PHYSICS INFORMED NEURAL NETWORKS FOR ENERGY EFFICIENCY IN THE AUTOMOTIVE INDUSTRY

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BACKGROUND

- **Toyota Motor Manufacturing (TM) UK** has set aims to be **carbon neutral** by 2030 & **carbon zero** by 2040
- Since 2003, TMUK has made a **33%** improvement in energy efficiency and a **92%** reduction in CO_2
- Utilities are their 2^{nd} largest in-house cost after labour, making energy reduction critical for cost mitigation
- High energy used by **GPL Paint Booth** (largest energy usage) and Air Supply Unit

METHODOLOGY

Phase 1. Data Input

High-frequency temperature, pressure, power sensor readings from TMUK plastics shop (because it has the most monitoring equipment installed)

Phase 2. Hybrid PINN Model

Use a **memetic algorithm** to **inversely** find the machine's hidden parameters, such as unknown degradation rate coefficients, friction, heat loss

Program **PINN** and **physics constraints** from literature review papers (e.g. thermodynamics) [1, 2]

Phase 3. Multi-Objective Optimisation

Use Multi-Objective **Evolutionary Algorithm** (NSGA-II) to find most appropriate solution given by the PINNs

The algorithm explores thousands of combinations to find best balance between minimum energy use and maximum productivity, while maintaining quality

Phase 4. Operational Output for Toyota

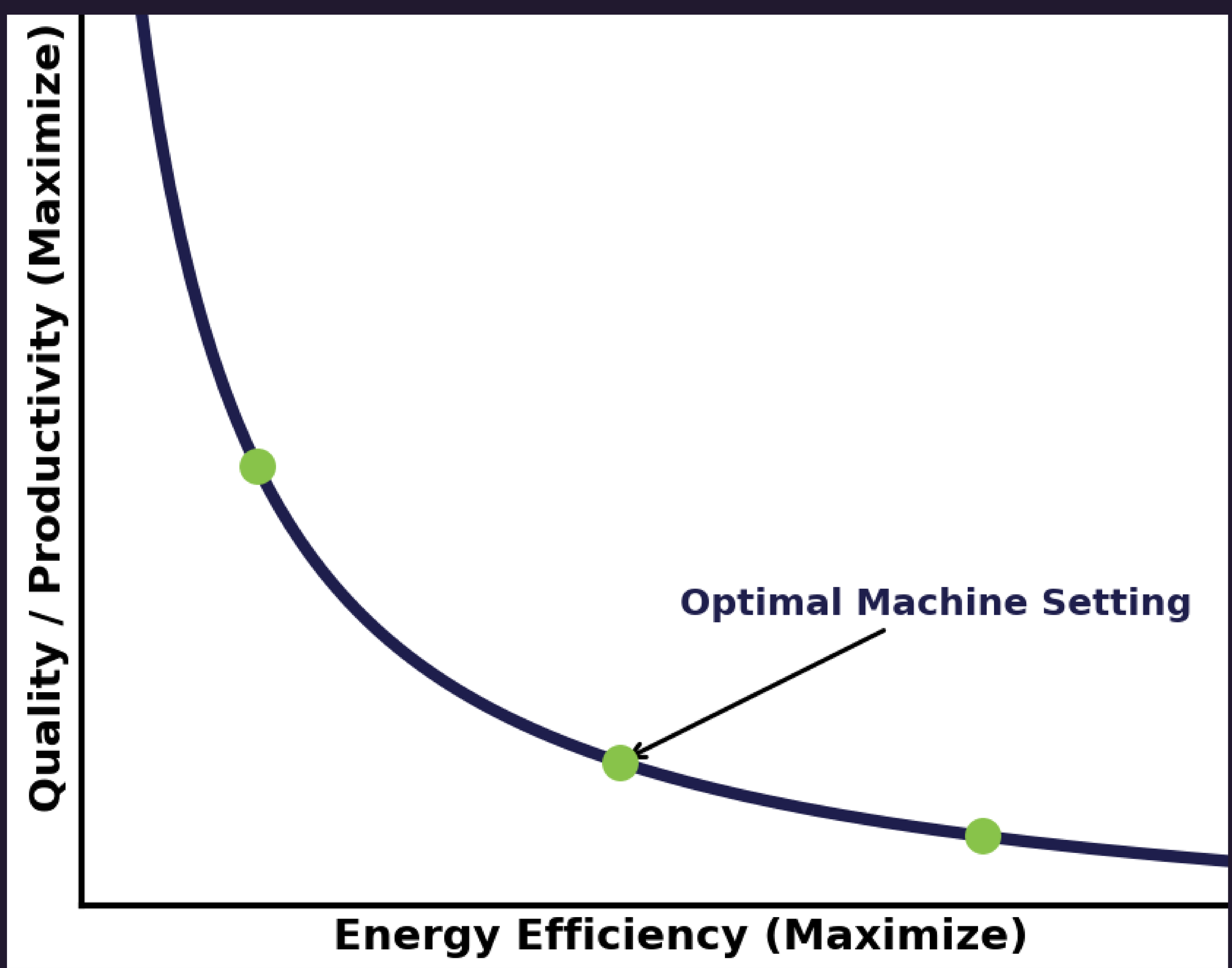

FIGURE 1: *Instead of one solution, a Pareto curve of optimal settings is provided, showing compromises between highest energy efficiency and production volume.*

REFERENCES

[1] H. Rees, Understanding Injection Mold Design. Munich: Hanser, 2001; [2] P. K. Kennedy, "Practical and scientific aspects of injection molding simulation," Ph.D. dissertation, Technische Universiteit Eindhoven, Eindhoven, Netherlands, 2008; [3] M. Wesselkamp, N. Moser, M. Kalweit, J. Boedecker, and C. F. Dormann, "Process-Informed Neural Networks: A Hybrid Modelling Approach to Improve Predictive Performance and Inference of Neural Networks in Ecology and Beyond," Ecology Letters, vol. 27, art. no. e70012, 2024; [4] B. Huang and J. Wang, "Applications of Physics-Informed Neural Networks in Power Systems - A Review," IEEE Transactions on Power Systems, vol. 38, no. 1, pp. 572-588, 2023; [5] J. Park and J. Park, "Physics-induced graph neural network: An application to wind-farm power estimation," Energy, vol. 187, p. 115883, 2019.

TABLE 1: *Comparing PINNs and Standard Neural Networks [3]*

LIMITATIONS OF BLACK BOX MODELS	ADVANTAGES OF PINNS MODEL
Only learns from **patterns** in **input data**	Respects **physical laws** when providing solutions
Great at **interpolation** but fails to **extrapolate** outside **trained dataset**	More reliable for **extrapolation**, applies physics to **unseen datasets**
Internal mechanisms are not transparent so cannot **explain decision process**	Can easily interrogate solutions and specific physical processes
Needs **extensive training datasets** to represent system dynamics accurately	Can work with **limited, noisy, disrupted** data to find patterns

RESEARCH AIMS

- **Papers** on PINNs focus on continuous systems (e.g., power grids, wind turbines), not cyclic systems [4, 5]
- Develop a novel **PINNs framework** to analyse stored **high-frequency sensor data** from **TMUK's plastics shop**
- Use PINNs & TMUK dataset to solve **inverse problem**
- Provide **optimal, energy-efficient machine settings** that **reduce costs** without compromising on quality

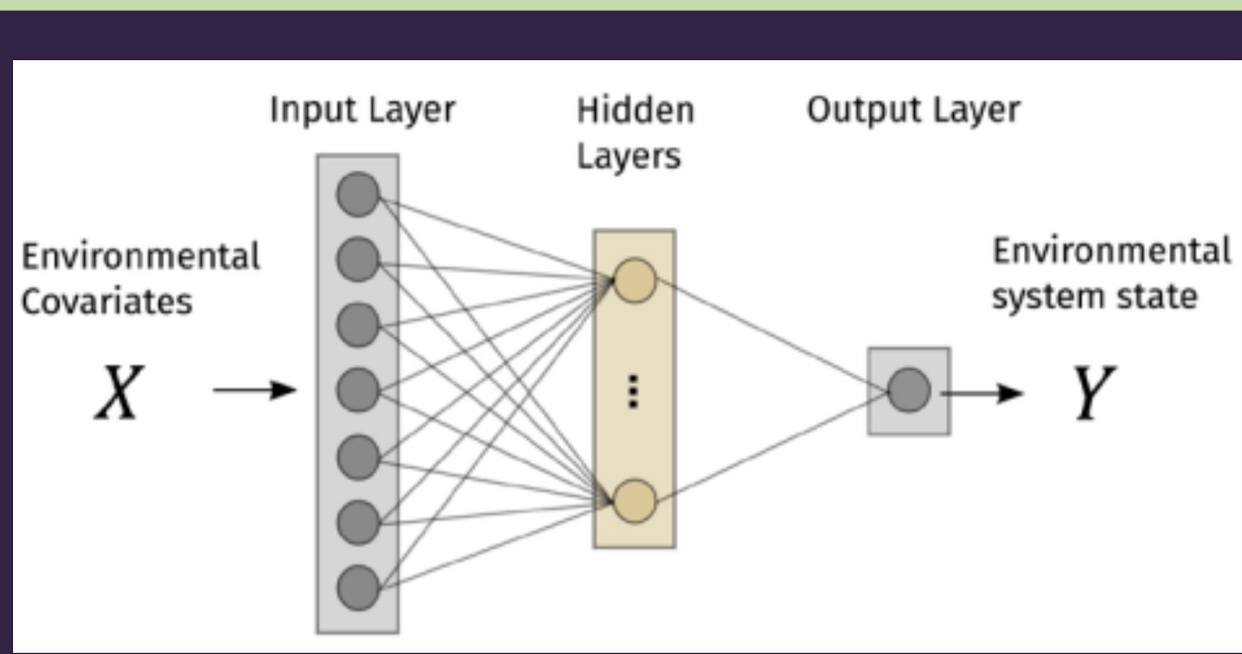

FIGURE 2: *A Standard Neural Network [3]*

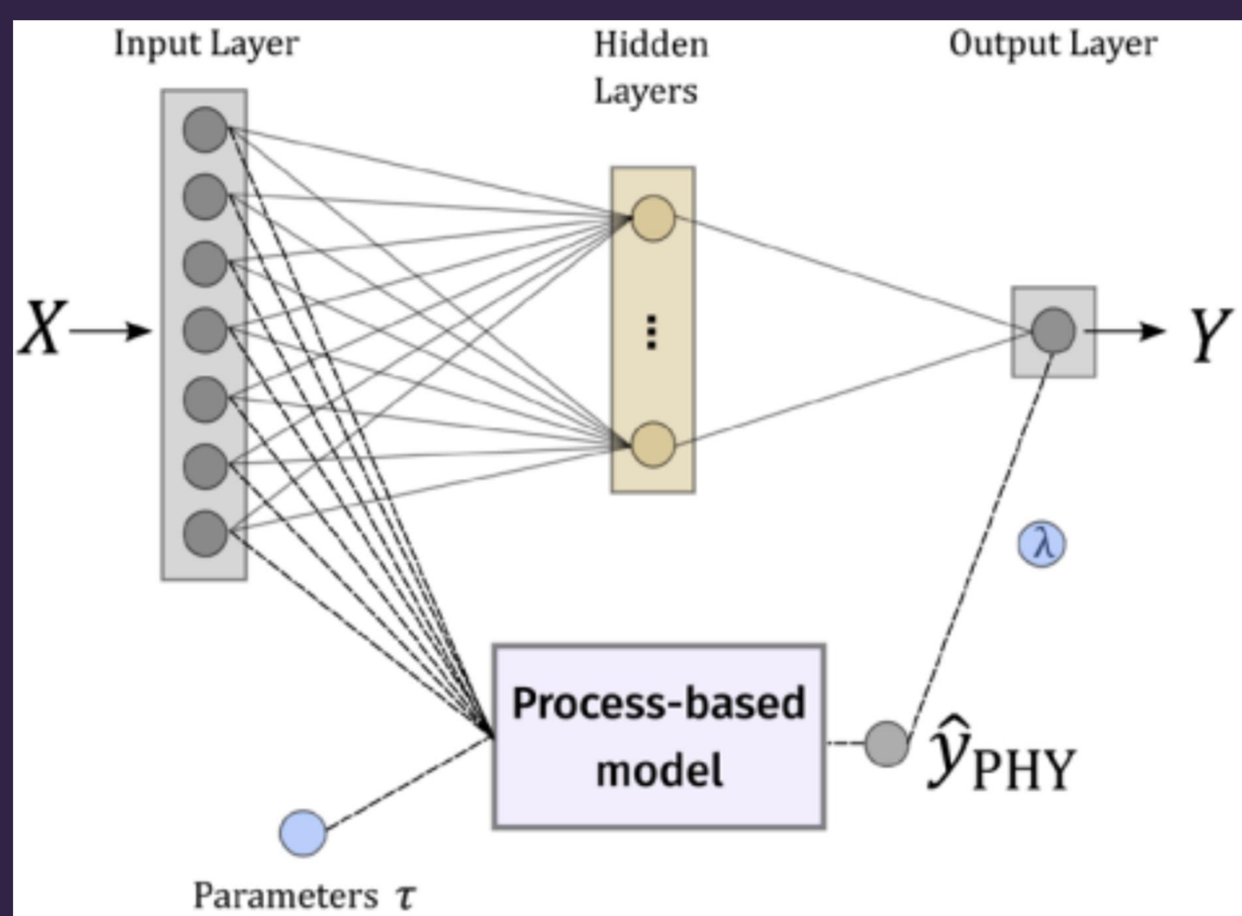

FIGURE 3: *Integrating a process-based model into the neural network to ensure solutions respect physics laws [3].*

IMPACTS

- Toyota engineers can use the **Pareto Front** of energy-efficient machine settings that will balance **production quality** and **energy usage**
- This directly accelerates TMUK's progress towards 2030/2040 targets and **reduces utility costs**
- While TMUK has significantly reduced its energy usage, this research targets the last milestone of their goals by optimising performance of their previously **untouched systems**
- Develops a highly **scalable** and **transferable** PINNs framework for energy systems that can be applied to **different Toyota plants**

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