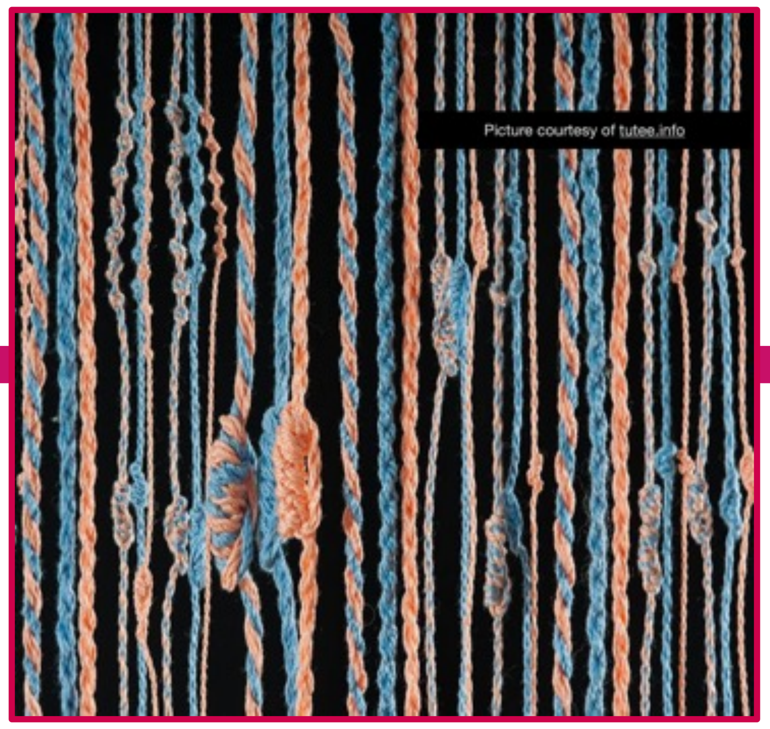
CONTROL IN STEEL



From controlling single processes to the complex automation of process chains by artificially intelligent control systems

M. J. Neuer, F. Marchiori, V. Colla, S. Dettori, J. Ordierés-Meré, M. Loos and A. Wolff

2022-11-25, IFAC COSY 2022

Research Fund for Coal & Steel

BFI Excellence in Applied Research

Sant'Anna Scuola Universitaria Superiore Pisa

CSM Centro Sviluppo Materiali

Structure of this talk

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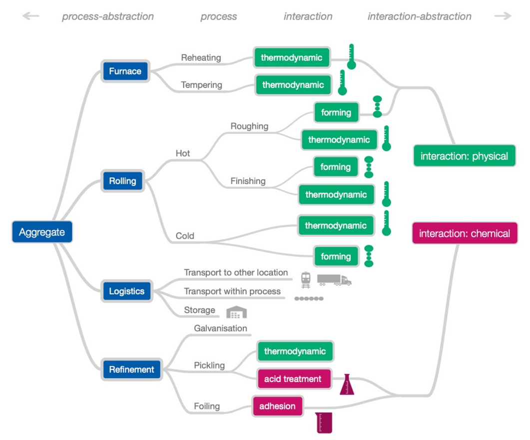
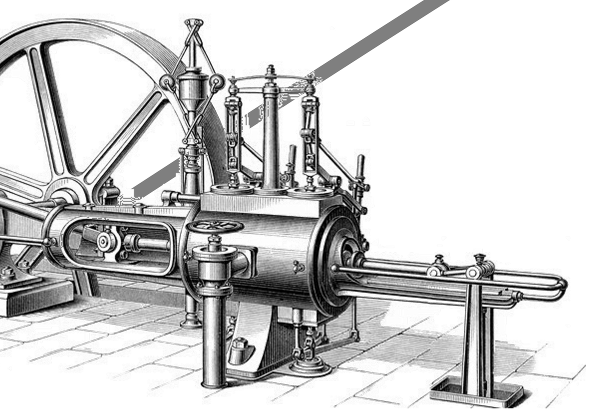
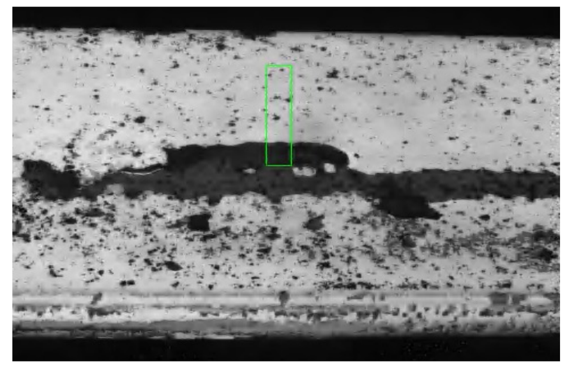


Part 2.
Taxonomy approach and graph connection



Part 1.
Ultra-short introduction

Part 4.
Unadressed methods in steel industry



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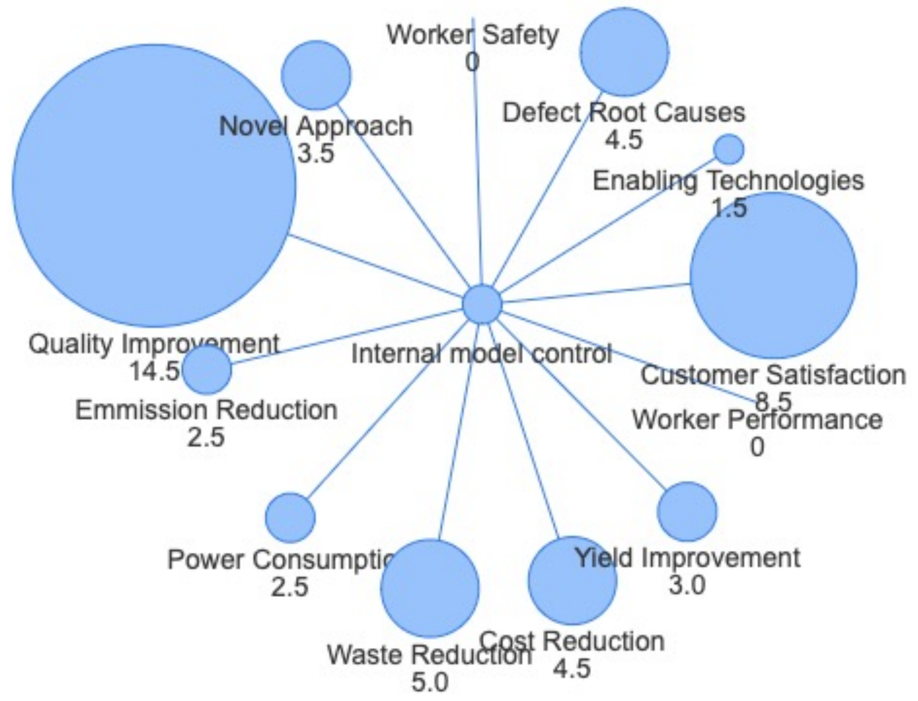
Results and application examples



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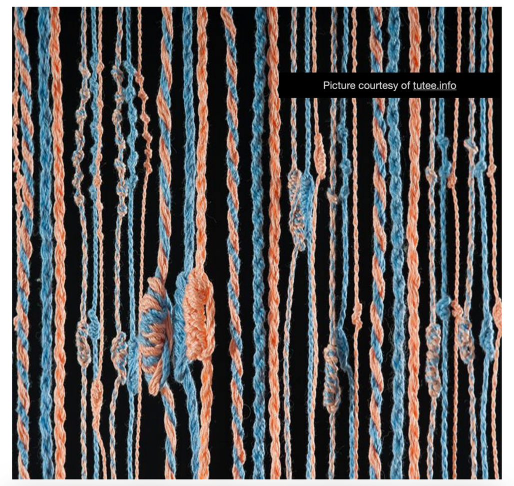
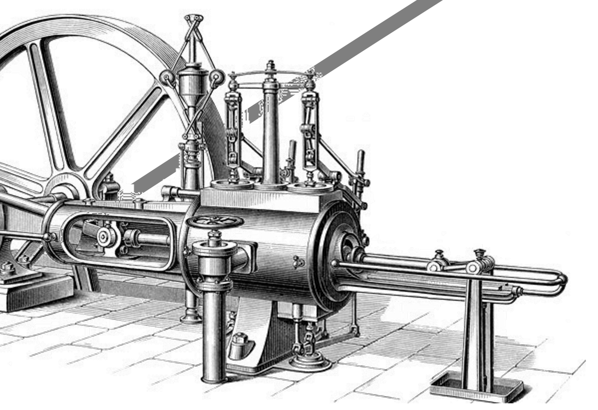
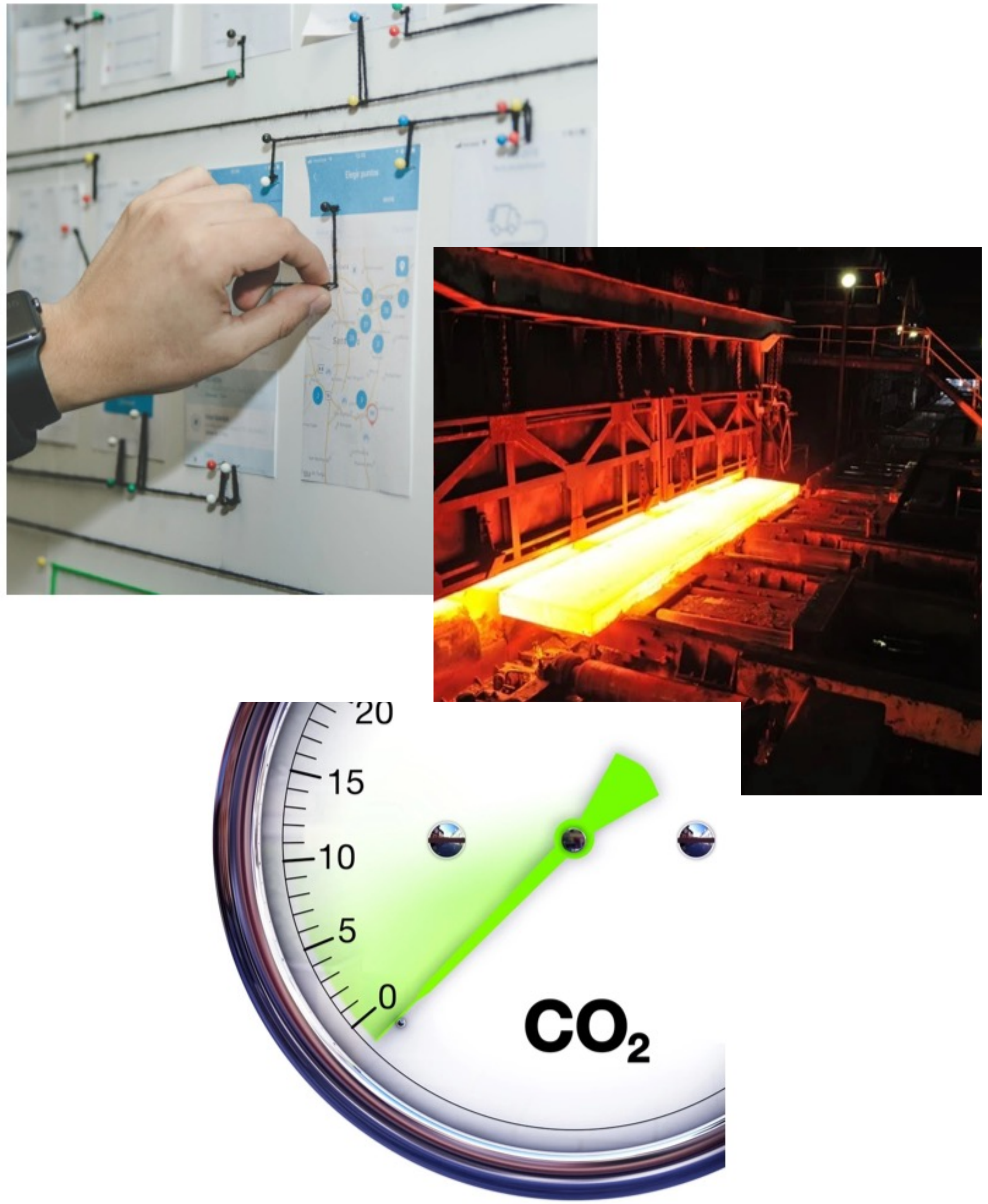




Part 1.
Ultra-short introduction

About the project

- ControlInSteel is a dissemination activity focusing **advanced automation and control** running till 2022-11
- We selected around **45(+5) former RFCS research projects** for a scientific analysis
- Mission goals were
  - 1. Analyze and understand **dynamics** of the **problem-**, **solution-** and **impact space** which also includes **barriers** and **issues**, as well as **physical interaction channels**
  - 2. Perform **dissemination events**, e.g. conference sessions and workshops to effectively distribute knowledge from and about these former projects
  - 3. Provide a **roadmap for future research**



Structure of this talk

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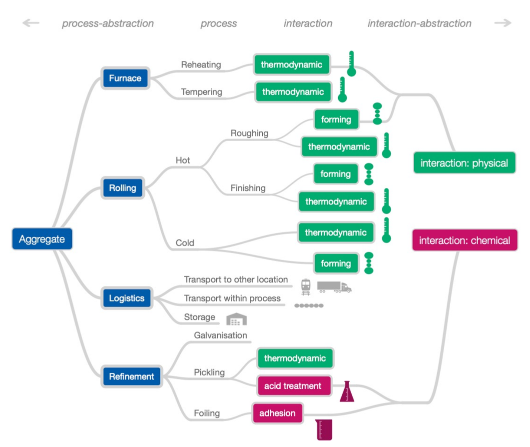

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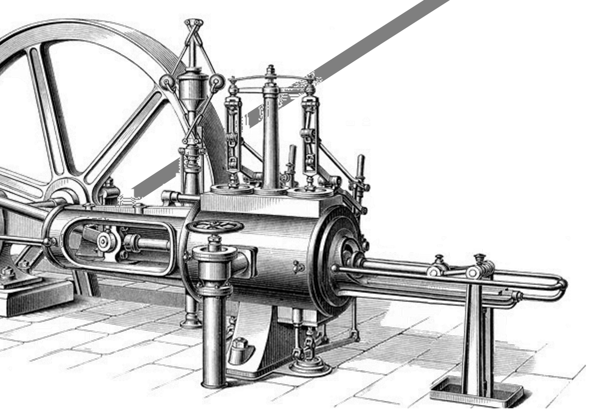

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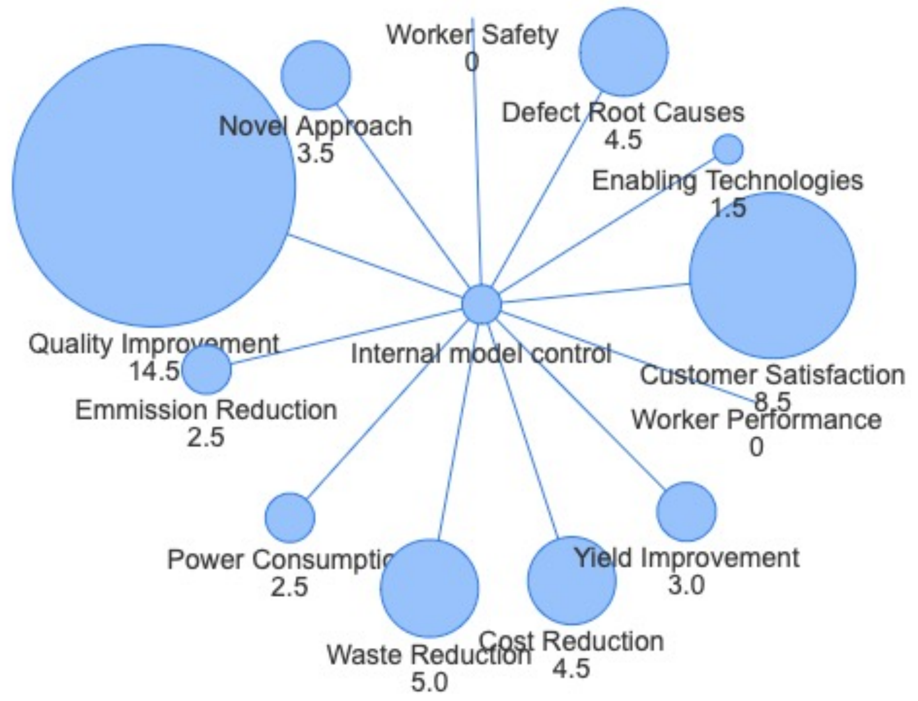
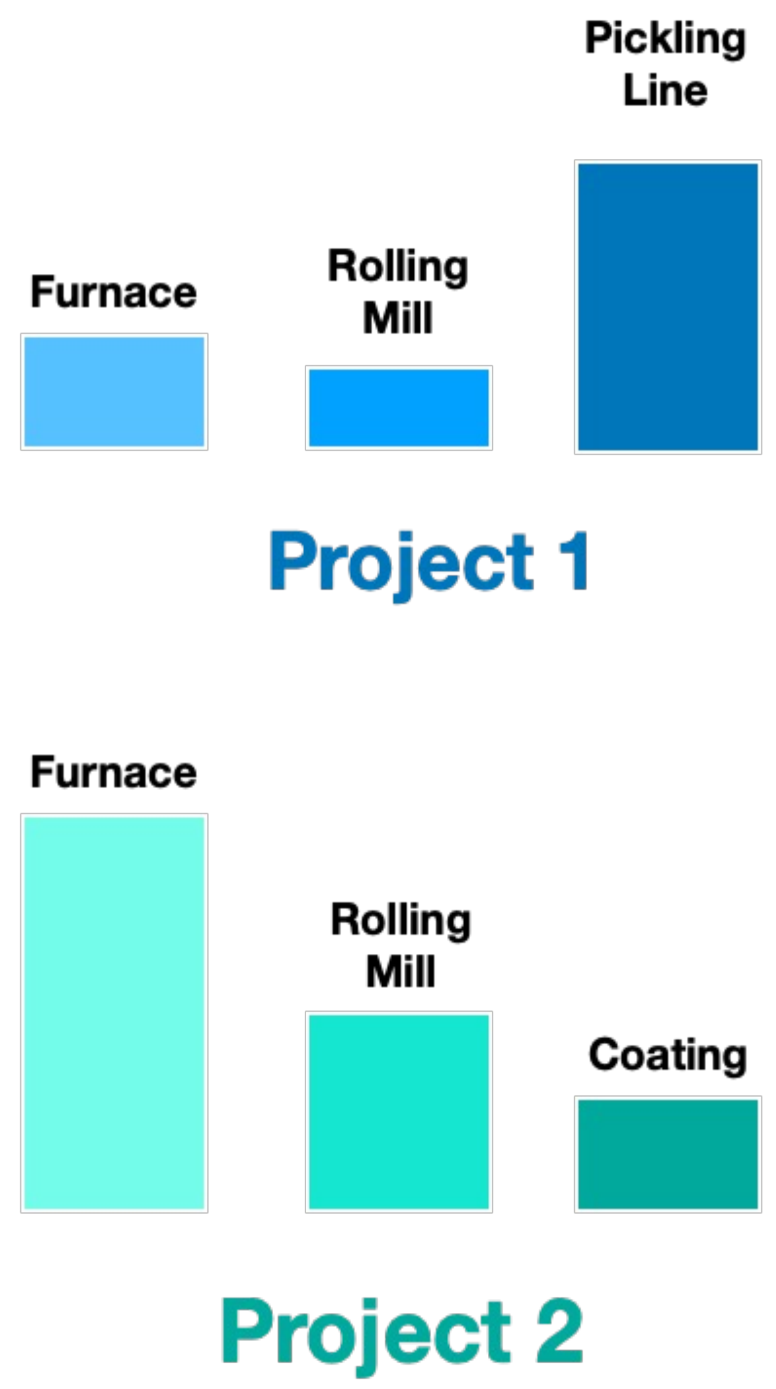
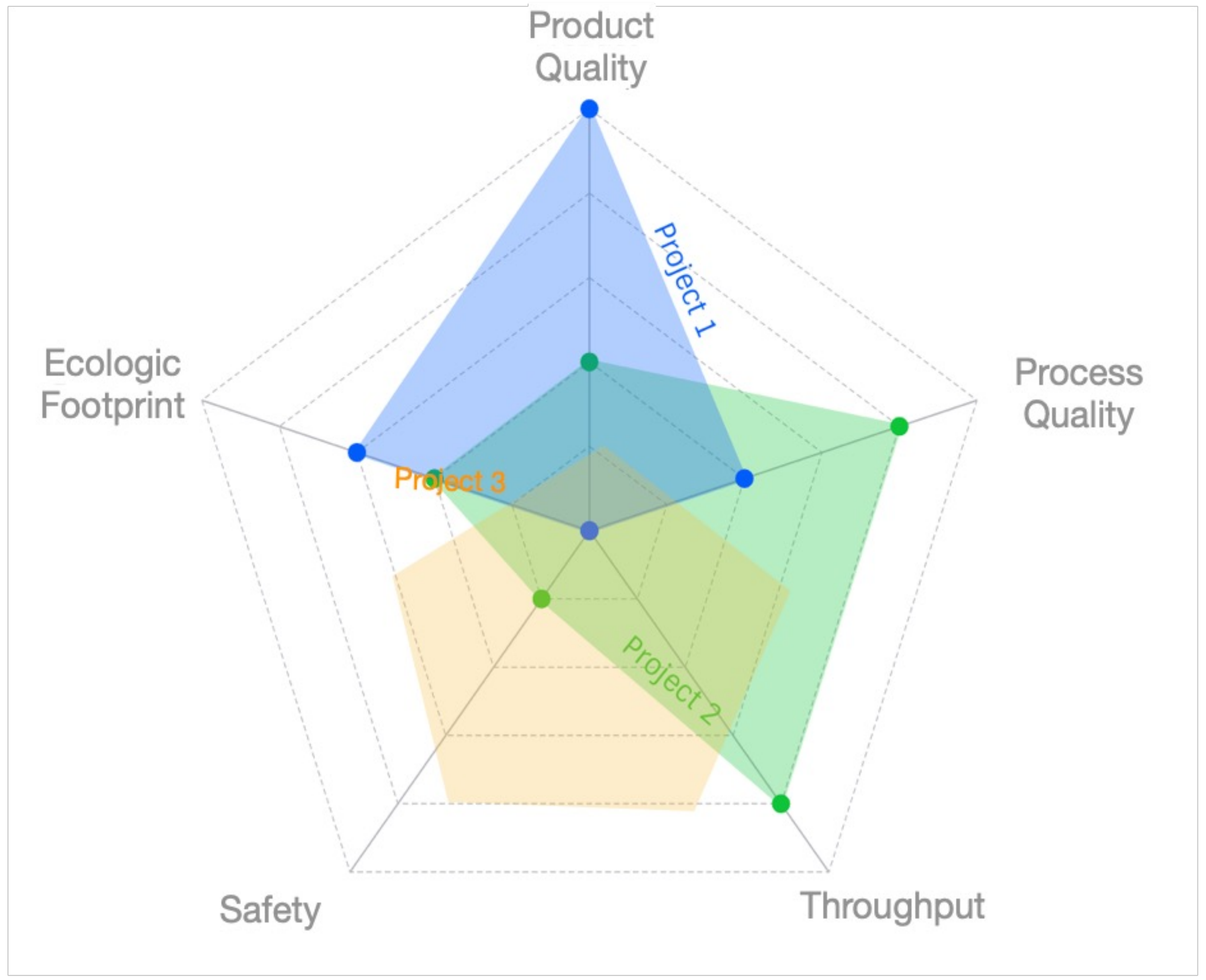


Conceptual approach towards project evaluation

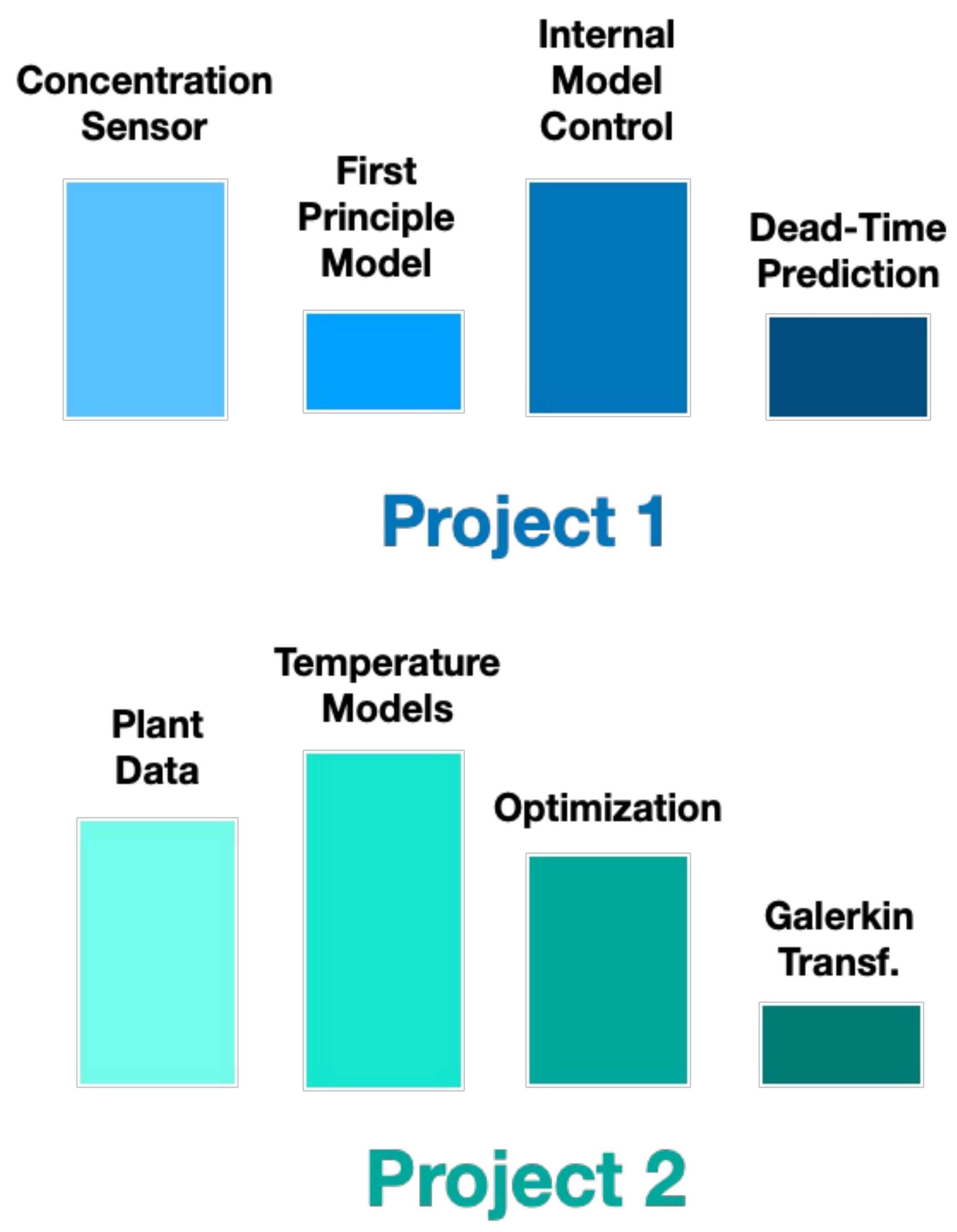
Problem space

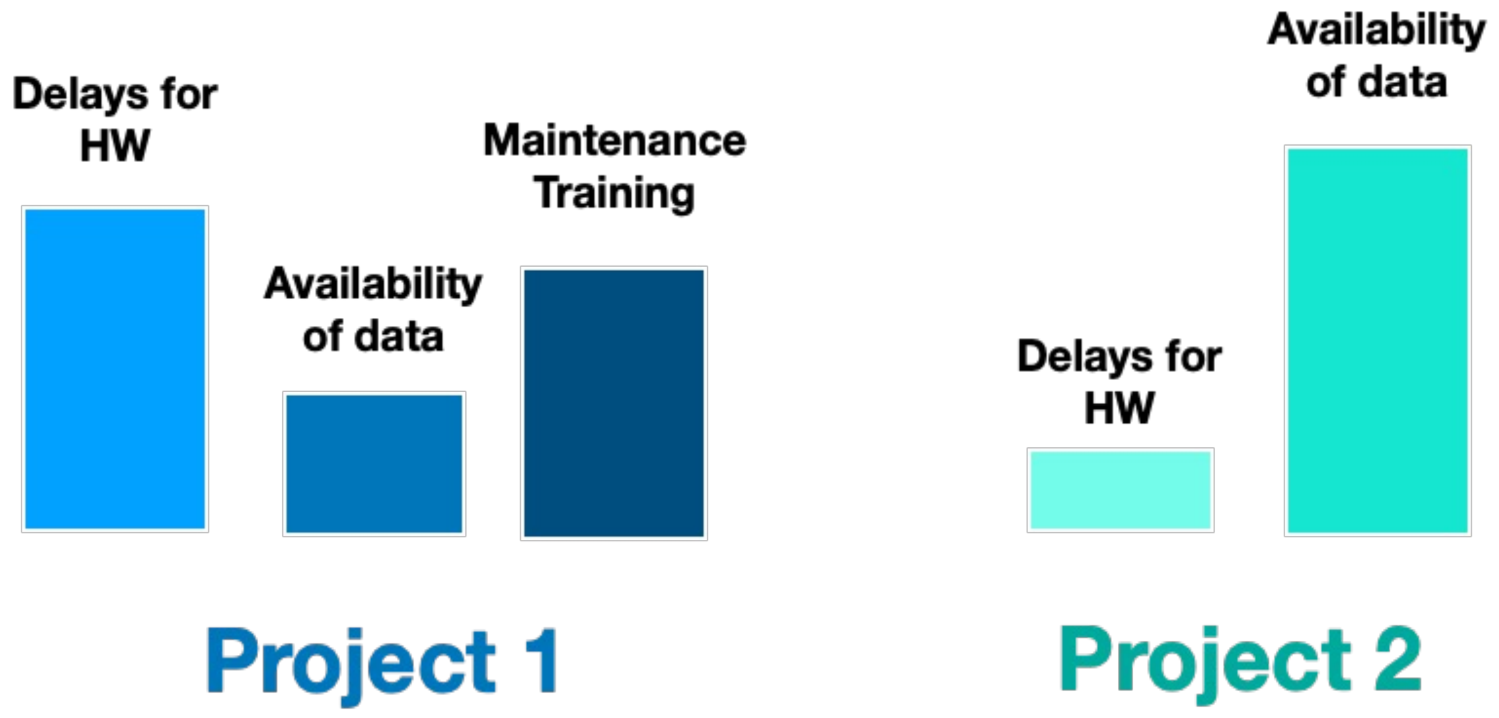


Impact space



Solution space

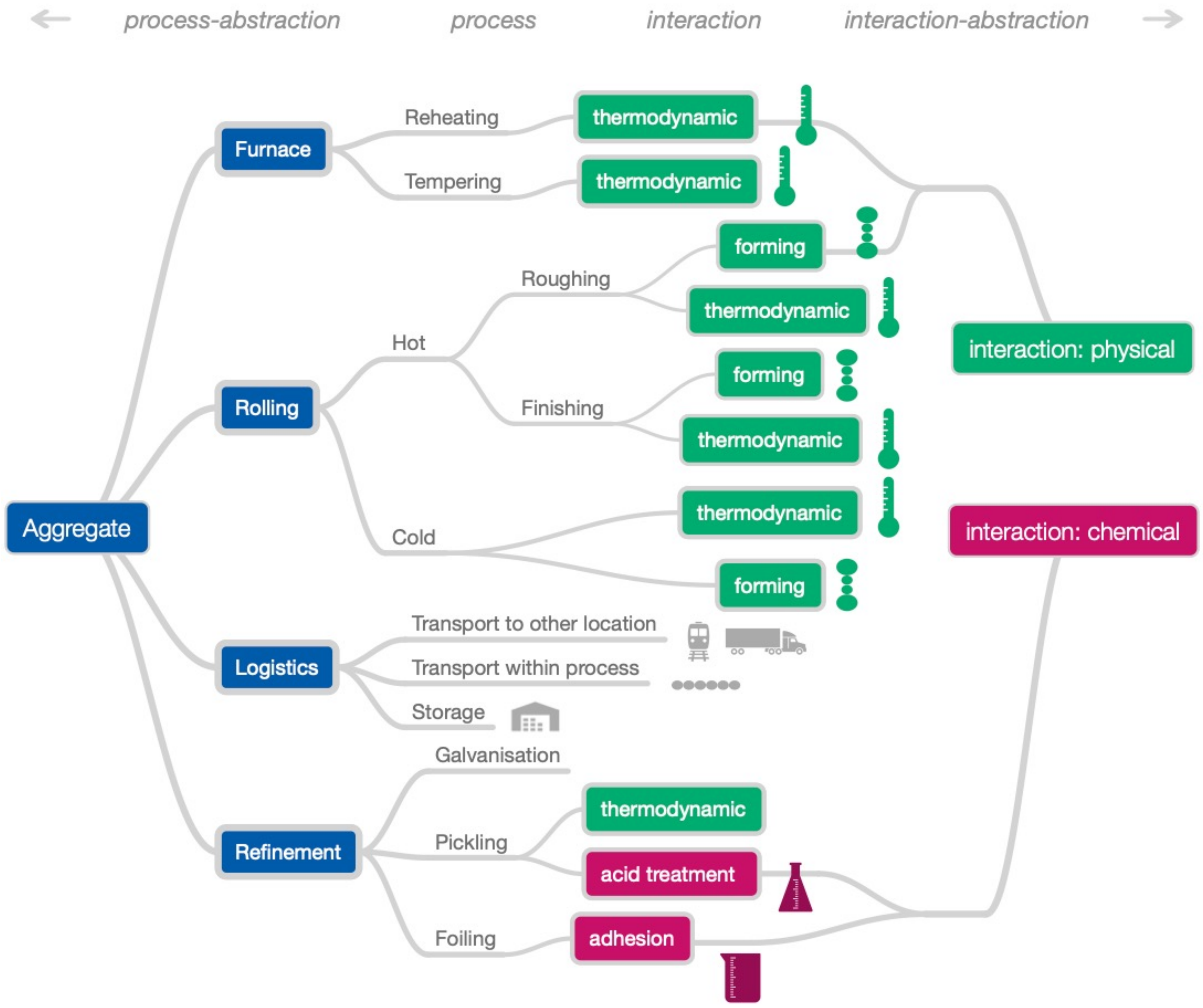




Barriers & issues space

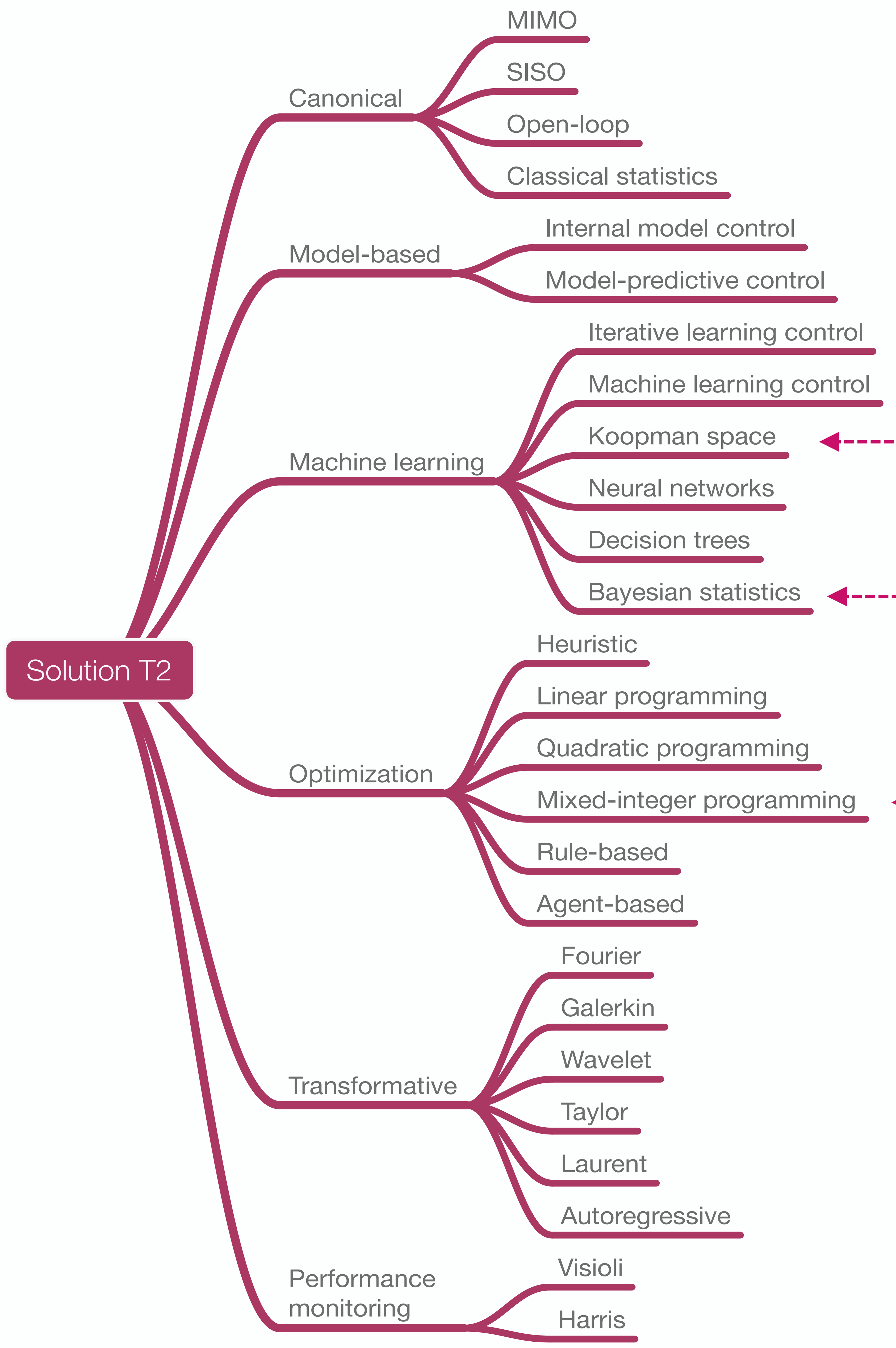
Taxonomy for problem space

T1) Aggregate	Type	Product	Interaction
Casting	Continuous casting	Slab	physics:thermodynamic
Furnace	Slab reheating	Slab	physics:thermodynamic
	Walking bean reheating	Slab	physics:thermodynamic
	Billet furnace	Billet	physics:thermodynamic
Logistics	Transport	Slab	logistics:displacement
Annealing	Continuous annealing	Strip	physics:thermodynamic
	Bright annealing		physics:thermodynamic
	Batch annealing		physics:thermodynamic
Rolling	Roughing mill	Slab	pyhsics:forming; physics:thermodynamic
	Finishing mill	Strip	pyhsics:forming; physics:thermodynamic
	Cold rolling	Strip	pyhsics:forming; physics:thermodynamic
	Temper rolling	Strip	pyhsics:forming; physics:thermodynamic
	Plate mill		
Cooling	Cooling	Slab, Strip	physics:thermodynamic
Refinement	Hot dip galvanization	Strip	chemical:galvanisation, physics:thermodynamic
	Electro galvanisation	Strip	chemical:galvanisation, physics:thermodynamic
	Pickling mill	Strip	chemical:etching;
	Coating	Strip	chemical: bond; physics:adhesion
	Foiling	Strip	chemical: bond; physics:adhesion
	Skin pass	Strip	physics:cutting;
	Scarfing		
	Levelling	Strip	physics:forming;
Thru-process			
Topical	Descaling	Slab, Strip	physics:evaporation
	Flatness	Strip	physics:forming
	Quality		
	Long		
	Flat		



Taxonomy on automation solution techniques

CONTROL IN STEEL



- **Source 1**: Solution Taxonomy of ControlInSteel
- **Source 2**: Gartner Hype Cycle
- **Source 3**: Research on automation methodology for non-steel process industries

Koopman space: high potential for substantial breakthrough for single aggregate control, not considered yet

Uncertainty, dramatically underrepresented in current (steel) research projects

Key technology for ecologic **optimization**

Taxonomy for impact dimensions

CONTROL IN STEEL

Quality
Yield
Costs
Root cause
Customer satisfaction
Emerging technologies
Waste reduction
Novel approach
Throughput
Power
Emission
Worker performance
Worker safety

Graph theory for connecting the projects

CONTROL IN STEEL

- Taxonomies
  - T_1 – problem space
  - T_2 – solution space
  - T_3 – impact space

Property vector

$$\mathbf{f}_\lambda(i) = [(f_{\lambda 0}(i), f_{\lambda 1}(i), ...] = \mathcal{T}_\lambda(i)$$

$$f_{\lambda j}(i) = \mathcal{T}_\lambda(i, j)$$

Project number

Taxonomy number

- Algorithm for retrieving conditional probabilities out of taxonomy entry combinations

$$P(j, T_\lambda | m = 1 \text{ with } m \in T_\rho) = \sum_{i \in \Pi} \sum_{k \in T_\lambda} \sum_{r \in T_\rho} f_{\lambda j}(i) \delta_{kj} \delta_{mr}$$

„just counting, because we have the data“

- Semantic graphc :onstructor, formal edge definition

Internal edges per taxonomy

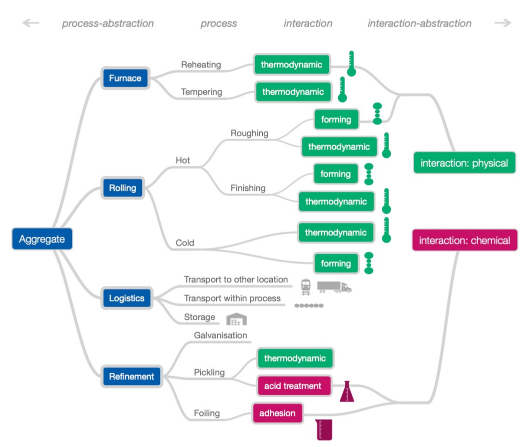
$$\phi_\lambda : E_\lambda(i) \rightarrow \{(f_{\lambda j}, \lambda) | f_{\lambda j} = \mathcal{T}_\lambda(i, j)\}$$

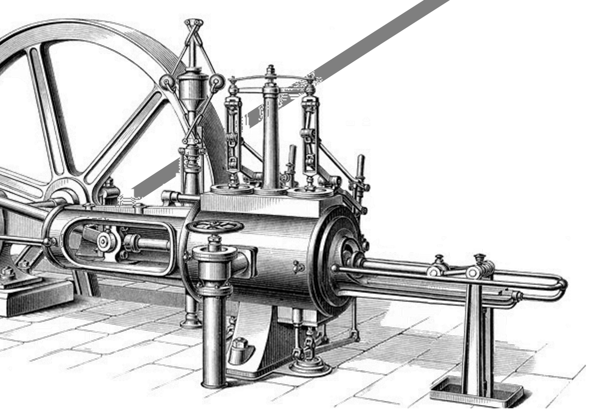
$$\phi_T : E_T(i) \rightarrow \{(\lambda, \pi(i)) | \lambda \in (1, 2, 3) \wedge \pi(i) \in \Pi\}$$

Top level taxonomy connectors

Structure of this talk

CONTROL IN STEEL





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Taxonomy approach and graph connection

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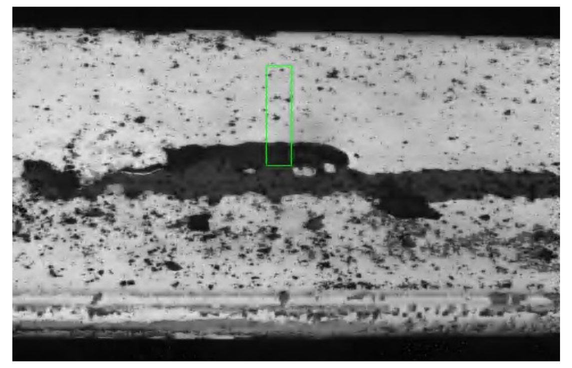
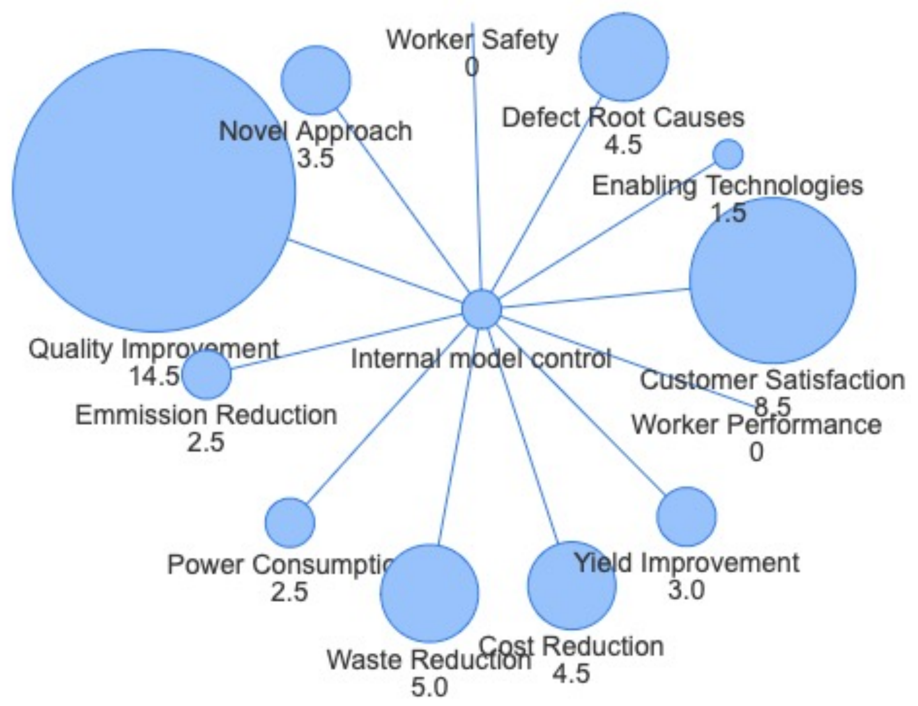
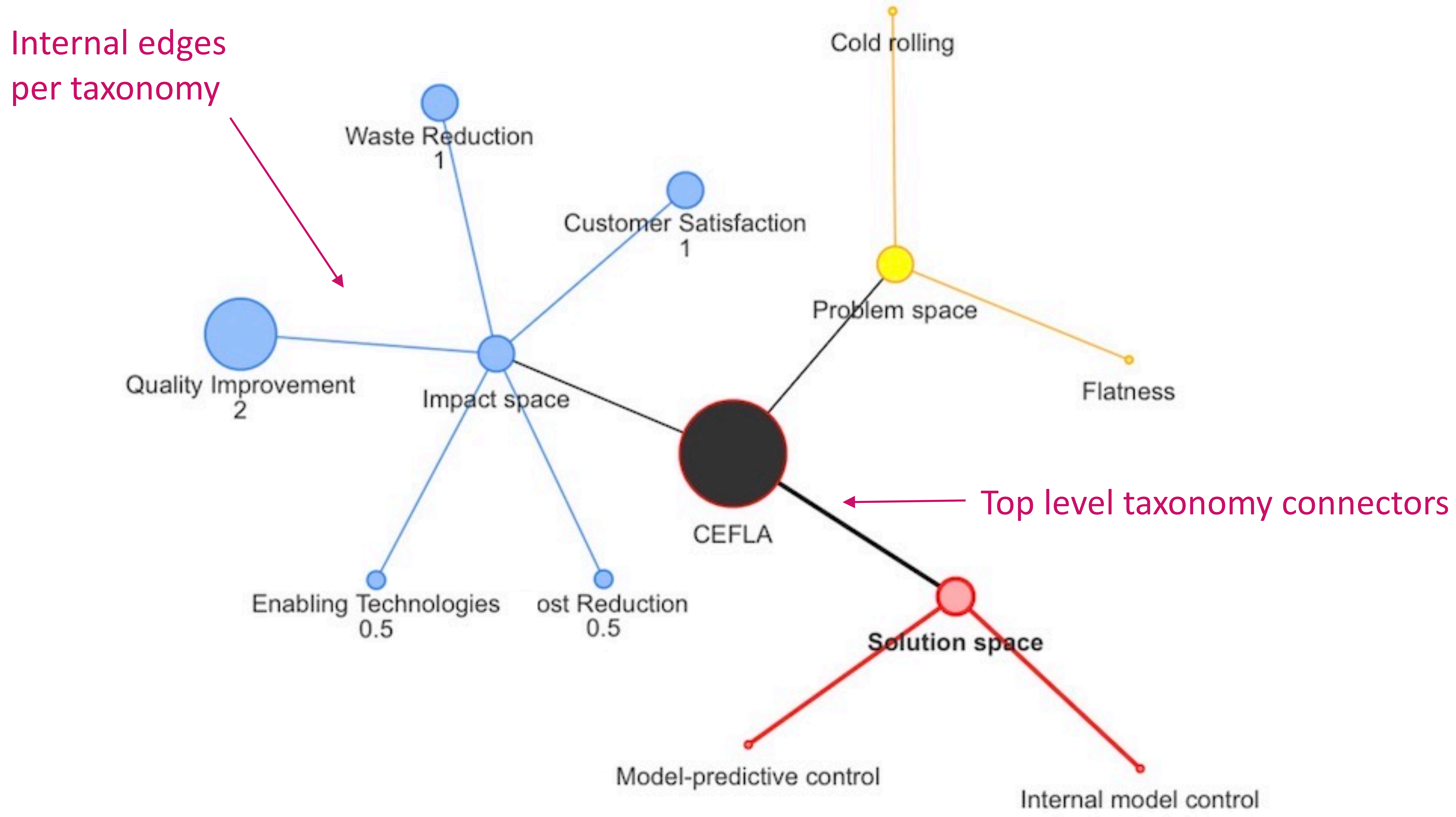




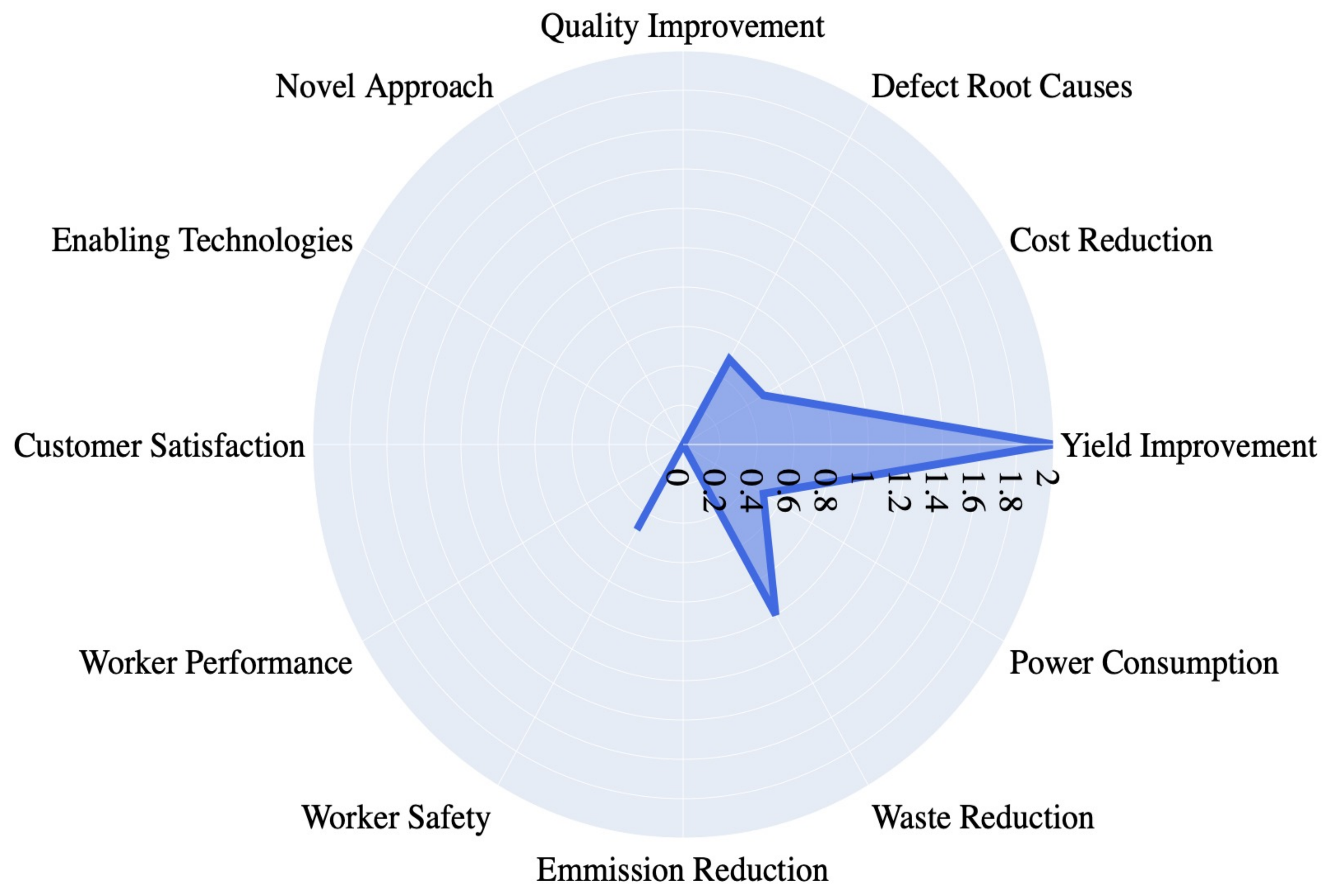
Part 3.
Results and application examples

Graph connecting the taxonomies per project

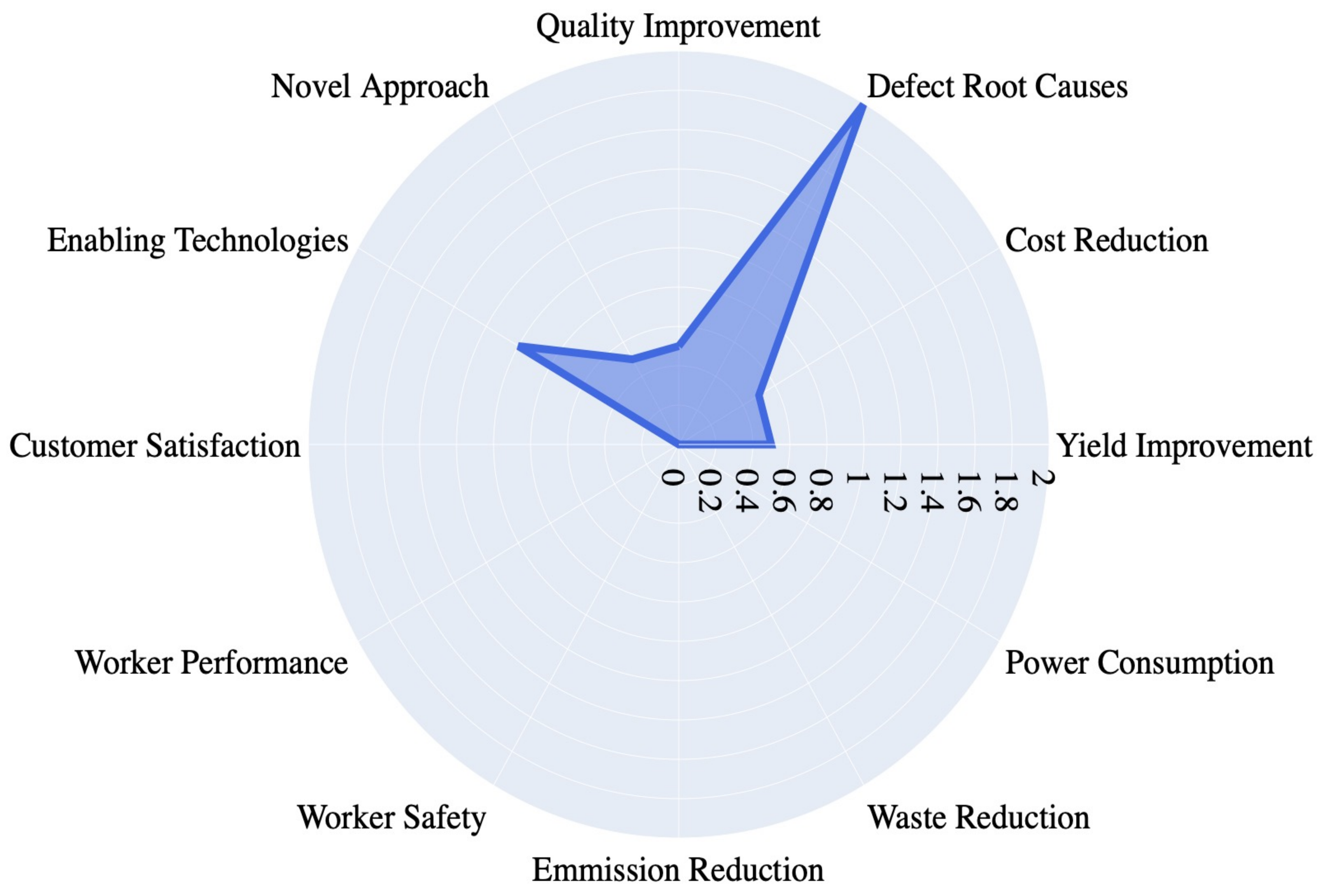


Impact distribution per project

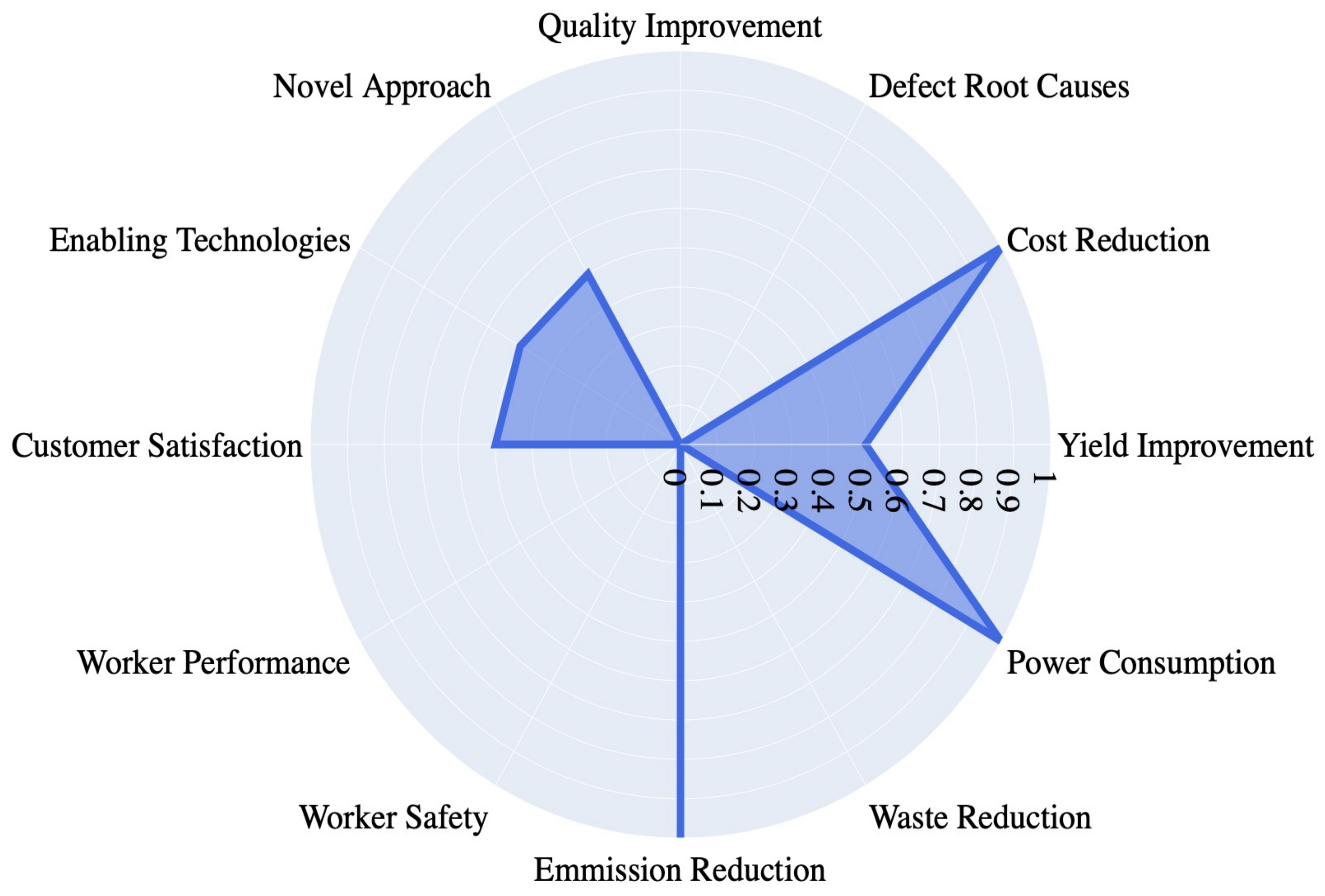
FlexGap



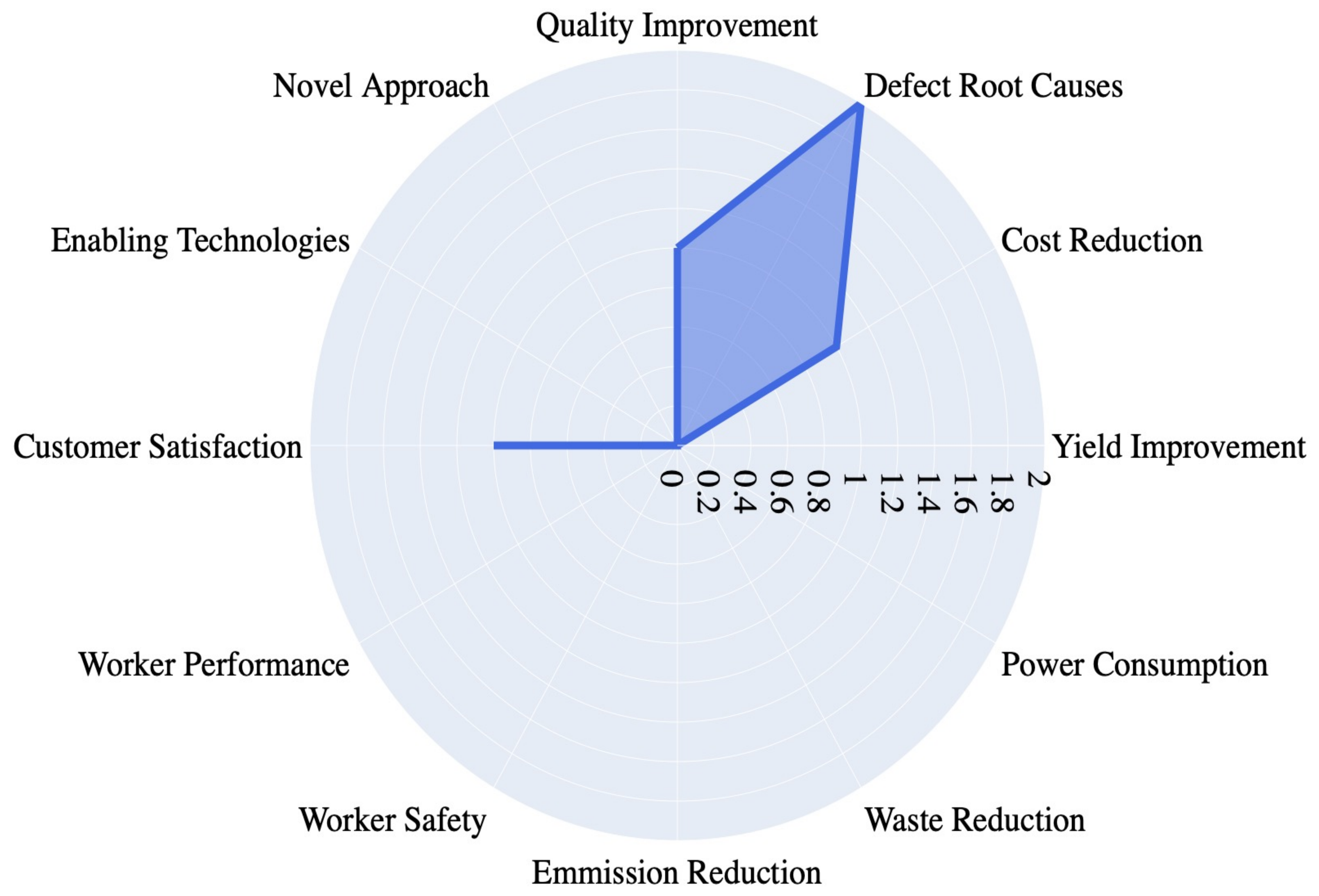
Deffree



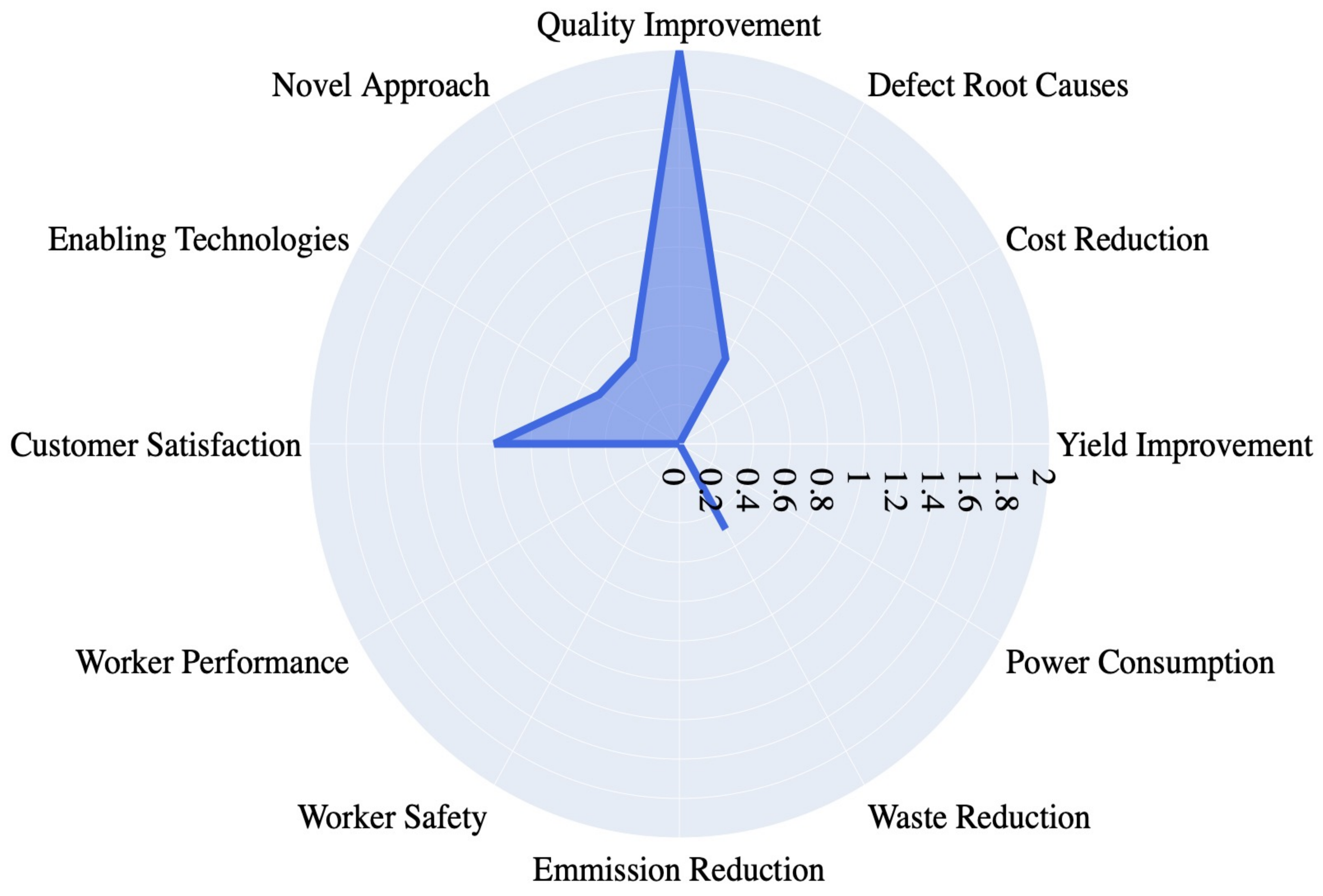
DYNERGYSteel



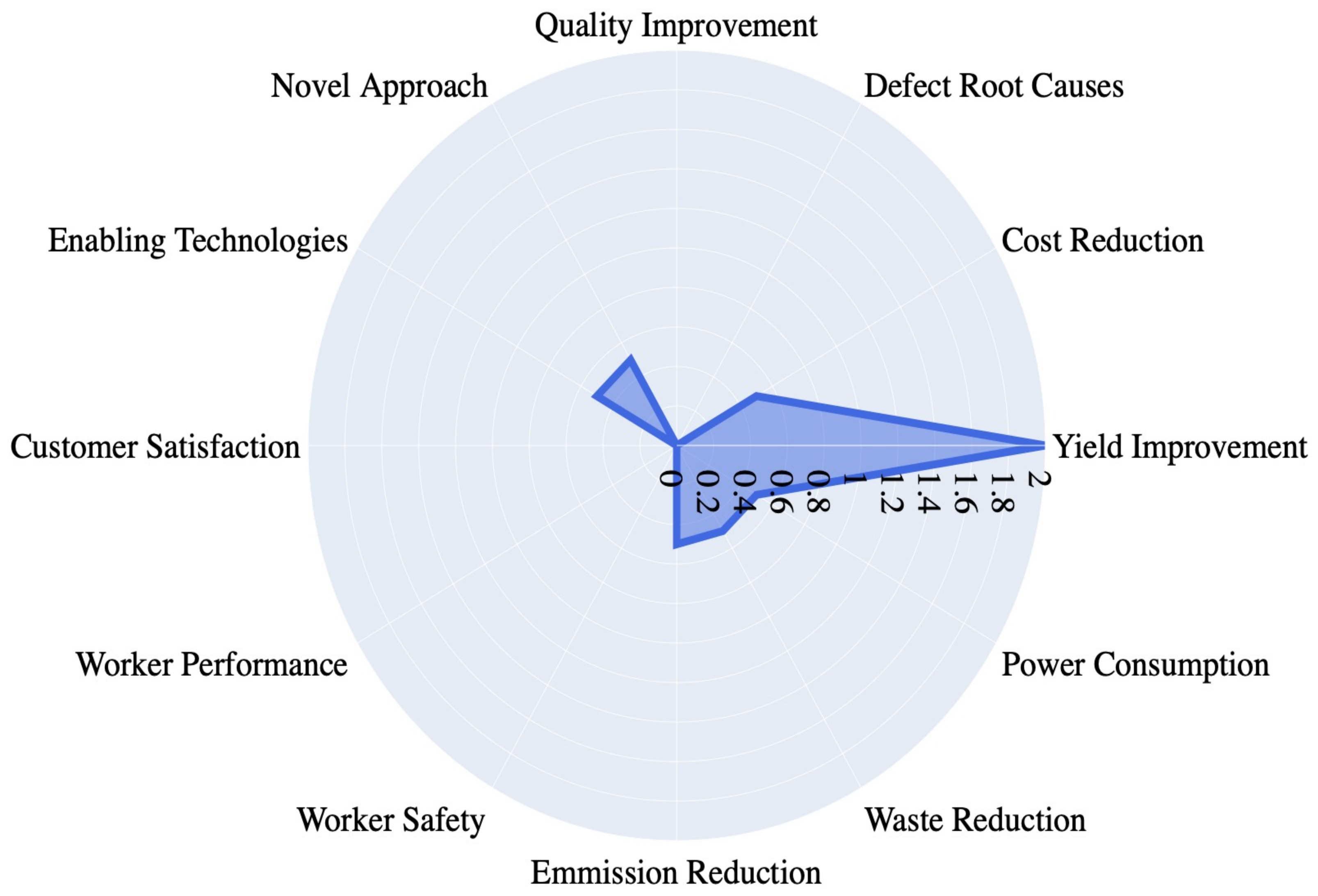
SISCON



SHAPEHPM

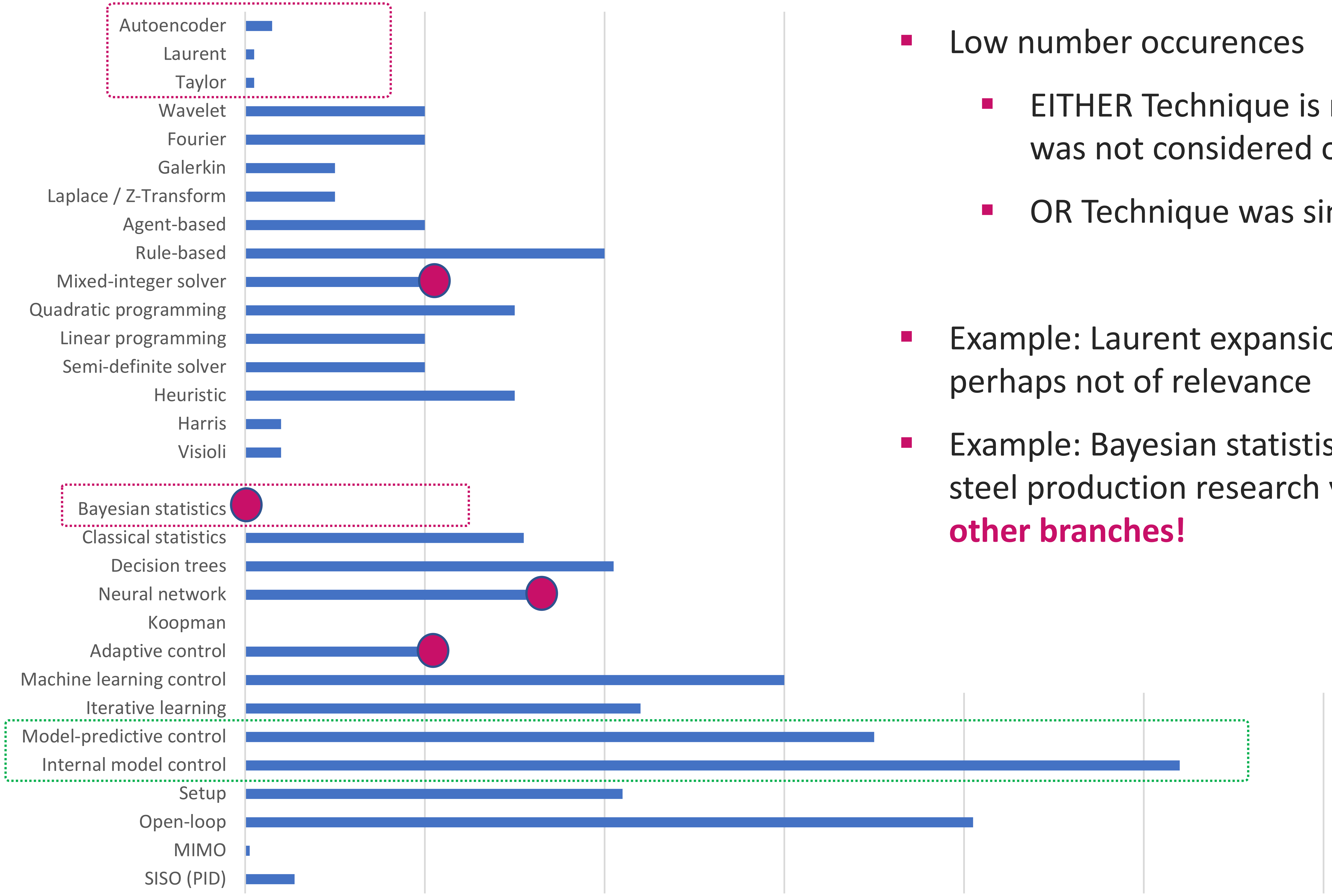


SOPROD



Identification of missing activities

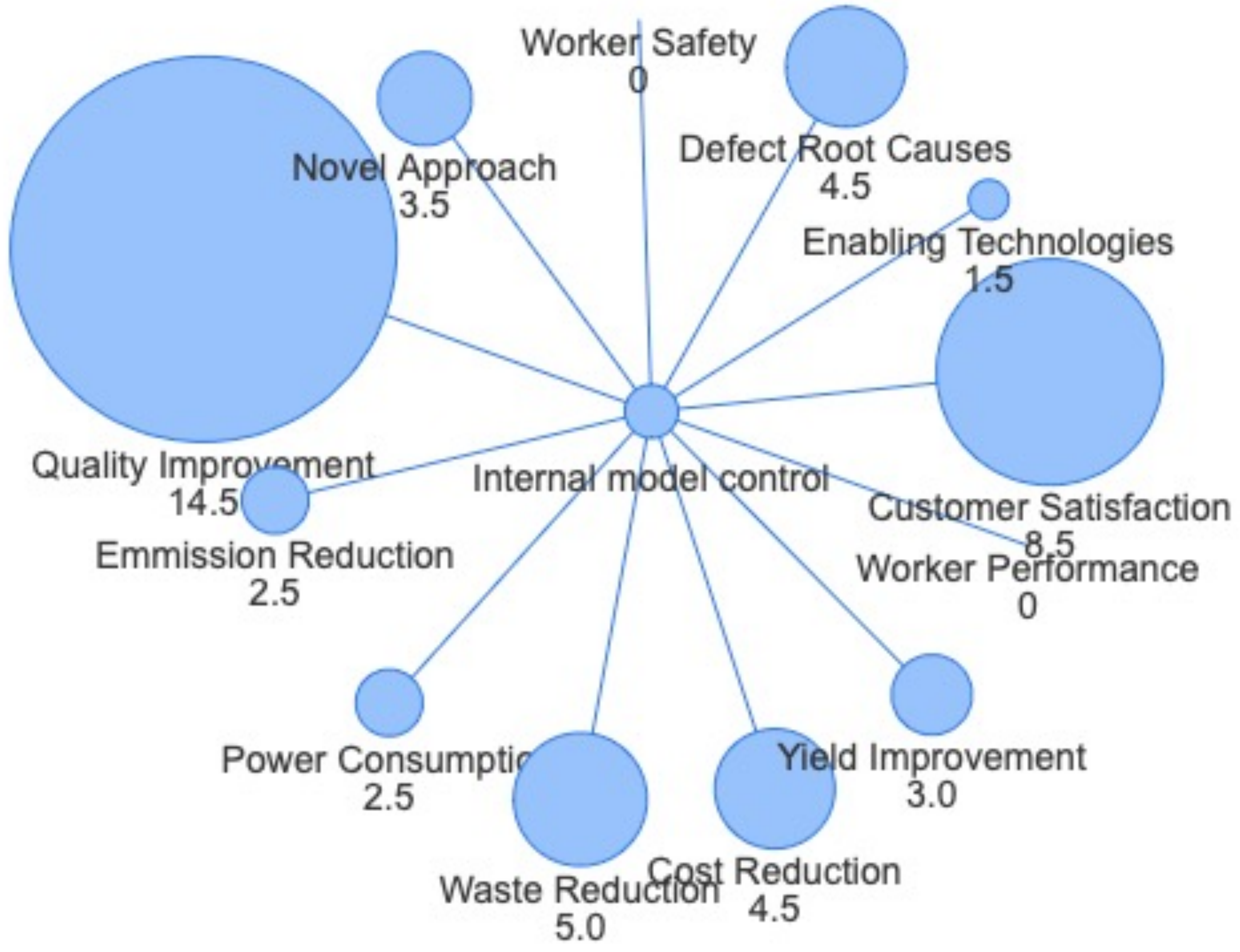
CONTROL IN STEEL



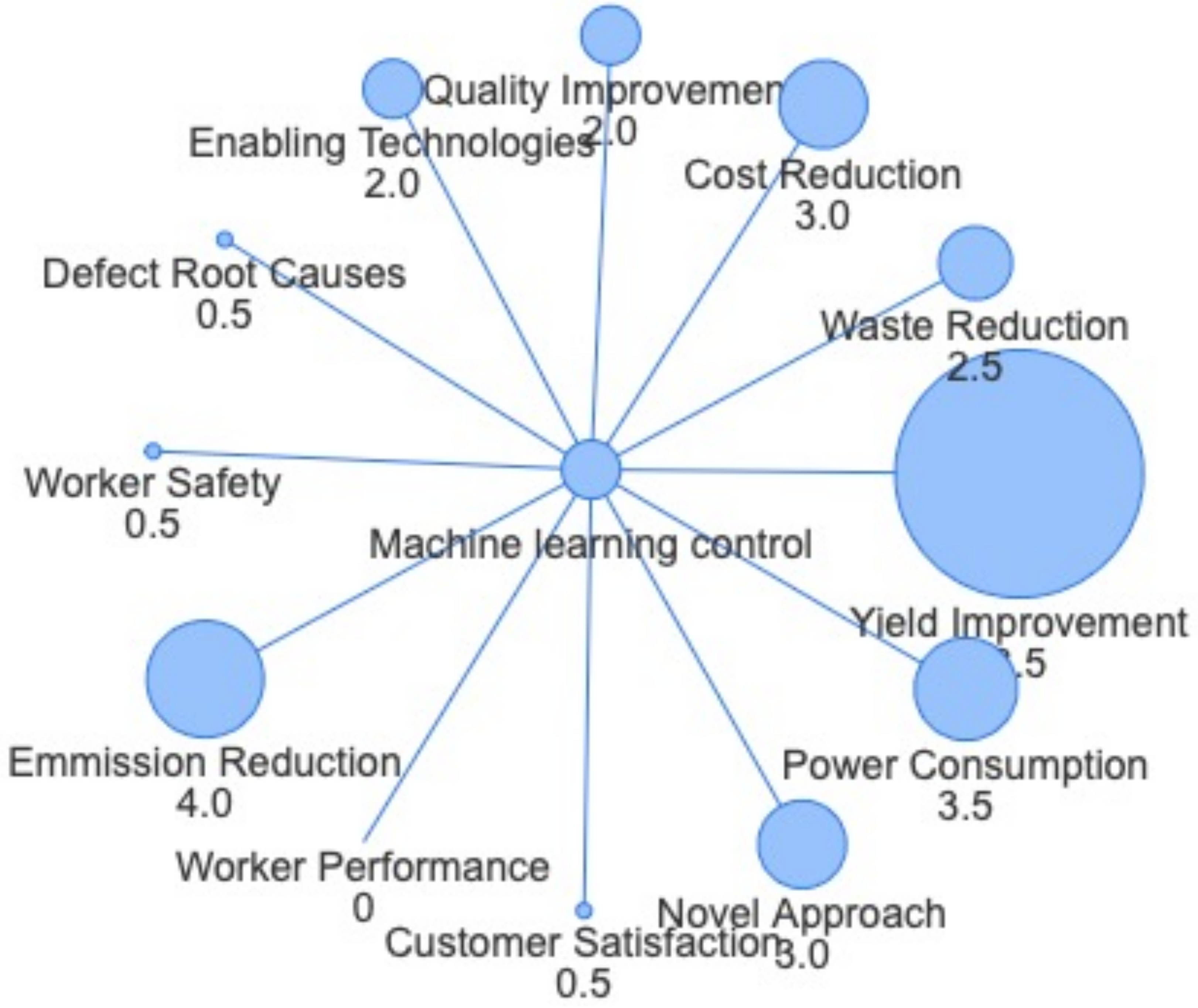
- Low number occurences
  - EITHER Technique is not helping many problems and was not considered out of good reasons
  - OR Technique was simply not covered by research
- Example: Laurent expansion never actually mentioned, perhaps not of relevance
- Example: Bayesian statistiscs has not been „embraced“ in steel production research yet, **despite massive successes in other branches!**

Impact distribution per method

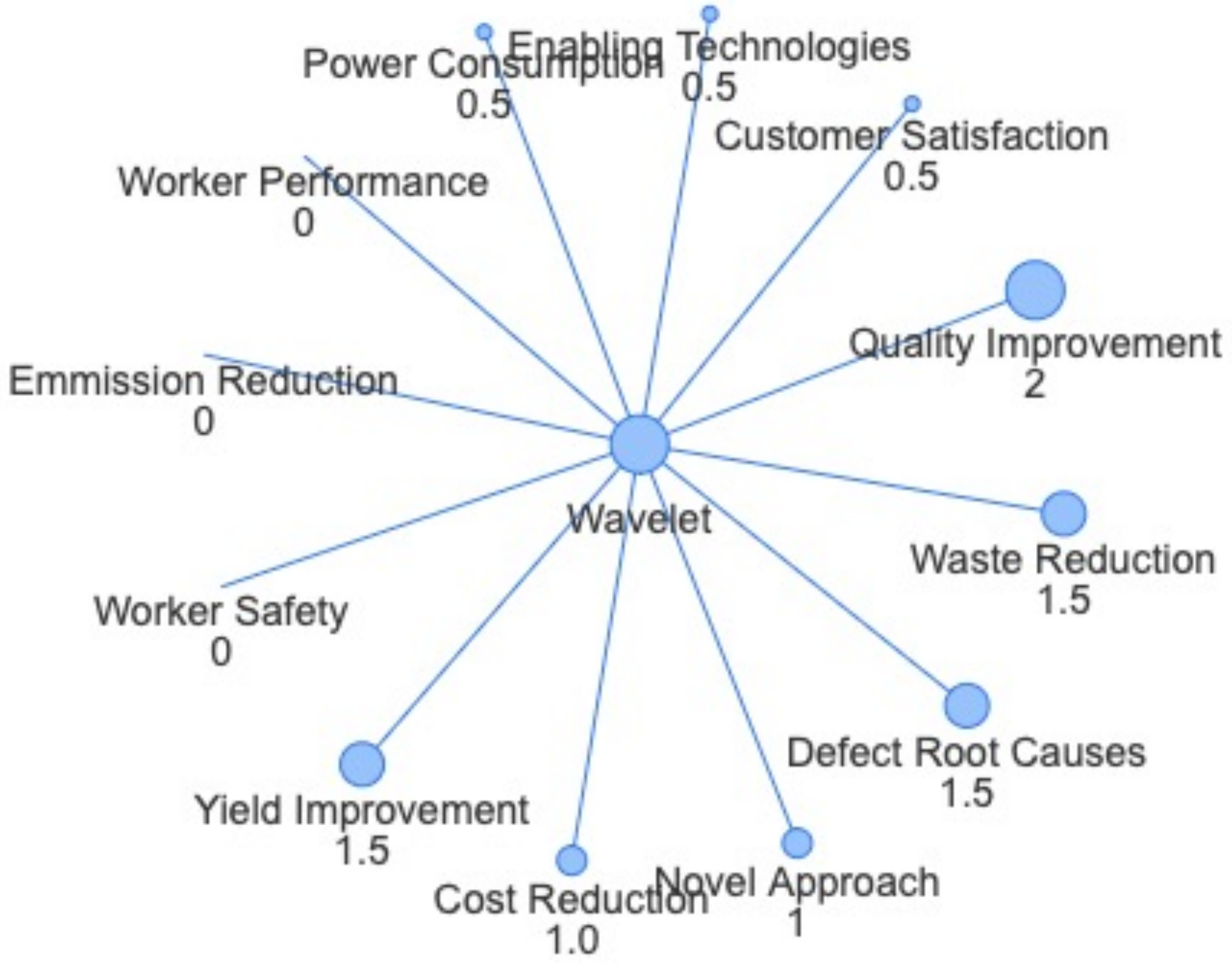
CONTROL IN STEEL



- Internal Model Control



- Machine Learning Control



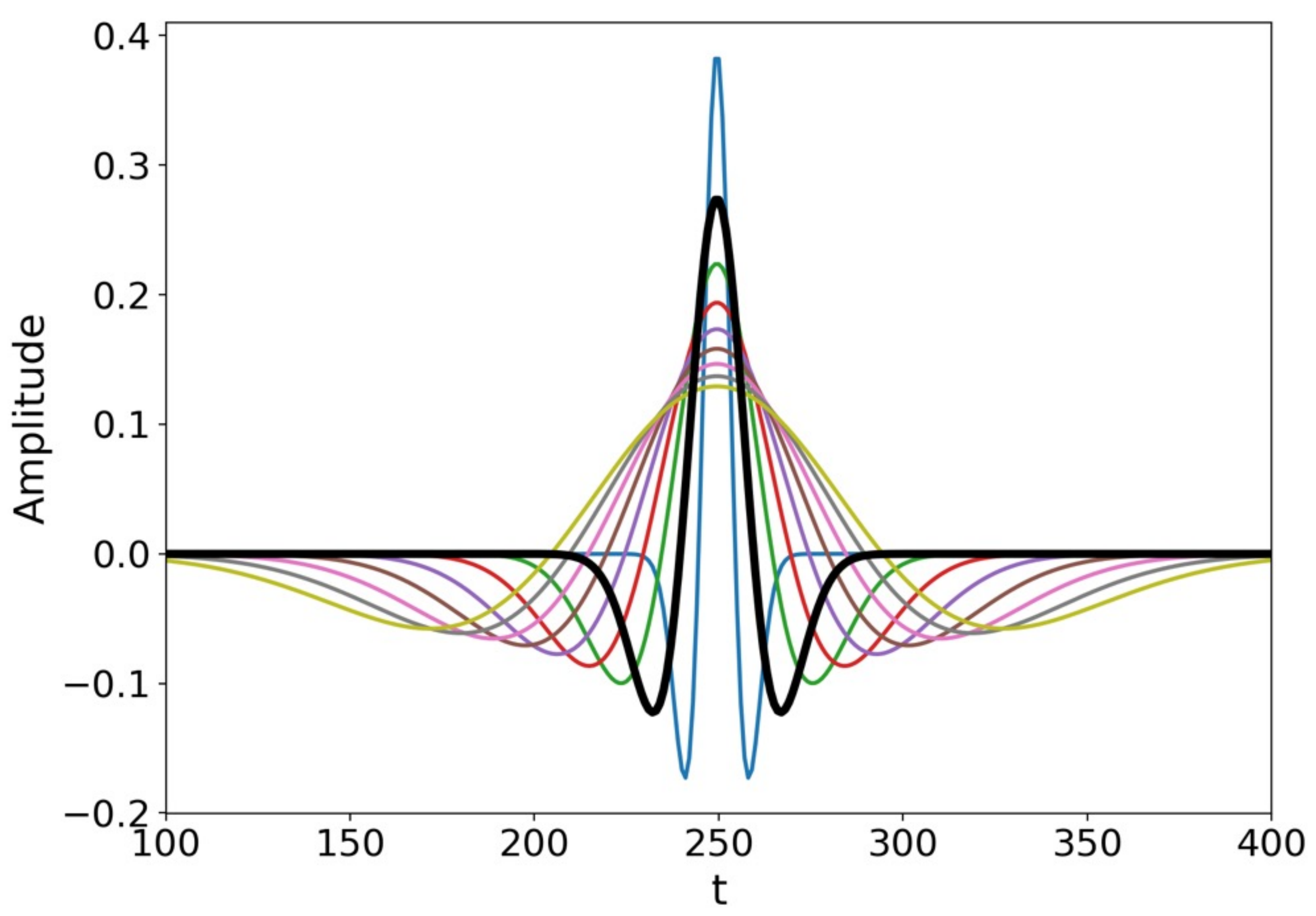
- Wavelet Transform

Impact evolution as function of time

Go further than the books...

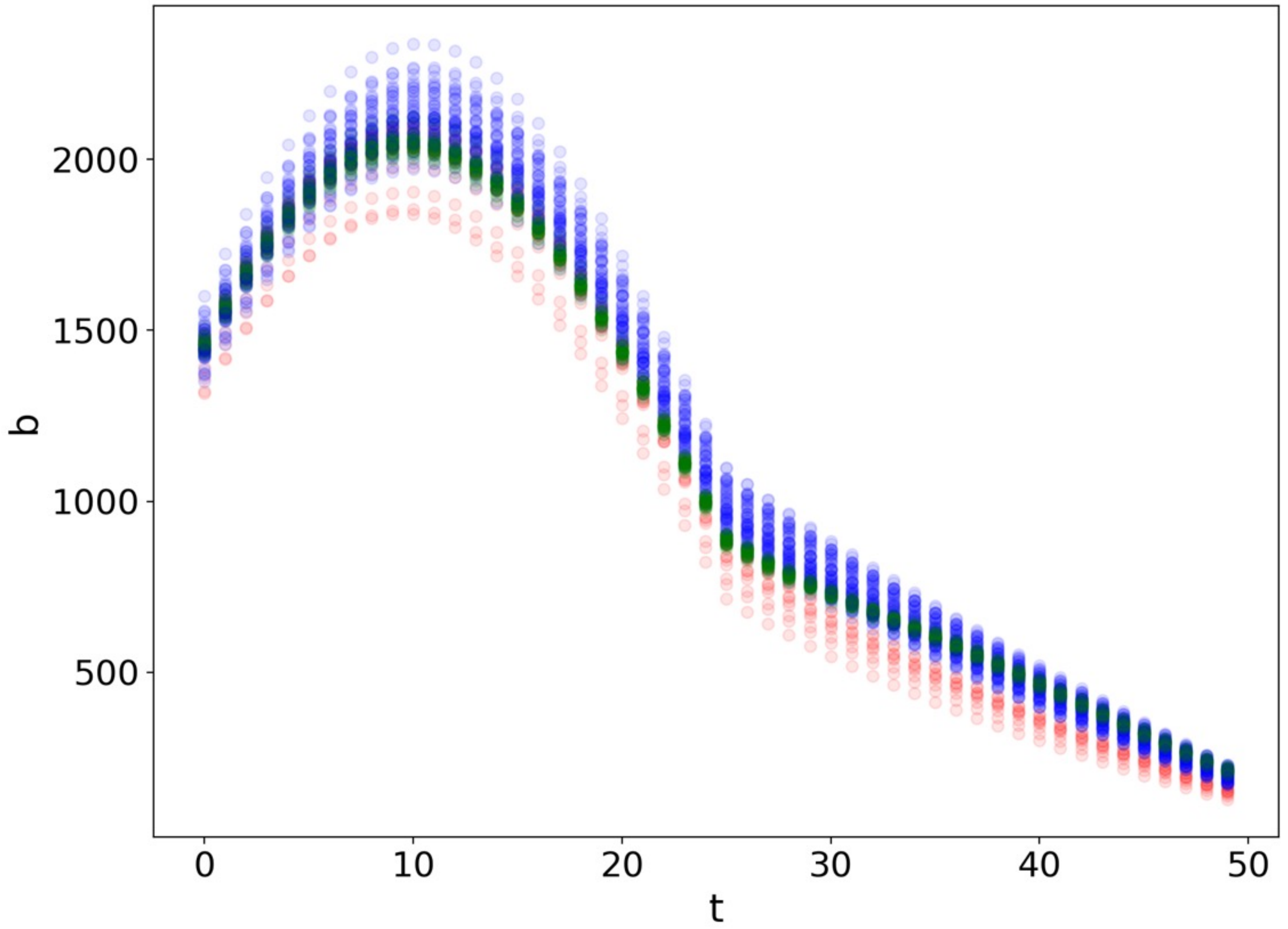
CONTROL IN STEEL

$$\mathrm{Cov}(\boldsymbol{X}) = \begin{pmatrix} \mathrm{Var}(\boldsymbol{x}_0) & \mathrm{Cov}(\boldsymbol{x}_0,\boldsymbol{x}_1) & \dots & \mathrm{Cov}(\boldsymbol{x}_0,\boldsymbol{x}_{N-1}) \\ \mathrm{Cov}(\boldsymbol{x}_1,\boldsymbol{x}_0) & \mathrm{Var}(\boldsymbol{x}_1) & \dots & \mathrm{Cov}(\boldsymbol{x}_1,\boldsymbol{x}_{N-1}) \\ \dots & \dots & \dots & \dots \\ \mathrm{Cov}(\boldsymbol{x}_{N-1},\boldsymbol{x}_0) & \mathrm{Cov}(\boldsymbol{x}_{N-1},\boldsymbol{x}_1) & \dots & \mathrm{Var}(\boldsymbol{x}_{N-1}) \end{pmatrix}$$



$$\mathrm{CWT}[x(t)](a,b) = \frac{1}{|a|^{\frac{1}{2}}} \int_{-\infty}^{\infty} x(t)\overline{\psi}\left(\frac{t-b}{a}\right) dt$$

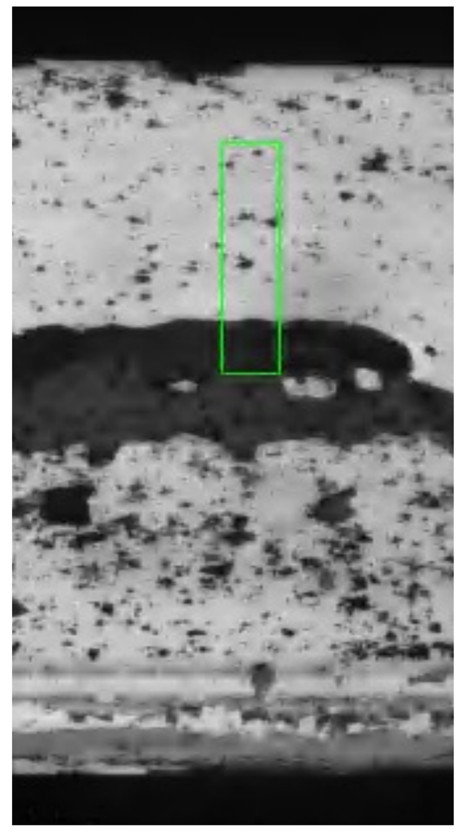
$$C = \mathrm{Cov}\{\mathrm{CWT}[x(t)](a,b)\} \qquad \boldsymbol{\Lambda} = \boldsymbol{S}^T \boldsymbol{C} \boldsymbol{S}$$

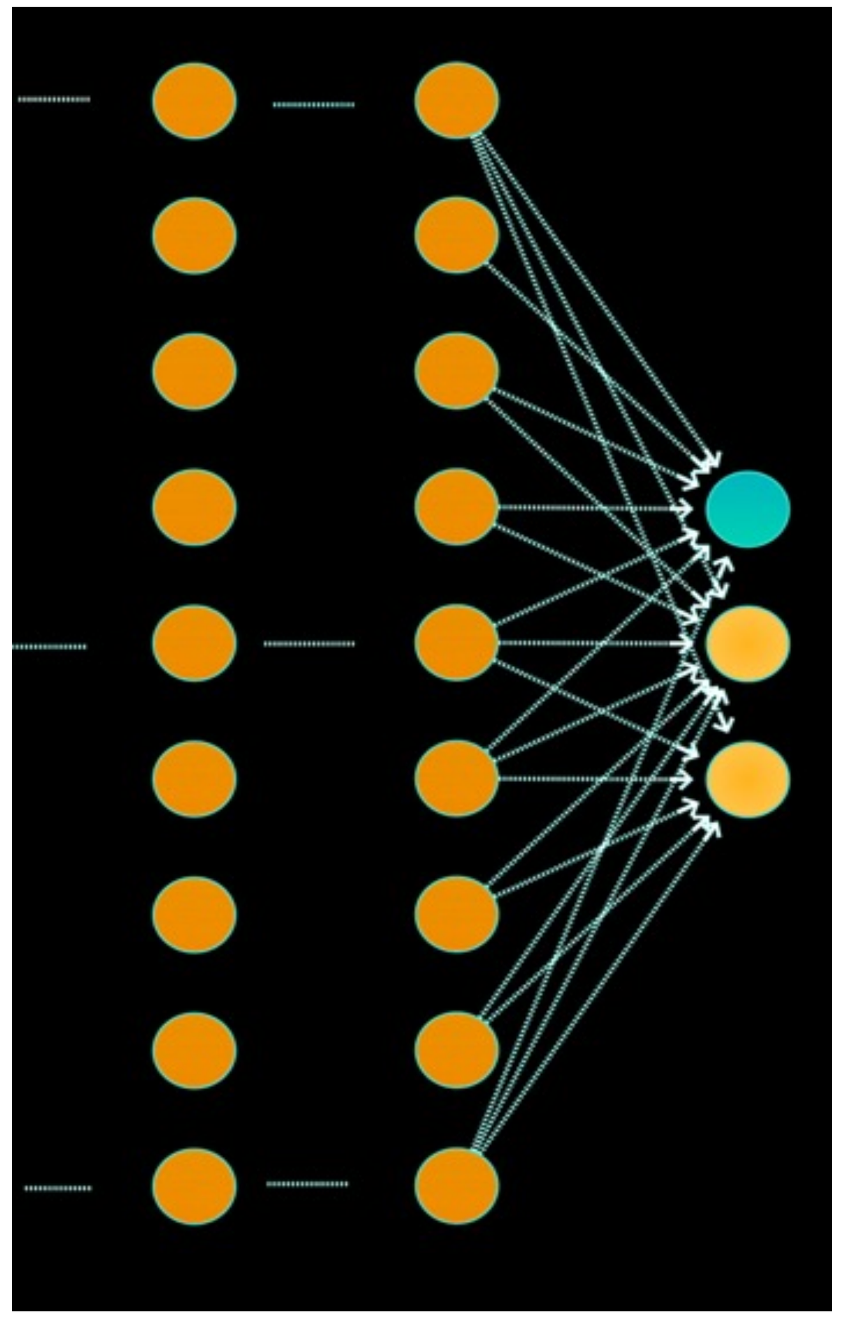


- Application case in steel: Anomaly detection at the continuous caster

Mixture-Density Network with Uncertainty Prediction

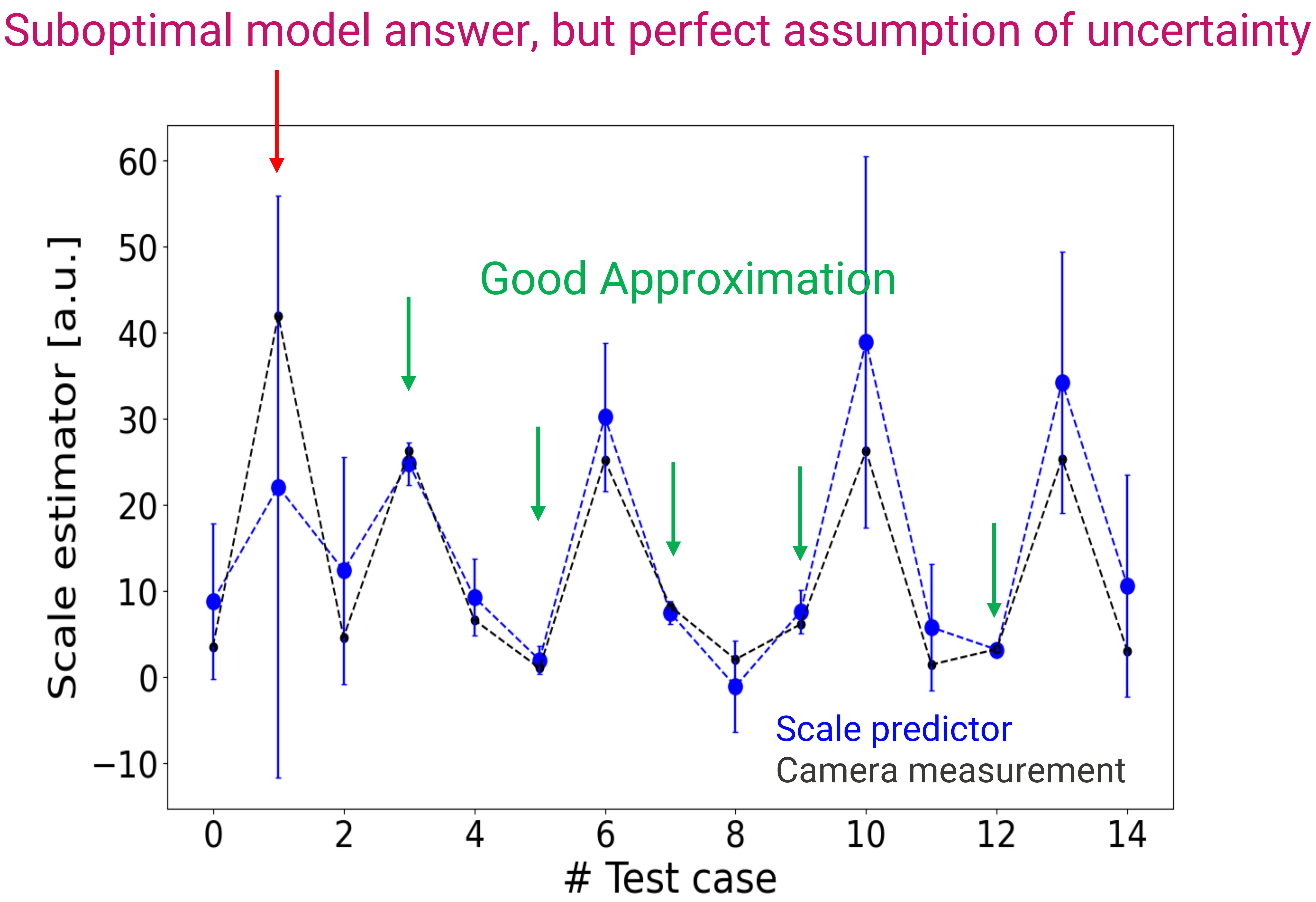
CONTROL IN STEEL



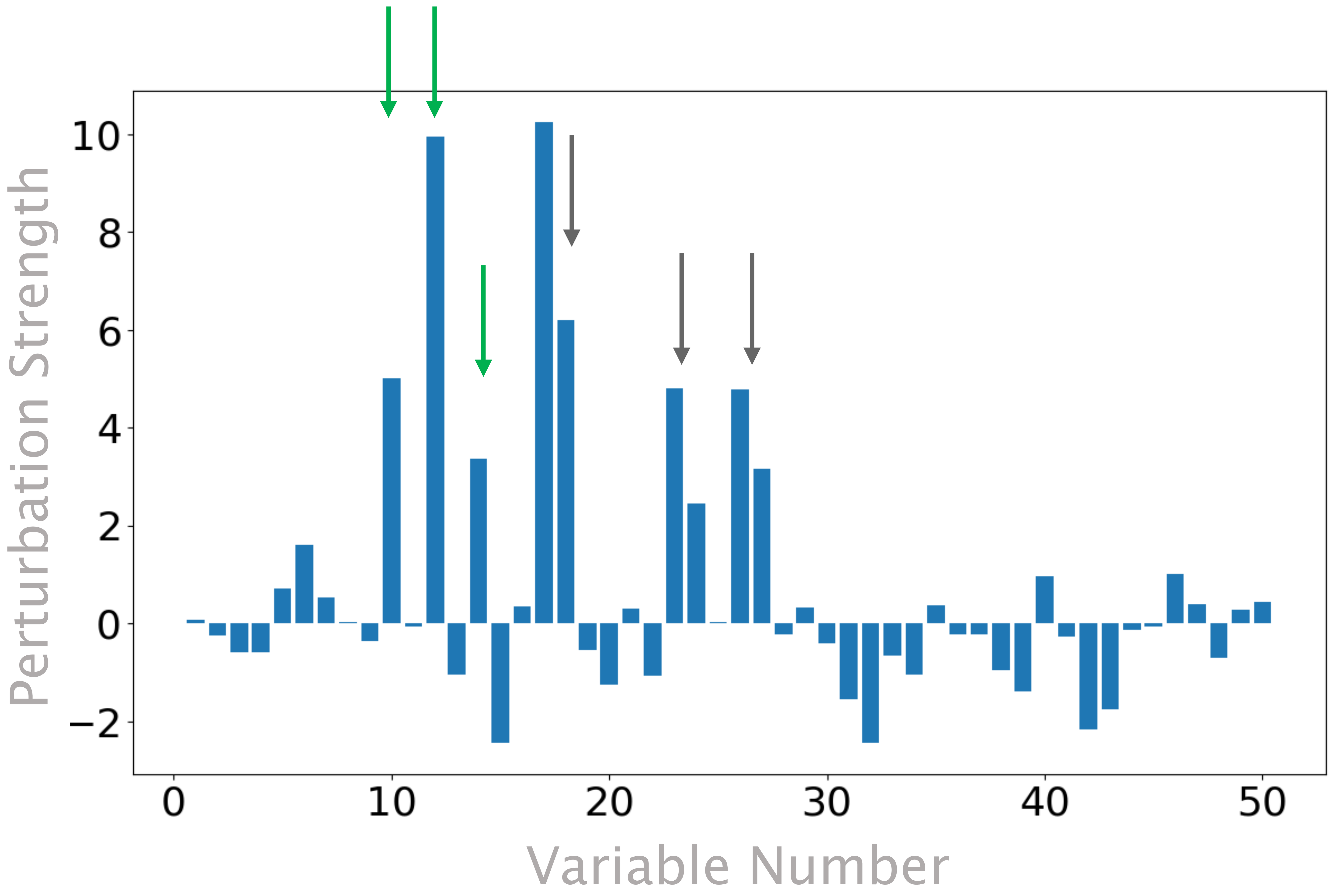


$$T_i, P, \delta t, \lambda,$$
$$\exp(-\lambda \Delta t),$$
$$\exp[-\mathrm{NN}(123)\Delta t],$$

- **Physics-informed** approach with NN-crossreference
- Control application case: Prediction of scale for **iterative learning control** for water flow



Counterfactual ML and MDNN-based reasoning



- Control application case: automatic feedforward **setup of water pressure for descaling** helps as optimizer for MPC

Perturbation theory & sensitivity analysis

- Test vectors

$$T = \{\mathbf{t}^{(1)}, \mathbf{t}^{(2)}, \ldots, \mathbf{t}^{(N)}\}$$

$$\mathbf{t}^{(i)} = (t_1^{(i)}, t_2^{(i)}, \ldots, t_{50}^{(i)})$$

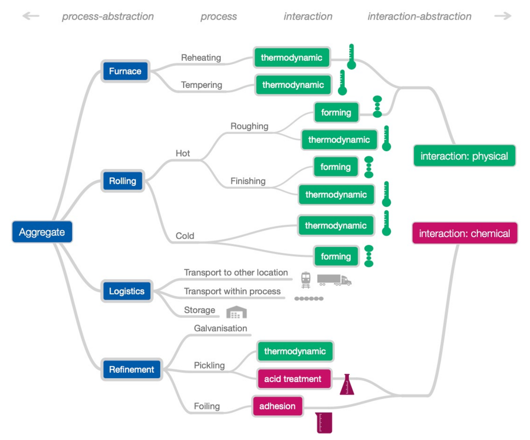
- Stochastic perturbation

$$\tilde{\mathbf{t}}(i,k) = \mathbf{t}^{(i)} + \sum_{\lambda} \delta_{\lambda,k} \mathbf{e}_\lambda \Delta t_k$$

- **Counterfactual: Let ML ask the „What-if?“ Question**

Structure of this talk

CONTROL IN STEEL



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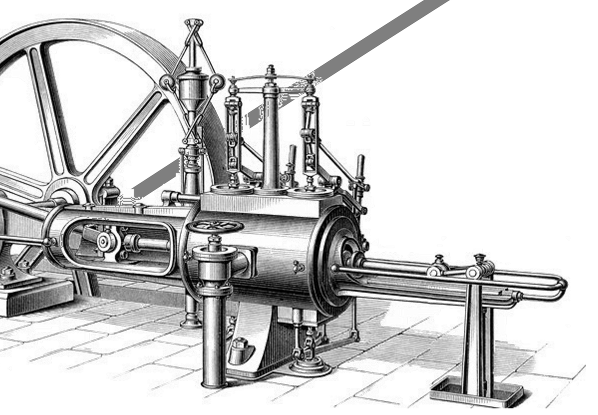

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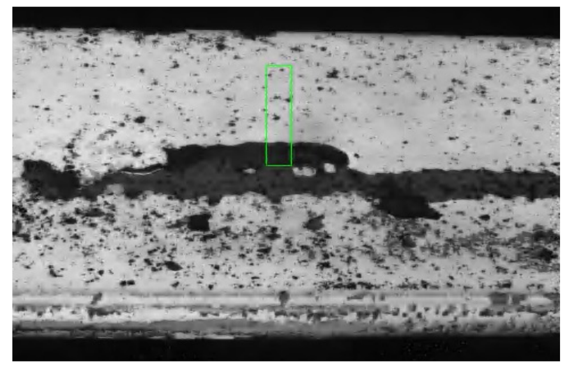

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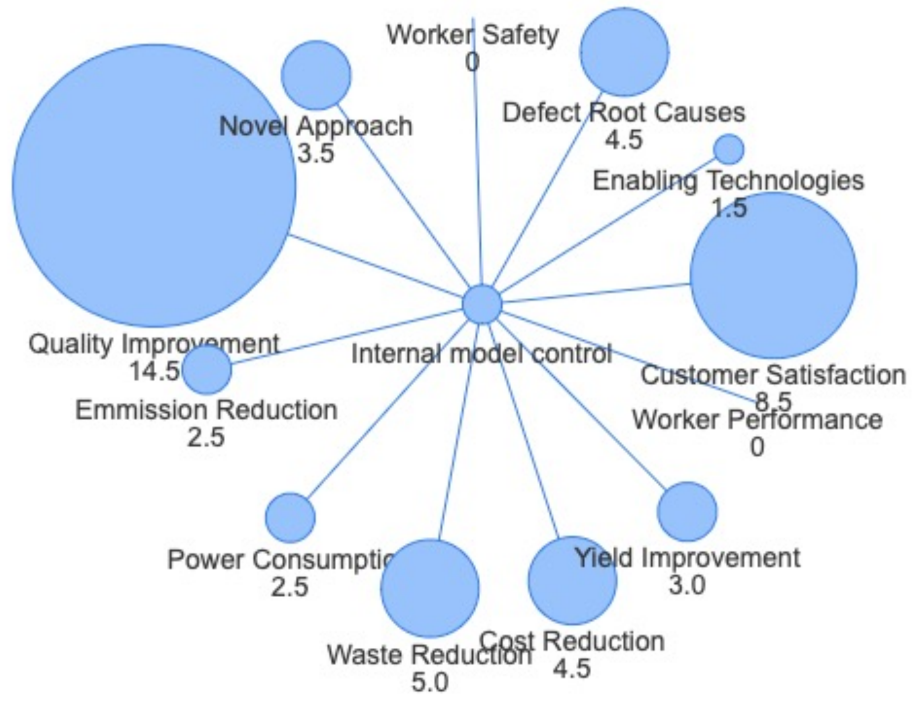


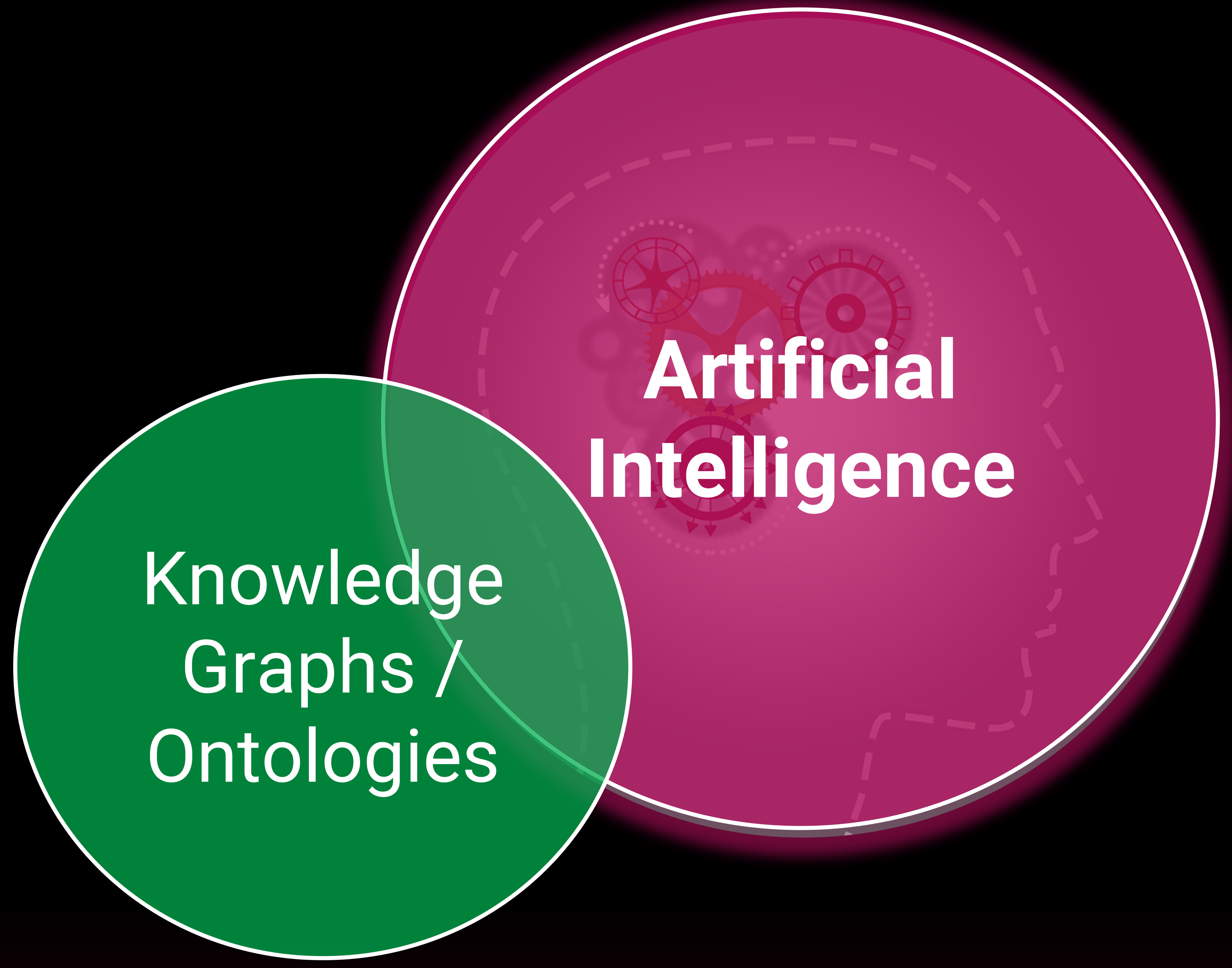
CONTROL IN STEEL

The object oriented input data point can also be marked by a semantic description operator:

$$x = \{x\} * [x] \pm u_x;\ t_x;\ P(x, \mu, \sigma);\ \mathbf{SD}(x) = \text{"Temperature"}$$

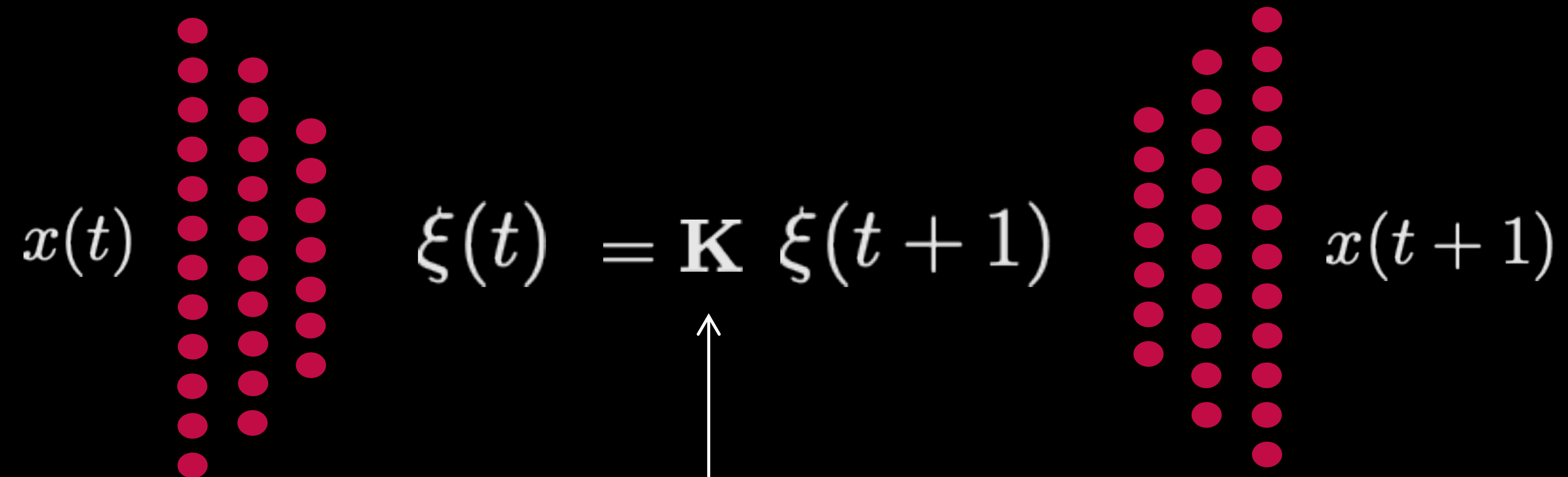
Today this appears like wasting storage.

With increasing plug´n-play demand of new sensors and actuators as well, as data provenance, this solution will become more and more status-quo.



AI Process Chain

Autoencoder Network



- If the **Koopman operator** can be found, the dynamics in latent space is fully linear
- The control solution then reduces to linear systems

Koopman Space

Summary

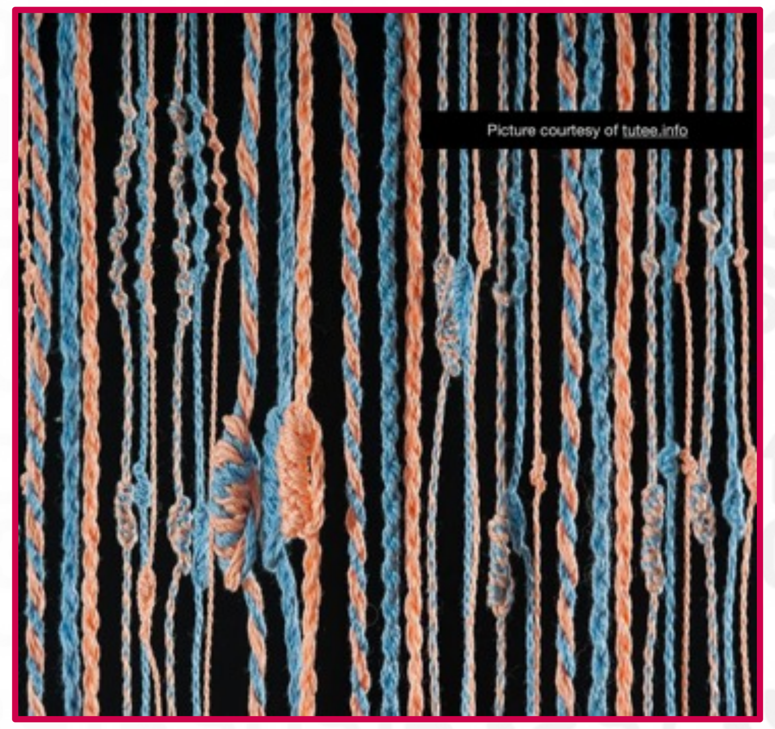
CONTROL IN STEEL

- ControlInSteel is a systematic, semantic analysis of **45(+5) former RFCS research projects**
- It shows the progress achieved by modern control solutions
- It also allows to scientifically investigate the path to impact per method
- Assorted successful methods have been shown

- Promising and recent techniques are yet missing and **potential chances for future projects**
  - Inclusion of uncertainty
  - Physics-informed approaches especially building upon expert knowledge
  - Koopman approach

CONTROL IN STEEL

Thank you for your interest!



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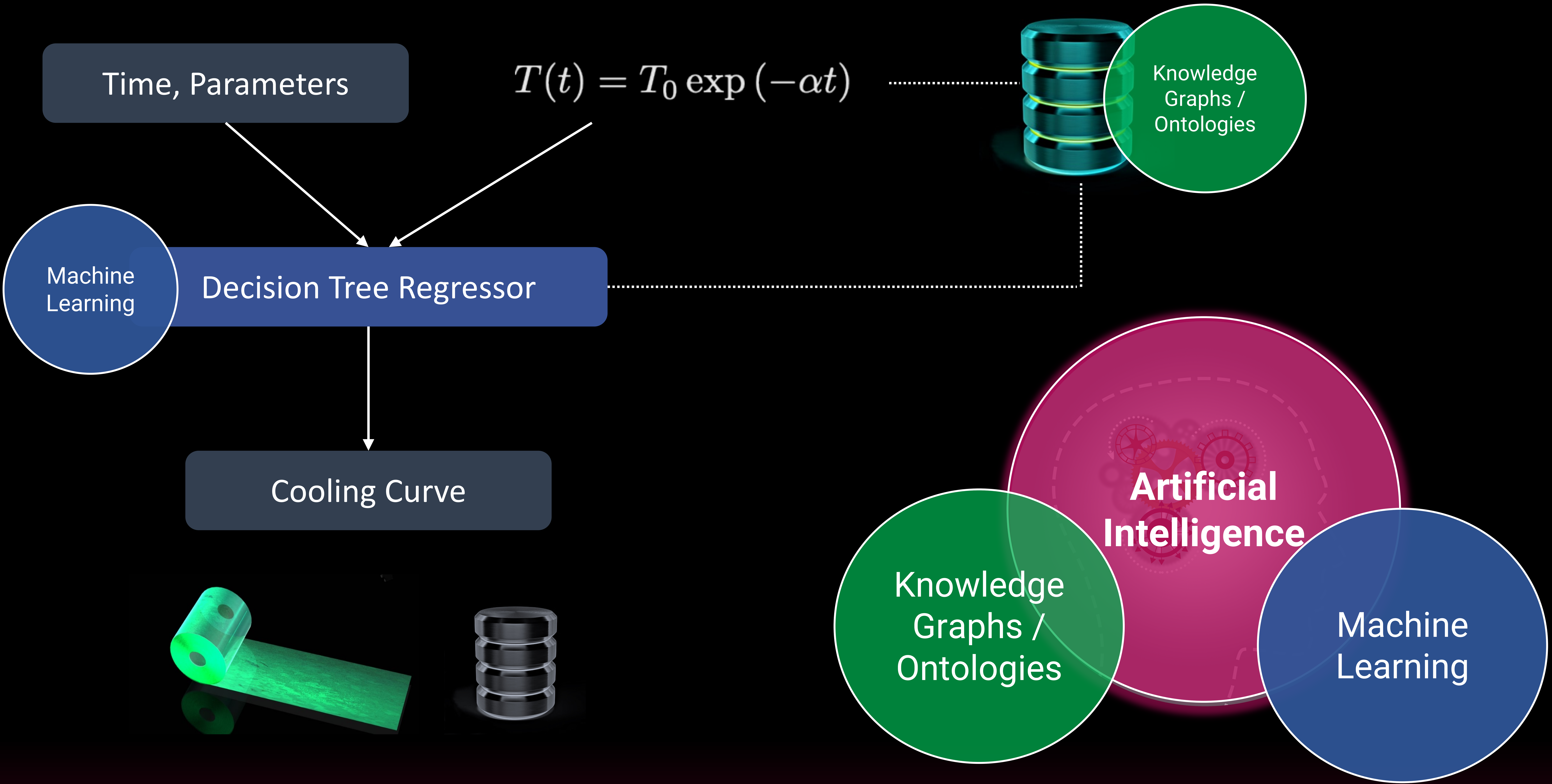

Physics-information

Impact vectors of research projects

CONTROL IN STEEL

- Example: RFCS SOPROD, because coordinator was the same
- Allows to define project by one or **multiple points (!)**
- Automatic Python code that runs on top of our assessment