F., Hussain, S., Rezazadegan, D., Liu, L., Ghavamzadeh, M., Fieguth, P., Cao, X., Khosravi, A., Acharya, U. R., Makarenkov, V., & Nahavandi, S. (2021). A review of uncertainty quantification in deep learning: Techniques, applications and challenges. *Information Fusion*, 76, 243–297. <https://doi.org/10.1016/j.infus.2021.05.008>
- Wang, Y., Pang, Y., Chen, O., Iyer, H. N., Dutta, P., Menon, P. K., & Liu, Y. (2021). Uncertainty quantification and reduction in aircraft trajectory prediction using Bayesian-Entropy Information fusion. *Reliability Engineering & System Safety*, 212, 107650. <https://doi.org/10.1016/j.res.2021.107650>
- H. Liu, R. Ji, J. Li, B. Zhang, Y. Gao, Y. Wu, F. Huang, Universal adversarial perturbation via prior driven uncertainty approximation, in: Proceedings of the IEEE International Conference on Computer Vision, 2019, pp. 2941–2949.
- Cheng et al., "A Deep Learning-Based Remaining Useful Life Prediction Approach for Bearings."
- Zhao et al., "Remaining Useful Life Prediction of Aircraft Engine Based on Degradation Pattern Learning."
- Wei et al., "Remaining Useful Life Prediction of Lithium-Ion Batteries Based on Stacked Autoencoder and Gaussian Mixture Regression."
- Sulzer, V., Marquis, S. G., Timms, R., Robinson, M., & Chapman, S. J. (2021). "Python Battery Mathematical Modelling (PyBaMM)". *Journal of Open Research Software*, 9 (1), 14.
- Wei He, Nicholas Willard, Michael Osterman, Michael Pecht, Prognostics of lithium-ion batteries based on Dempster-Shafer theory and the Bayesian Monte Carlo method, *Journal of Power Sources*, 196(23), pp.10314-10321, 2011.