Advanced Machine Learning Modeling of Chloride Ion Penetration and Service Life Prediction in Internally Cured Concrete

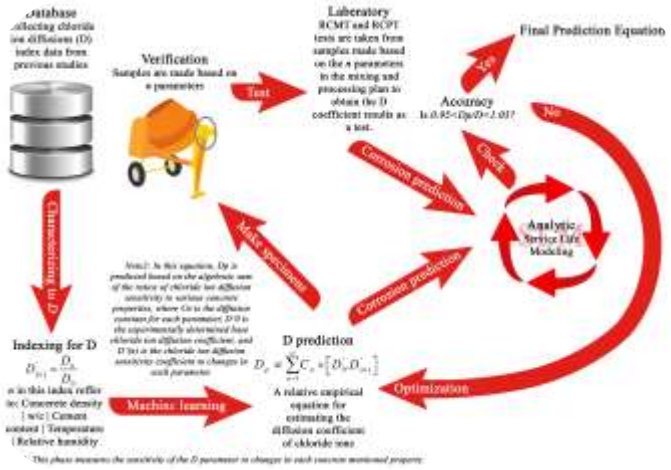
Ali A. Shakeri, Nikta Hasaninasab, Ali Reza Shirazi, Sadegh Dardaei, Ph.D.

Tarbiat Modares University

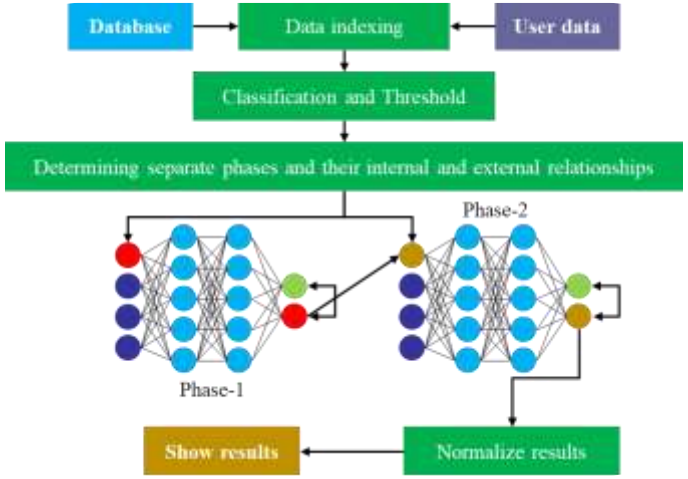
Fariborz M. Tehrani, Ph.D., PE, F.ASCE

California State University

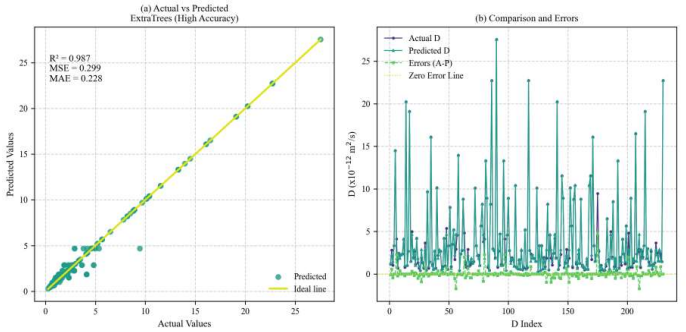
Outline



Introduction

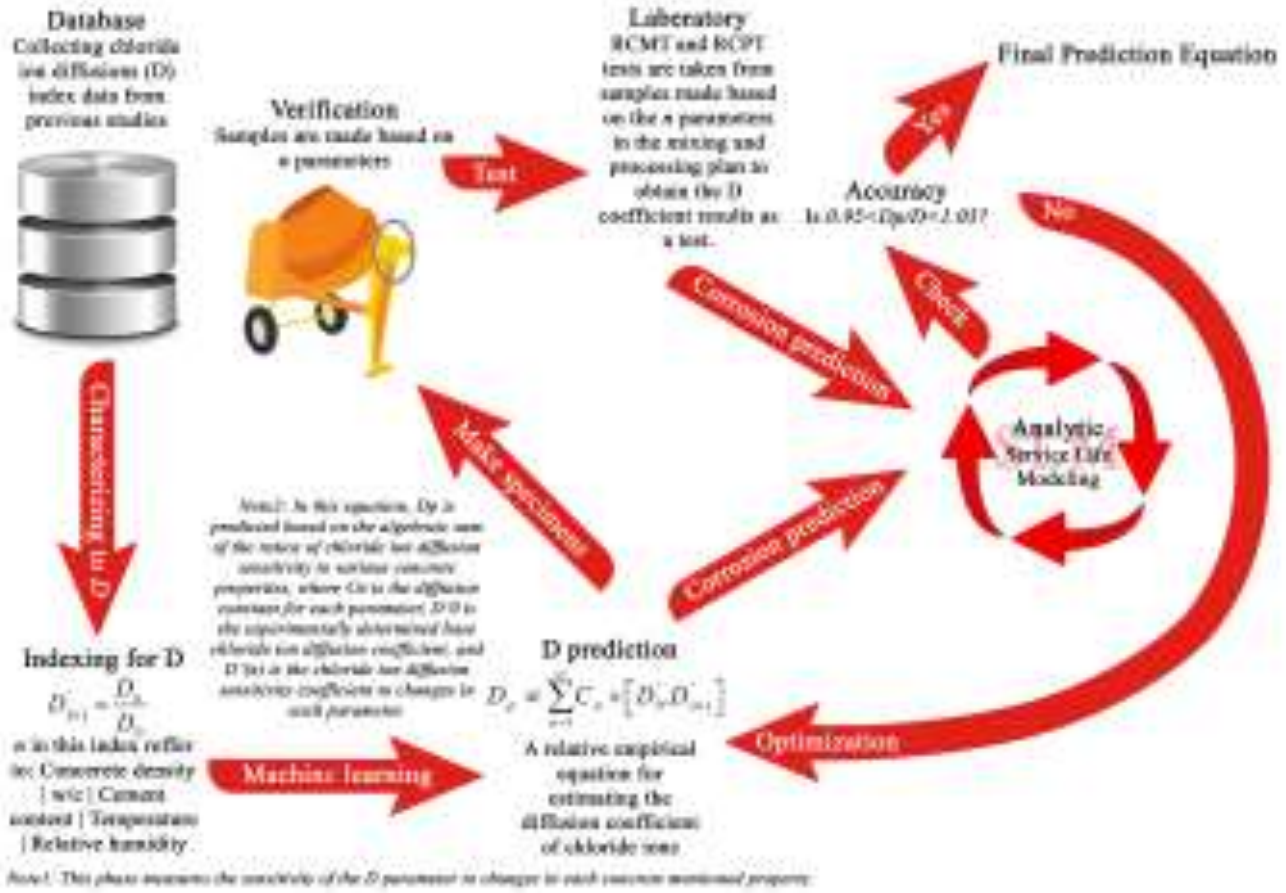


Procedure



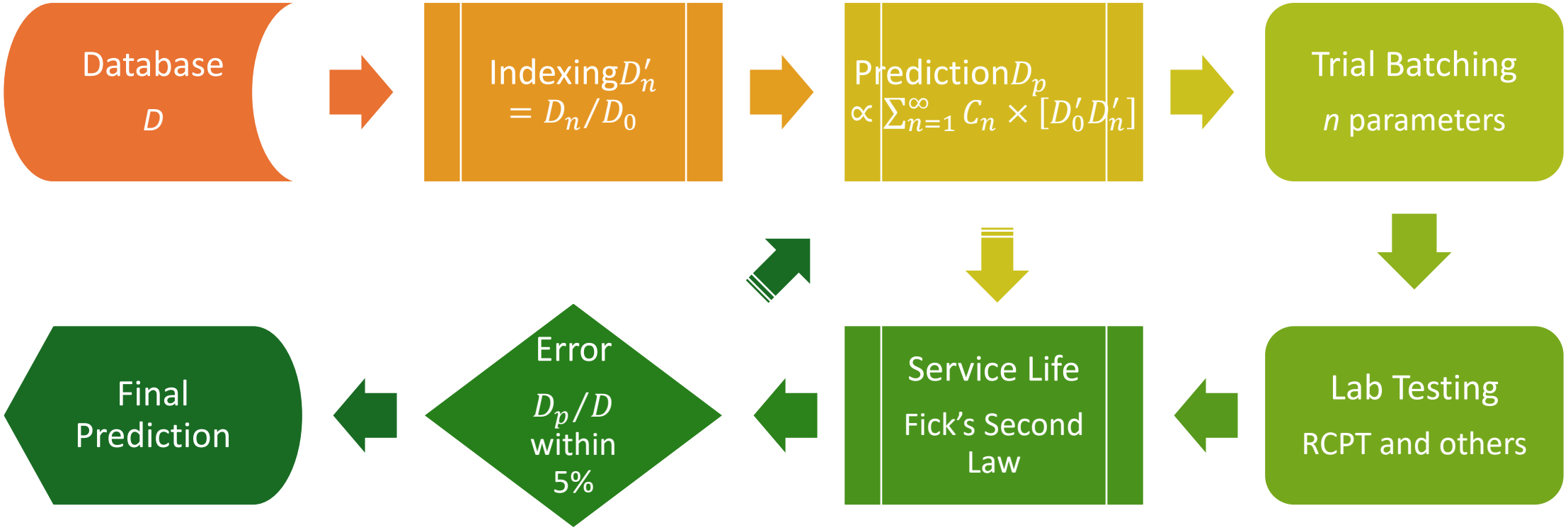
Outcomes

Introduction

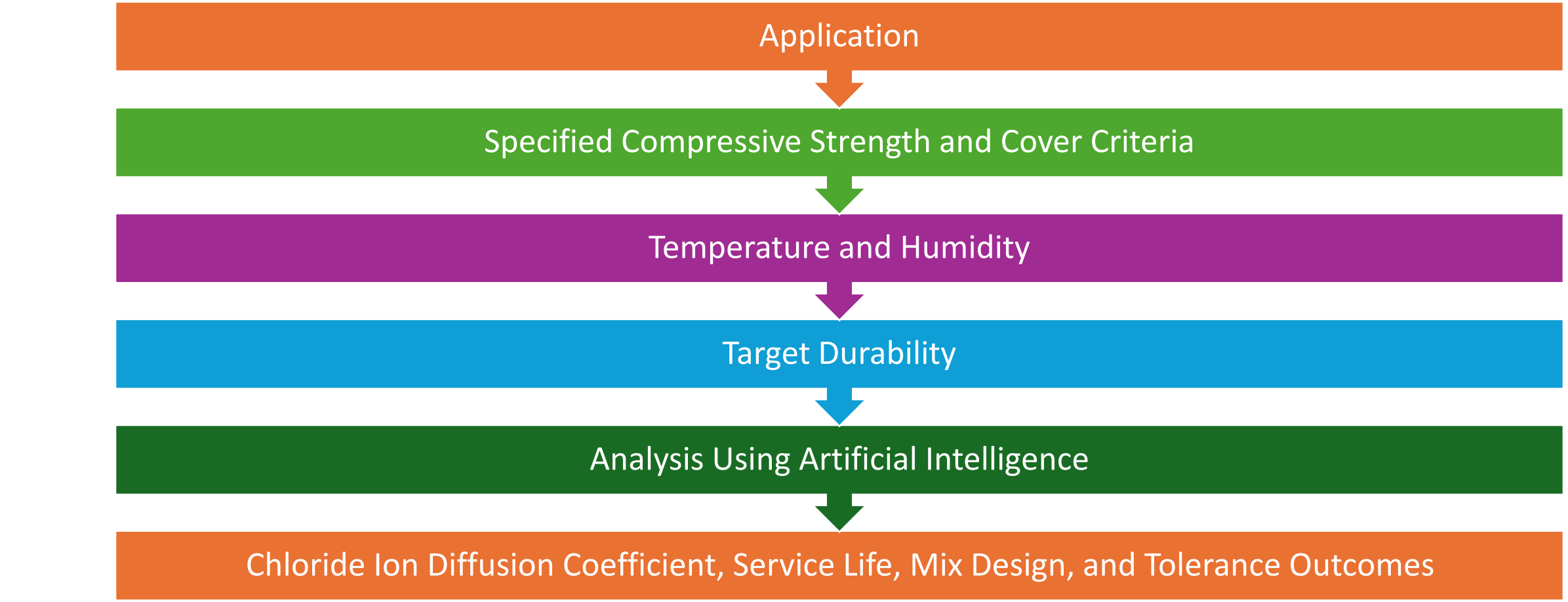


- Service Life Prediction Using
  - Environmental Information
  - Concrete Application
  - Specified Compressive Strength

Introduction: Application/Material/Environment



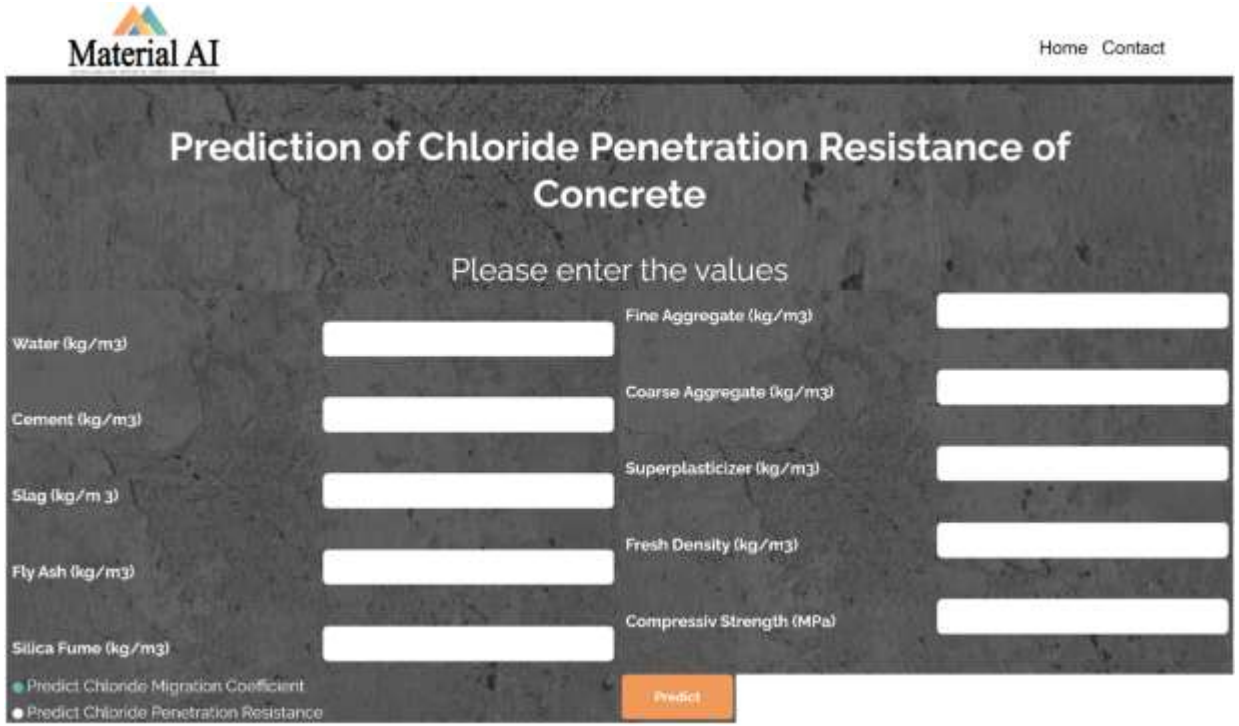
Input Data


Application
Specified Compressive Strength and Cover Criteria
Temperature and Humidity
Target Durability
Analysis Using Artificial Intelligence
Chloride Ion Diffusion Coefficient, Service Life, Mix Design, and Tolerance Outcomes

Research Background

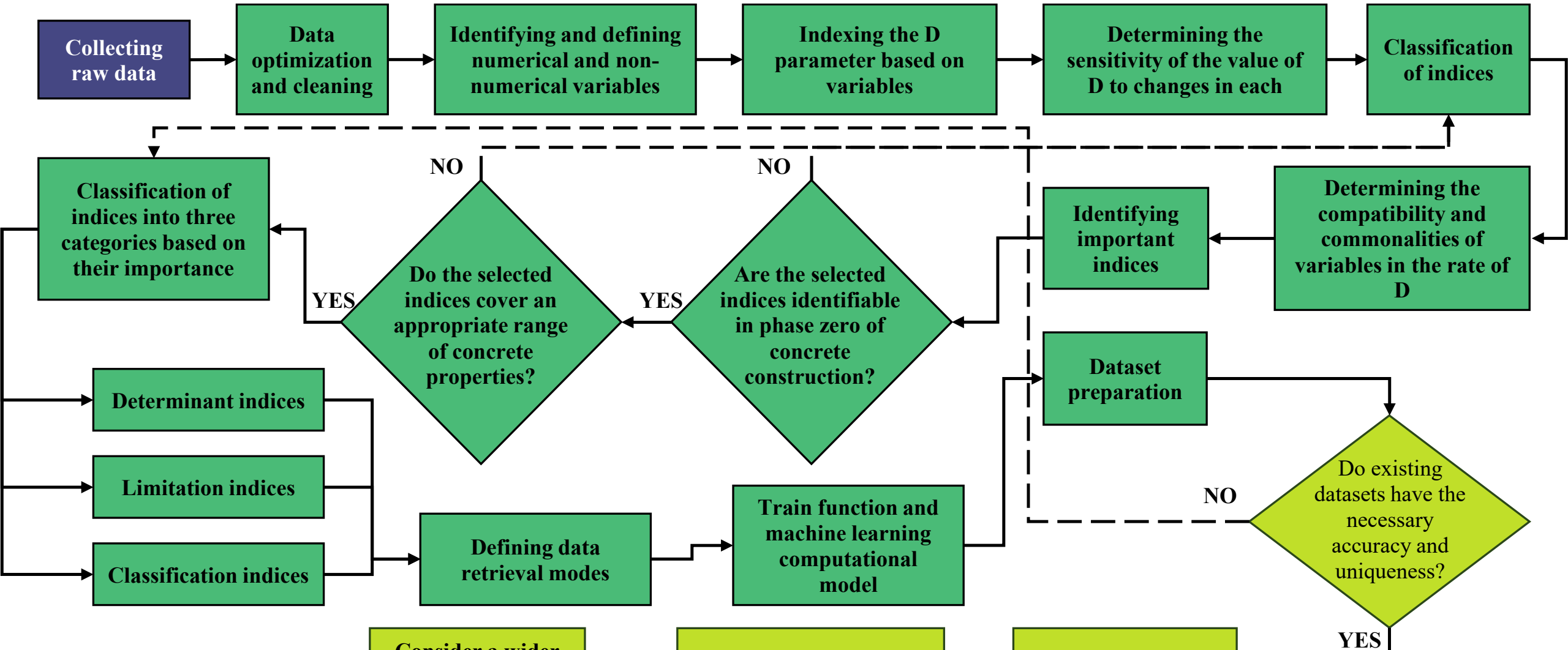


Tehrani. *MTI 2447* (2025).
https://doi.org/10.31979/mti.2025.2447



Hosseinzadeh *et al. Sci Rep* **13**, 15024 (2023).
https://doi.org/10.1038/s41598-023-42270-3

Research Process



Data Processing Types

Data Receiving Layers

User Data

(f'_c, RH, Temp, SL_{req})

Database

D=f(C_1...C_n)

Hidden Layers

Outer Layer

Inner Layer

Exposed Layer

Main Layer → Display Output

Data Processing: Converting Data to Indices

Hydration Kinetics

- $\frac{dW_{hydration}}{dt} = w_c \frac{d\alpha(t)}{dt} \rightarrow W_{hydration}(\mathrm{t}) = w_c \alpha(t) w_{cement}$

Moisture Transport

- $\frac{\delta\theta(x,t)}{\delta t} = \nabla.\left(D_m(\theta,T)\nabla\theta(x,t)\right) - S(x,t);\ J = h_m \rho_v^{sat}(T)(1-RH);\ \rho_v^{sat}(T) = \frac{p_{sat} M_w}{RT};\ W_{evaporation} = \int_0^t J(T,RH)Adt$

Internal Curing Release

- $\frac{dW_i}{dt} = -k_d\left(W_i(t) - W_{eq}\right);\ W_i(0) = W_{abs};\ W_{abs} = M_{LA} \times A_{abs}$

Water Balance

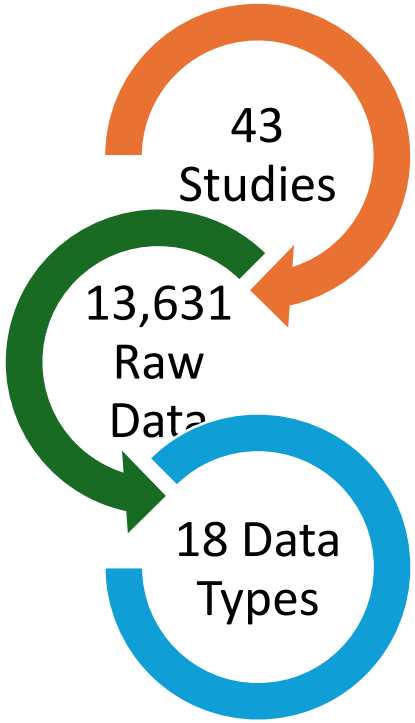
- $W_{mix} + \int_0^t k_d\left(W_i - W_{eq}\right)dt - \int_0^t J(T,RH)Adt \geq w_c \alpha(t) w_{cement}$

Maximum *D'* Based on the Minimum Required Service Life of the Project:

- $D' = \frac{x_{cover}^2}{4SL_{(ACI)}} \times \left(erf^{-1}\left(1 - \frac{C_{th}}{C_s}\right)\right)^2$

Data Types – Database: Collection and Identification

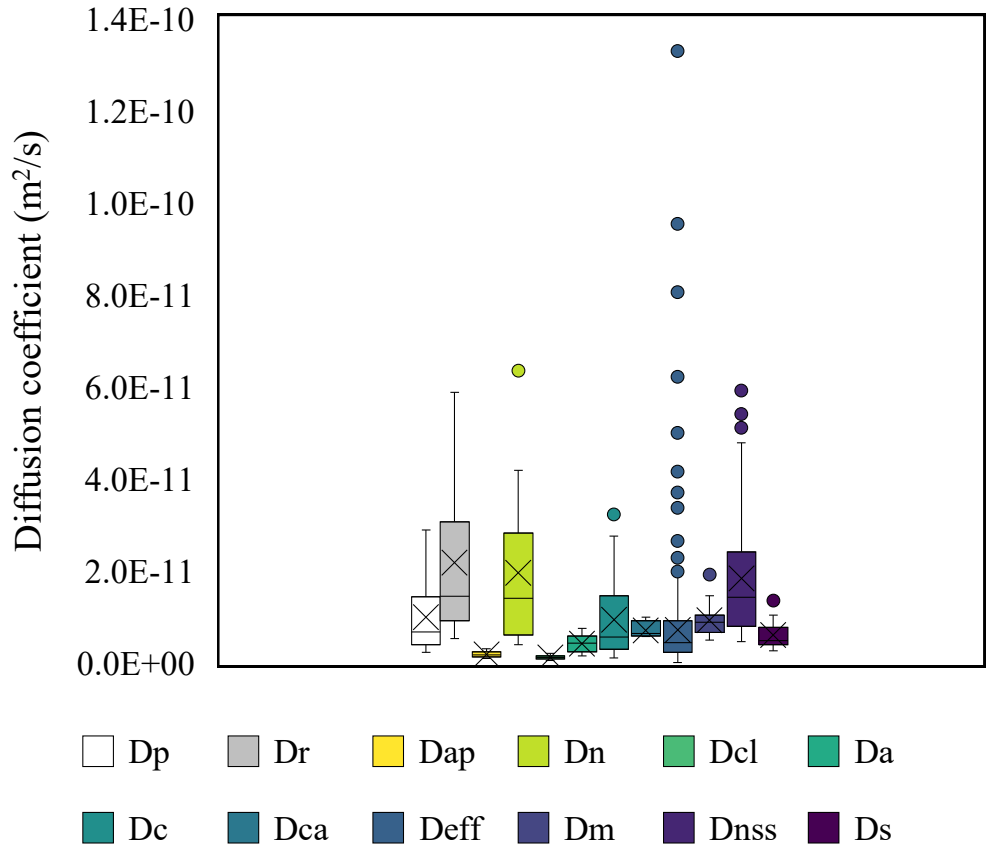
Cement (Ce)	Fly Ash (FA)	Silica Fume (SF)	Slag (Sl)	Meta Kaolin (MK)
Binder (Bi)	Cement Type (CT)	Superplasticizer (SP)	Fine Aggregate / Coarse Aggregate (FA/CA)	Water/Binder (w/b)
Curing rate (Cu)	Fresh Density (De)	Porosity (Po)	Specific Gravity (SG)	Chloride ion Diffusion coefficient (D)
	Specimen age (DA)	Compressive strength (Fc)	Chlorine ion concentration for the experiment (TT)	

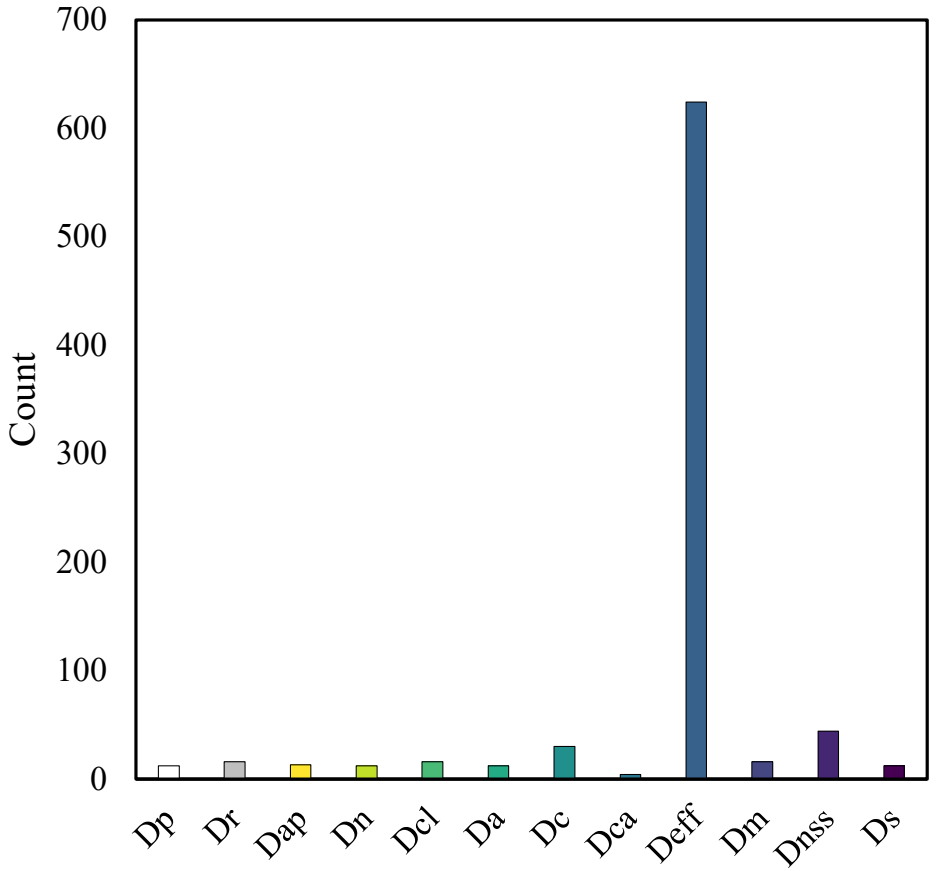


Selected Studies

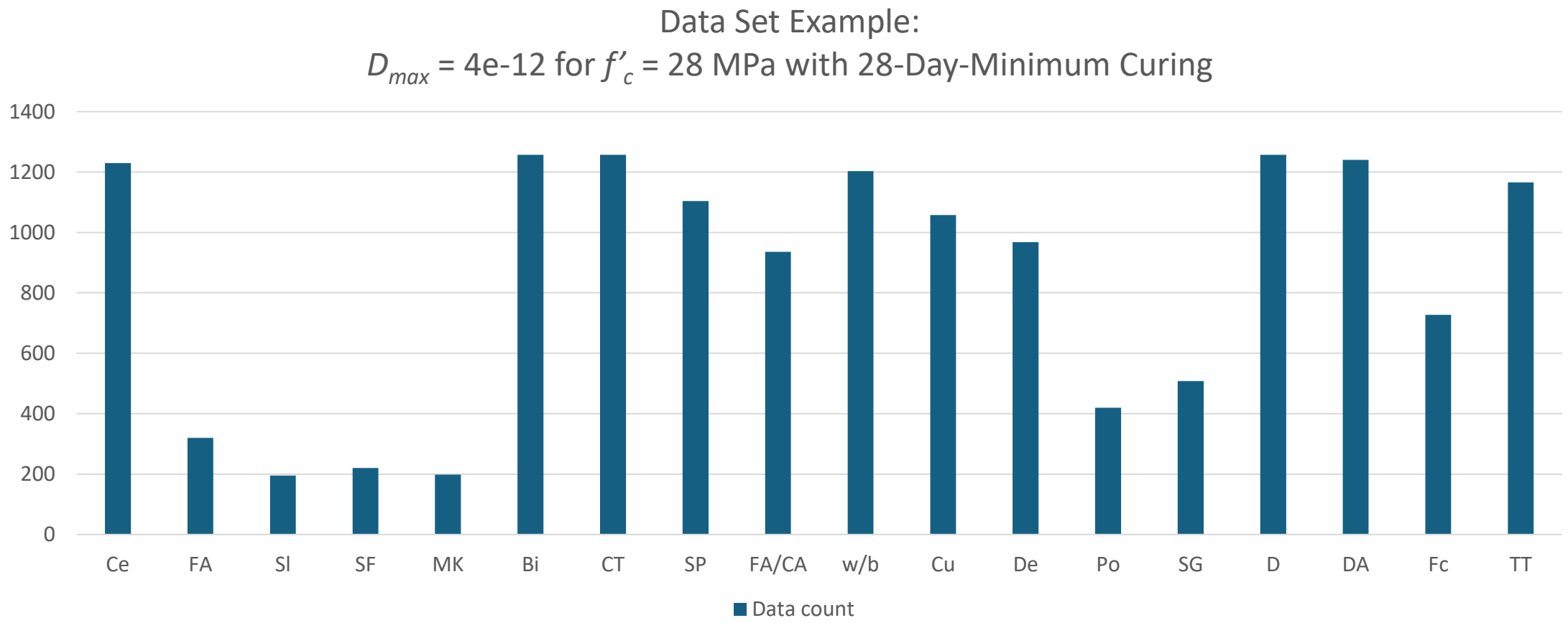
Raw	Name	Date	Raw	Name	Date	Raw	Name	Date
1	R Vedalakshmi et al.	2008	16	H Hao-bo et al.	2016	31	J Sobhani et al.	2023
2	V Elfmarkova et al.	2015	17	A Costa et al.	1999	32	GM Lafta et al.	2024
3	C Andrade et al.	2014	18	R Alizadeh et al.	2008	33	S Real et al.	2015
4	AD Tegguer et al.	2013	19	JI Park et al.	2016	34	MN Sepehr	2014
5	J Lizarazo-Marriaga et al.	2009	20	RM Ferreira et al.	2016	35	H Pourahmadi Sefat Arabani et al.	2017
6	G Sun et al.	2011	21	HW Song et al.	2009	36	PL Dao et al.	2023
7	HS Al-alaily et al.	2016	22	S Real et al.	2015	37	SV Dinesh et al.	2023
8	O Truc et al.	2000	23	YC Choi et al.	2017	38	M Monika et al.	2022
9	S Caré et al.	2003	24	M Shekarchi et al.	2009	39	BLN Reddy et al.	2020
10	CC Yang et al.	2003	25	K Audenaert et al.	2010	40	MO Kim et al.	2017
11	A Djerbi et al.	2008	26	CC Yang et al.	2004	41	BB Winsley et al.	2018
12	KY Yeau et al.	2005	27	X Liu et al.	2011	42	MF Ejaz et al.	2022
13	S Care et al.	2008	28	J Liu et al.	2017	43	V Prahatheswaran et al.	2022
14	BH Oh et al.	2007	29	M Maes et al.	2013			
15	X Liu et al.	2015	30	A Pilvar et al.	2016			

Data Types – Database: Indicators and Indices

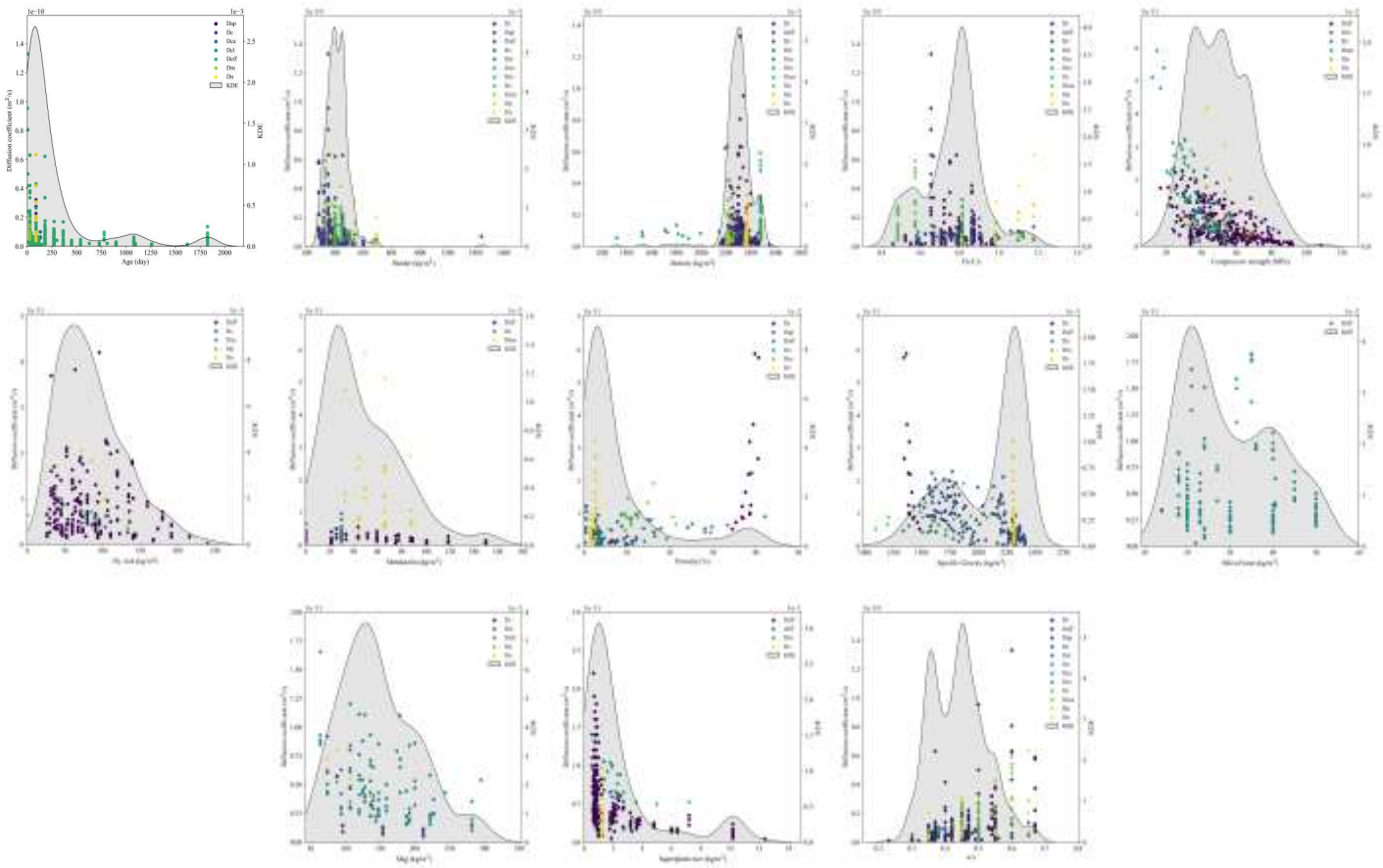


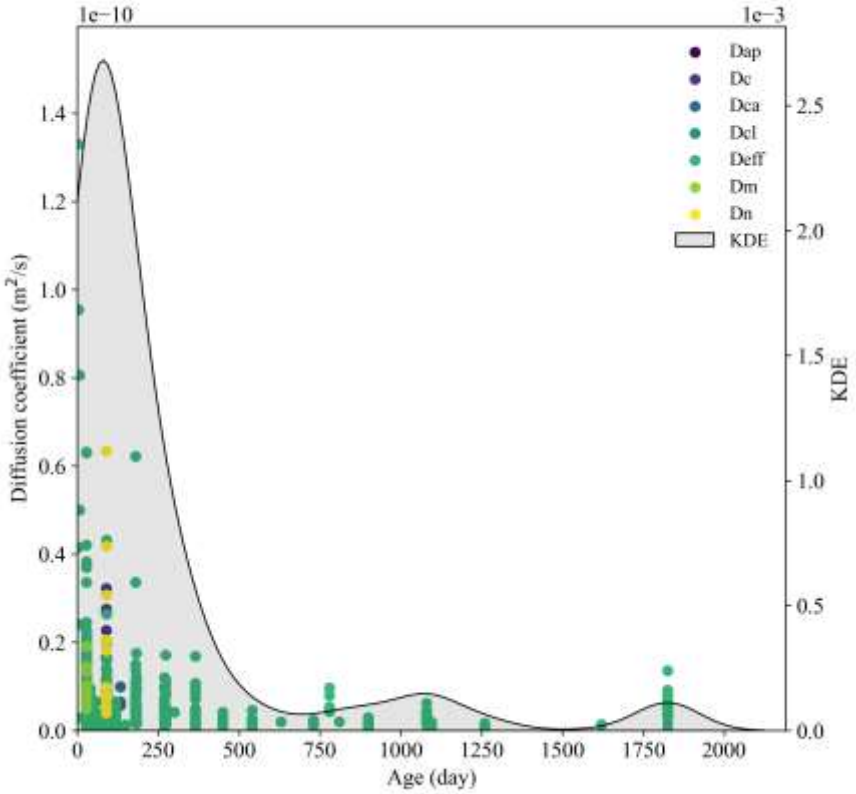


Data Types – Database: Cleaned Data Sets and Indices

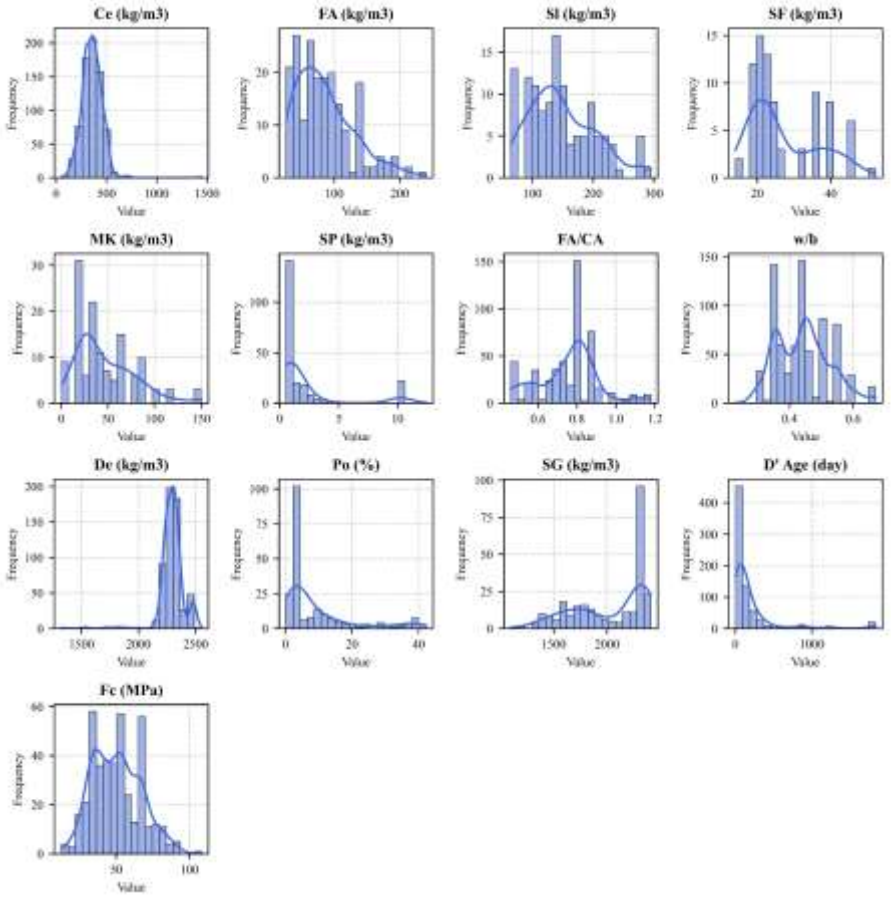


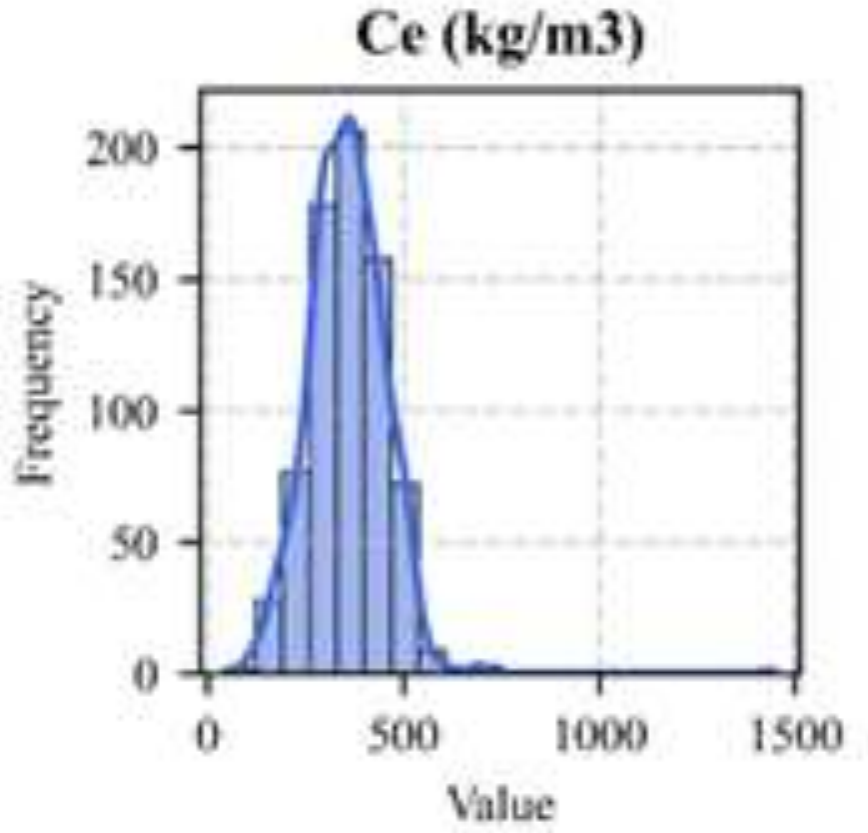
Data Types – Database: Ranges and Trends



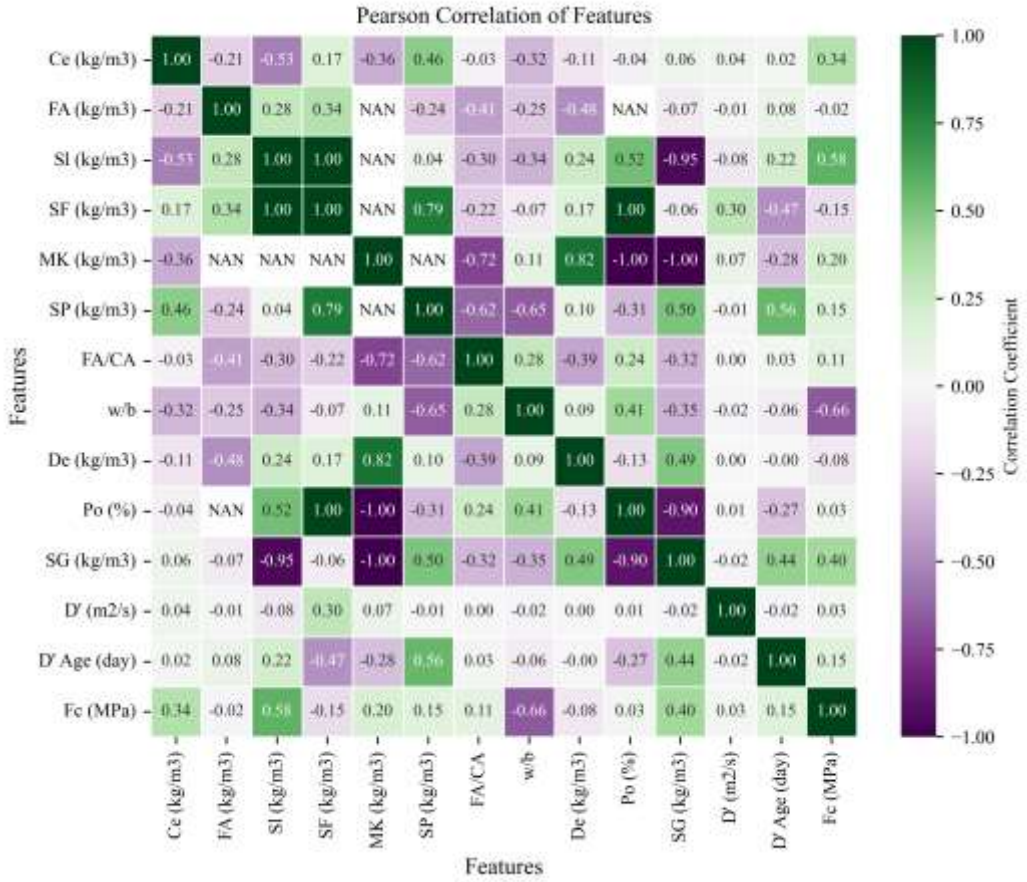


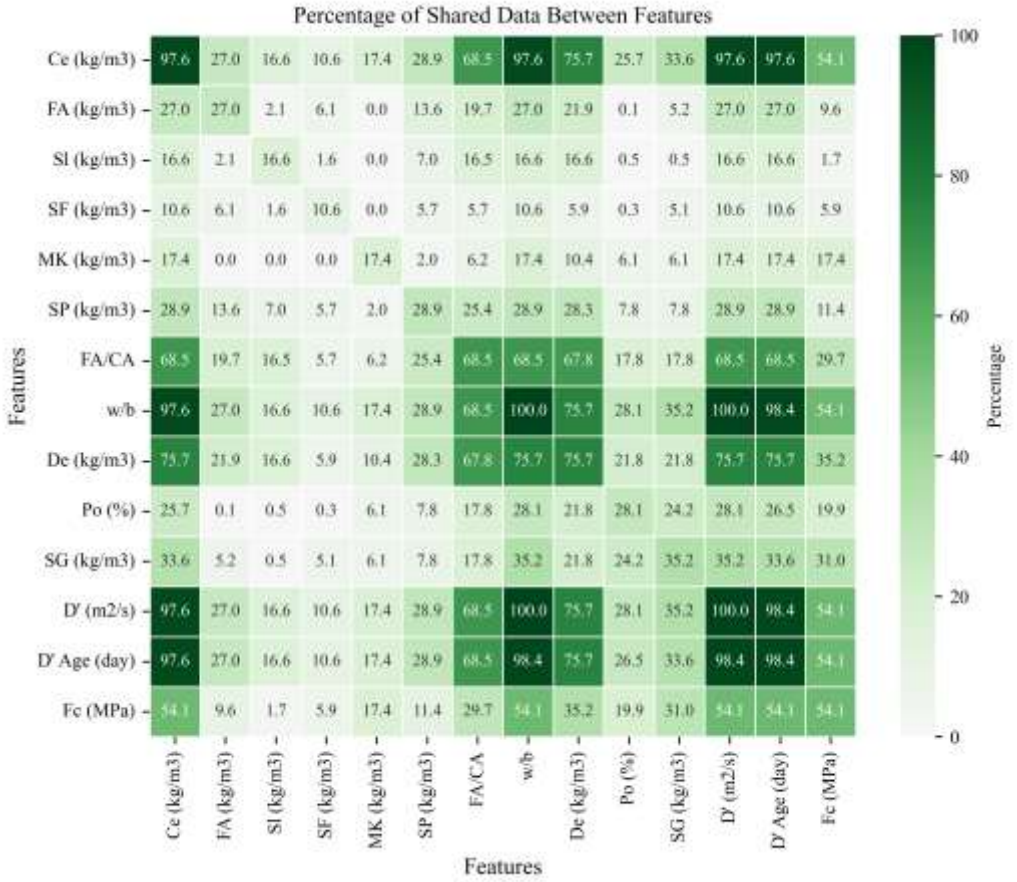
Data Types – Database: Determining Efficiency



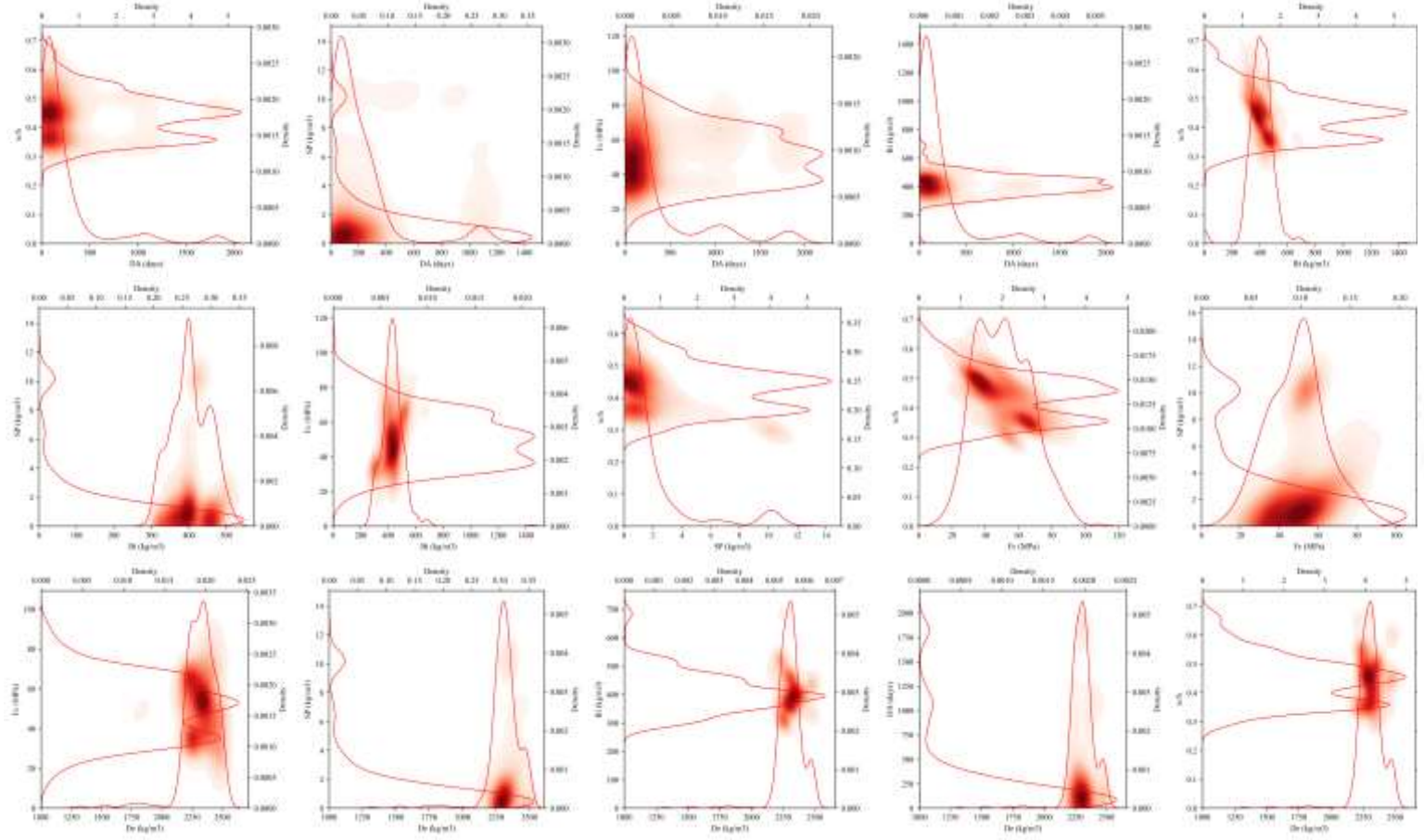


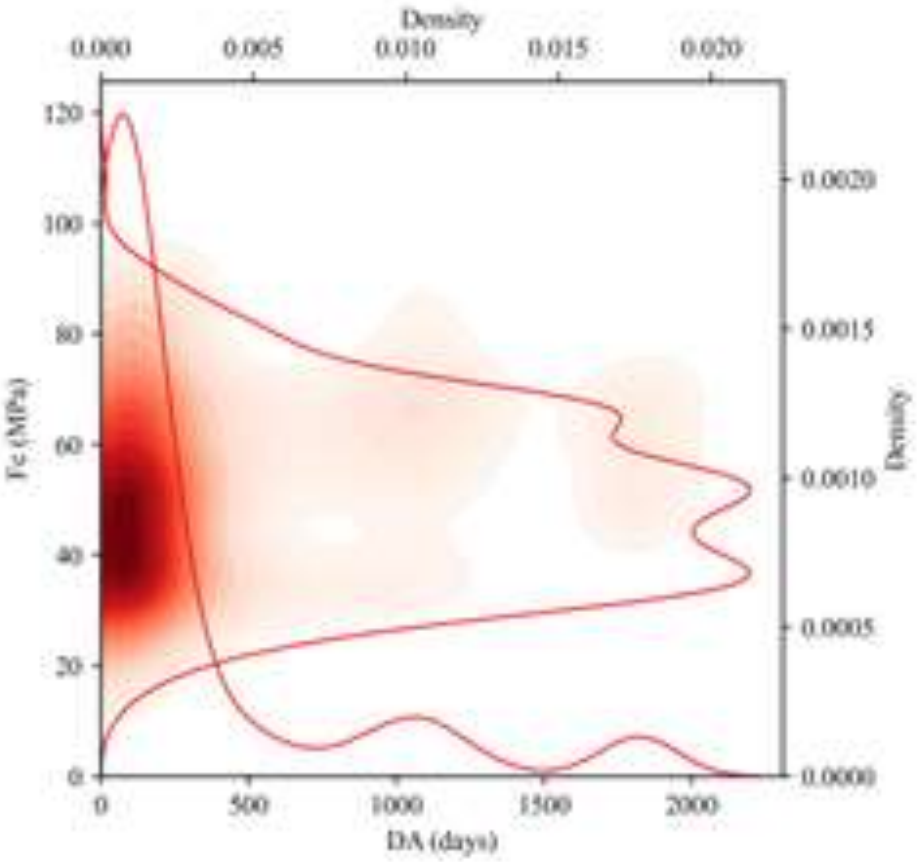
Data Types – Database: Correlation and Density





Data Types – Database: Initial Classification of Bulk Data





Machine Learning: Deep/Artificial Neural Networks

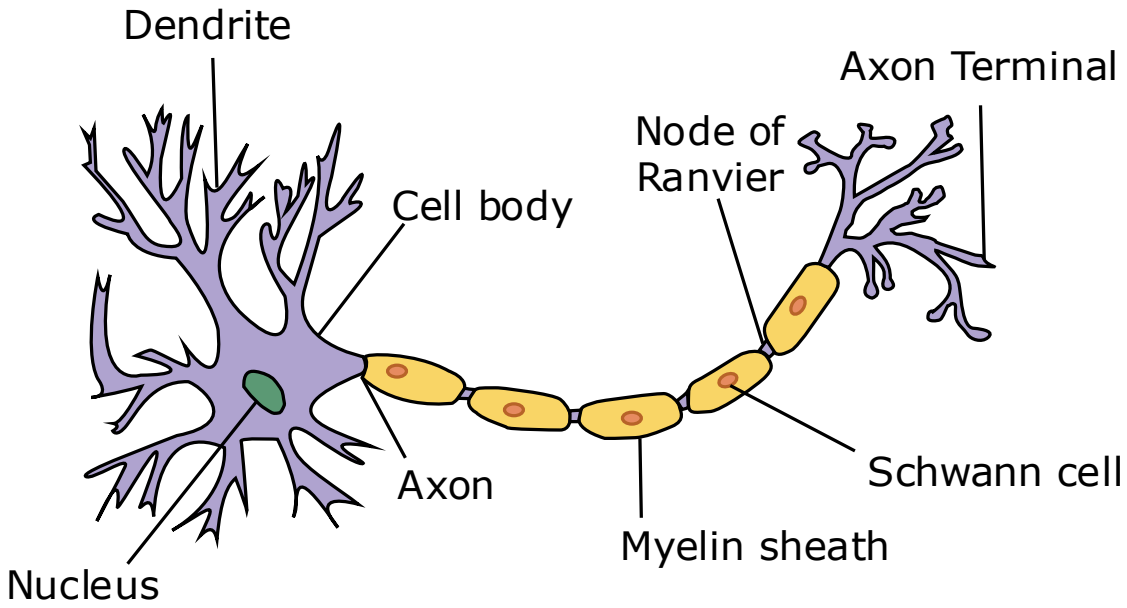
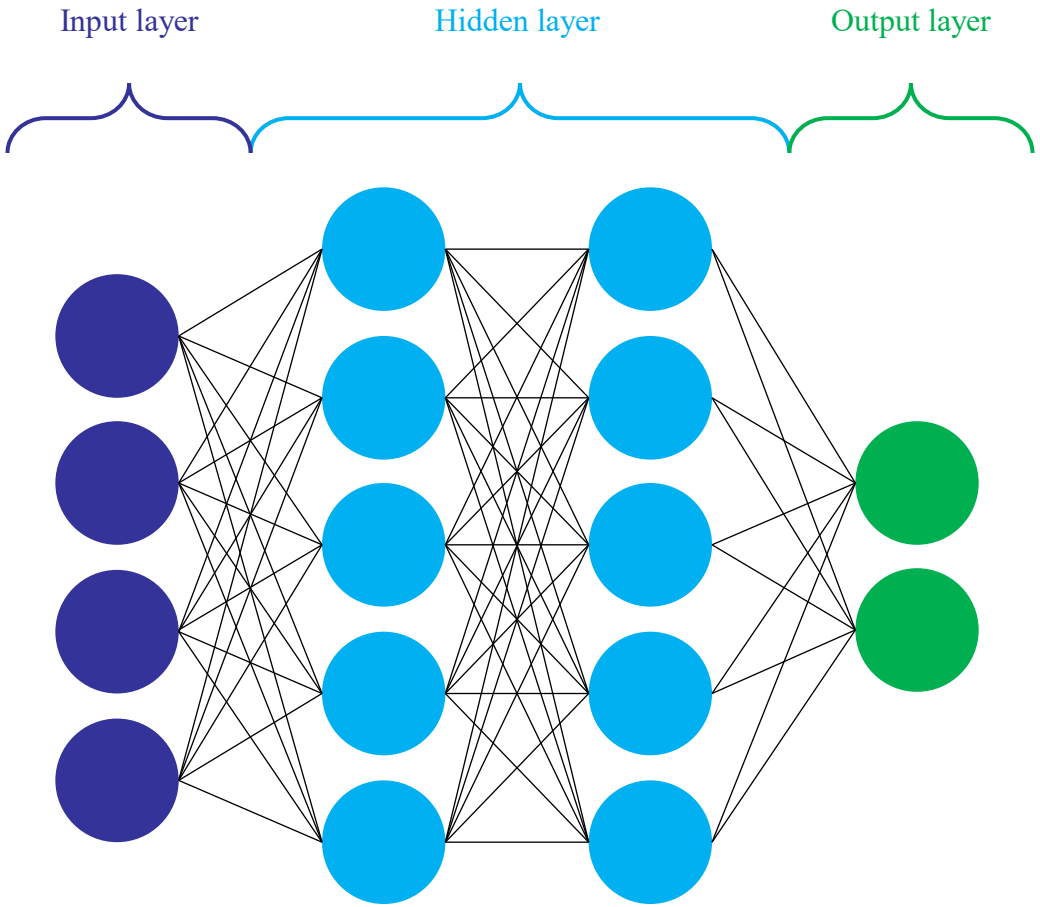
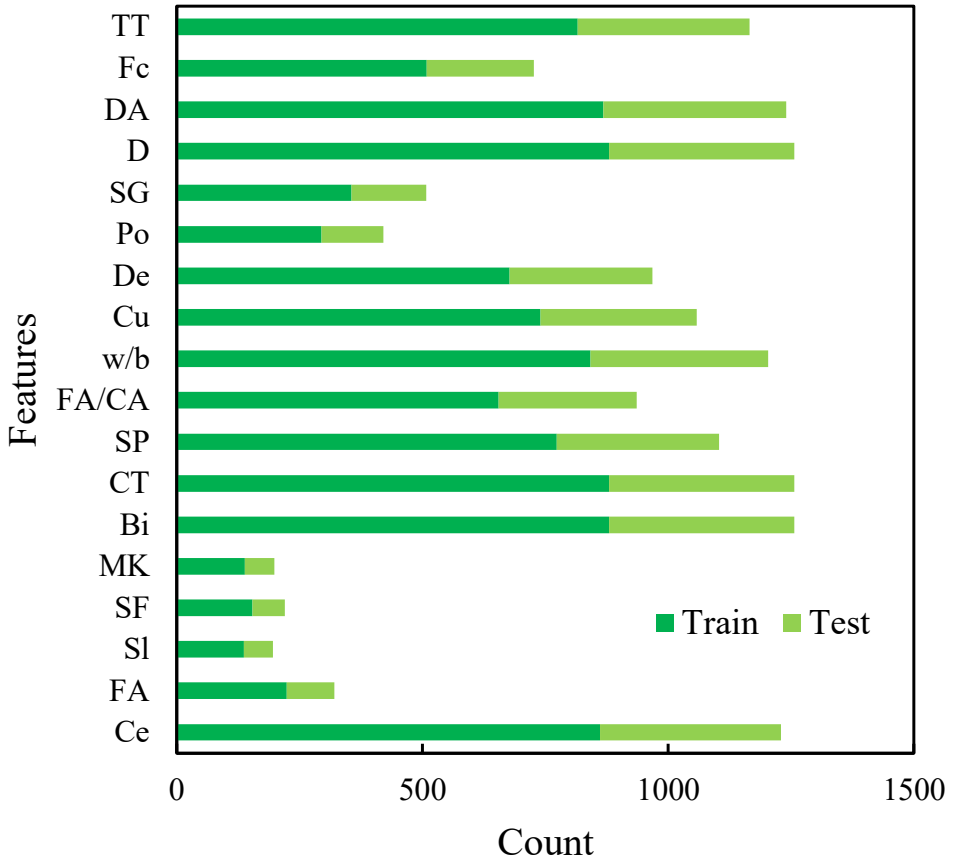


Image Courtesy of US National Cancer Institute SEER Program. "Anatomy and Physiology." CC BY-SA 3.0. Wikimedia.org



Machine Learning – Evaluation: 70% Training – 30% Testing



- Model training
  - Classification
  - Relationship building
    - Linear regression
    - Decision tree
    - Random forest
    - Gradient boosting
    - Extra trees
  - Find parameters
  - Evaluating
  - Showing results

Machine Learning – Evaluation: Models

Linear Regression

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + \epsilon$$

Decision Tree

$$If\ x_{i(j)} \leq t_j, go\ left; else\ go\ right, with\ leaf\ prediction\ y_{leaf}$$

Random Forest

$$\hat{y}(x) = \frac{1}{N} \sum_{m=1}^{N} f_m(x)$$

Gradient Boosting

$$f(x) = F_0(x) + \sum_{m=1}^{M} \eta f_m(x)$$

Extra Trees (Extremely Randomized Trees)

$$\hat{y}(x) = \frac{1}{N} \sum_{m=1}^{N} f_m^{Extra}(x)$$

Machine Learning – Evaluation: Data Types

Input data

Determination Indices

Bi
DA
Fc
w/b
SP

Limitation Indices

FA=Binary
Sl=Binary
MK=Binary
SF=Binary

SG or Po or De=Range
FA/CA=Range

Classification Indices

CT
TT

Output

D

SL

Mix design

Accuracy

Similarity

Reliability

Machine Learning – Evaluation: Reliability vs. Input Limitations

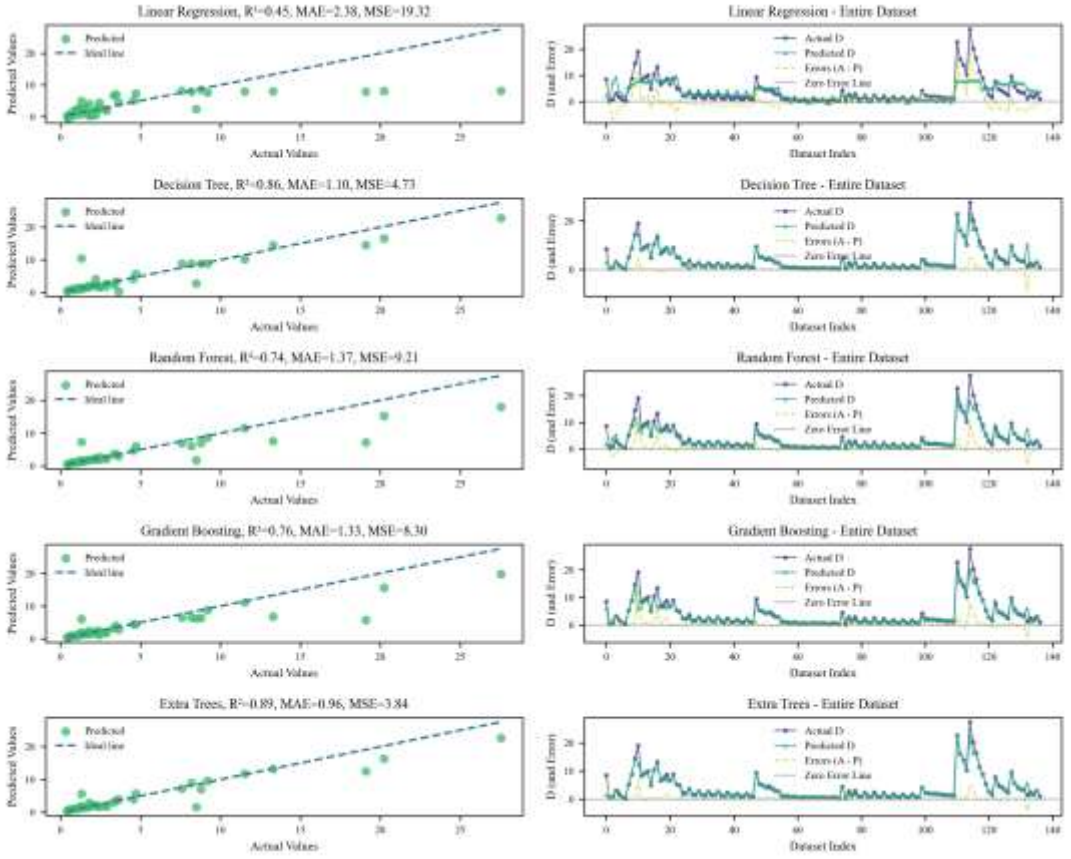
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1	0	0	0	0	2.19	7403	0.00%	1442	52	0.00%	240	0	0.00%	295	0
0	1	0	0	0	0.49	7462	0.00%	1442	52	0.00%	240	0	0.79%	295	0
0	0	1	0	0	42.65	4317	40.93%	1442	192	63.46%	240	0	88.28%	208.2	0
0	0	0	1	0	45.93	3010	65.58%	520	178	50.00%	216	0	57.03%	227	
0	0	0	0	1	0.73	7462	0.00%	1442	52	0.00%	240	0	0.78%	295	
1	1	0	0	0	2.078	7368	0.00%	1442	52	0.00%	240	0	0.78%	295	
1	0	1	0	0	42.65	4317	40.93%	1442	192	63.46%	240	0	88.28%	208.2	
1	0	0	1	0	45.93	4345	44.31%	520	128	28.37%	216	0	21.88%	282	
1	0	0	0	1	2.19	7402	0.00%	1442	52	0.00%	240	0	0.78%	295	
0	1	0	0	1	0.73	7462	0.00%	1442	52	0.00%	240	0	0.78%	295	
0	0	1	1	0	74.61	2107	73.84%	520	192	87.98%	216	0	94.53%	208.2	
0	0	1	0	1	42.65	4317	40.93%	1442	192	63.46%	240	0	88.28%	208.2	
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1	1	0	0	1	2.19	7402	0.00%	1442	52	0.00%	240	0	0.78%	295	
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1	1	1	1	0	74.61	2107	73.84%	520	192	87.98%	216	0	94.53%	208.2	
1	1	1	0	1	42.65	4317	40.93%	1442	192	63.46%	240	0	88.28%	208.2	
1	1	0	1	1	45.93	4345	44.31%	520	128	28.37%	216	0	21.88%	282	
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0	1	1	1	1	74.61	2107	73.84%	520	192	87.98%	216	0	94.53%	208.2	
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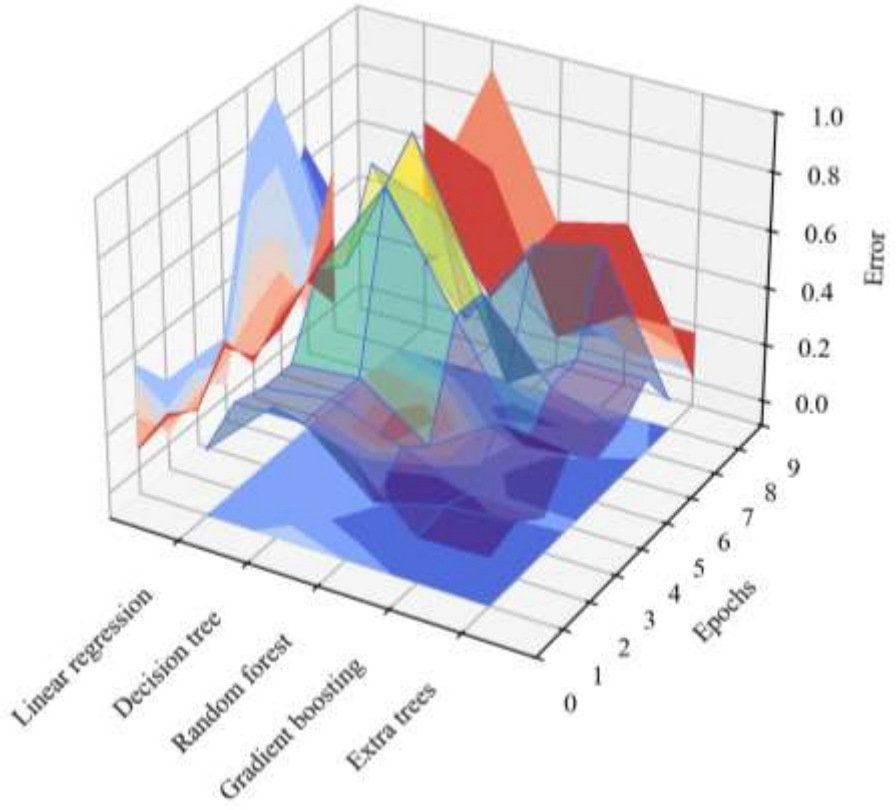
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1	0	0	0	0	0.00%	52.1	0	0.00%	150	0	1.71%	1442	284	0.00%	12.4	0	0.00%	1.18	0.00	1.47%	0.67	0.23	0.00%	780	0
0	1	0	0	0	0.00%	52.1	0	0.00%	150	0	0.24%	1442	284	0.00%	12.4	0	0.00%	1.18	0.00	0.00%	0.67	0.23	0.00%	780	0
0	0	1	0	0	25.17%	52.1	0	0.00%	150	0	42.37%	1442	300	53.03%	12.4	0	48.03%	1.18	0.00	42.23%	0.65	0.3	43.76%	365	0

DA	Bi	Fc	SP	w/b	De Missed (%)	De Rem. range max	De Rem. range min	Po Missed (%)	Po Rem. range max	Po Rem. range min	SG Missed (%)	SG Rem. range max	SG Rem. range min	D' Missed (%)	D' Rem. range max	D' Rem. range min	DA Missed (%)	DA Rem. range max	DA Rem. range min	Fc Missed (%)	Fc Rem. range max	Fc Rem. range min	CT Missed (%)	CT Variants Count	TT Missed (%)	TT Variants Count
1	0	0	0	0	0.00%	2550	1323.6	4.40%	42.20%	0.26%	3.64%	2410	1097.26	1.48%	1.33E-10	1.50E-13	0.00%	1825	3	0.00%	108	12.4	20.00%	16	0.00%	13
0	1	0	0	0	0.00%	2550	1323.6	0.00%	42.20%	0.26%	0.00%	2410	1097.26	0.00%	1.33E-10	1.50E-13	0.00%	1825	3	0.00%	108	12.4	0.00%	20	0.00%	13
0	0	1	0	0	48.33%	2550	1323.6	22.34%	0.422	0.016	9.70%	2410	1097.26	42.54%	6.34E-11	1.50E-13	41.37%	1825	3	0.00%	108	12.4	20.00%	16	23.08%	10

DA	Bi	Fc	SP	w/b	Data: Missed sets (%)	Data: Remained Count	Ce Missed (%)	Ce Rem. range max	Ce Rem. range min	FA Missed (%)	FA Rem. range max	FA Rem. range min
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0	1	0	0	0	0.49	7462	0.00%	1442	52	0.00%	240	0
0	0	1	0	0	42.65	4317	40.93%	1442	192	63.46%	240	0
0	0	0	1	0	45.93	3010	65.58%	520	178	50.00%	216	0
0	0	0	0	1	0.73	7462	0.00%	1442	52	0.00%	240	0
1	1	0	0	0	2.078	7368	0.00%	1442	52	0.00%	240	0
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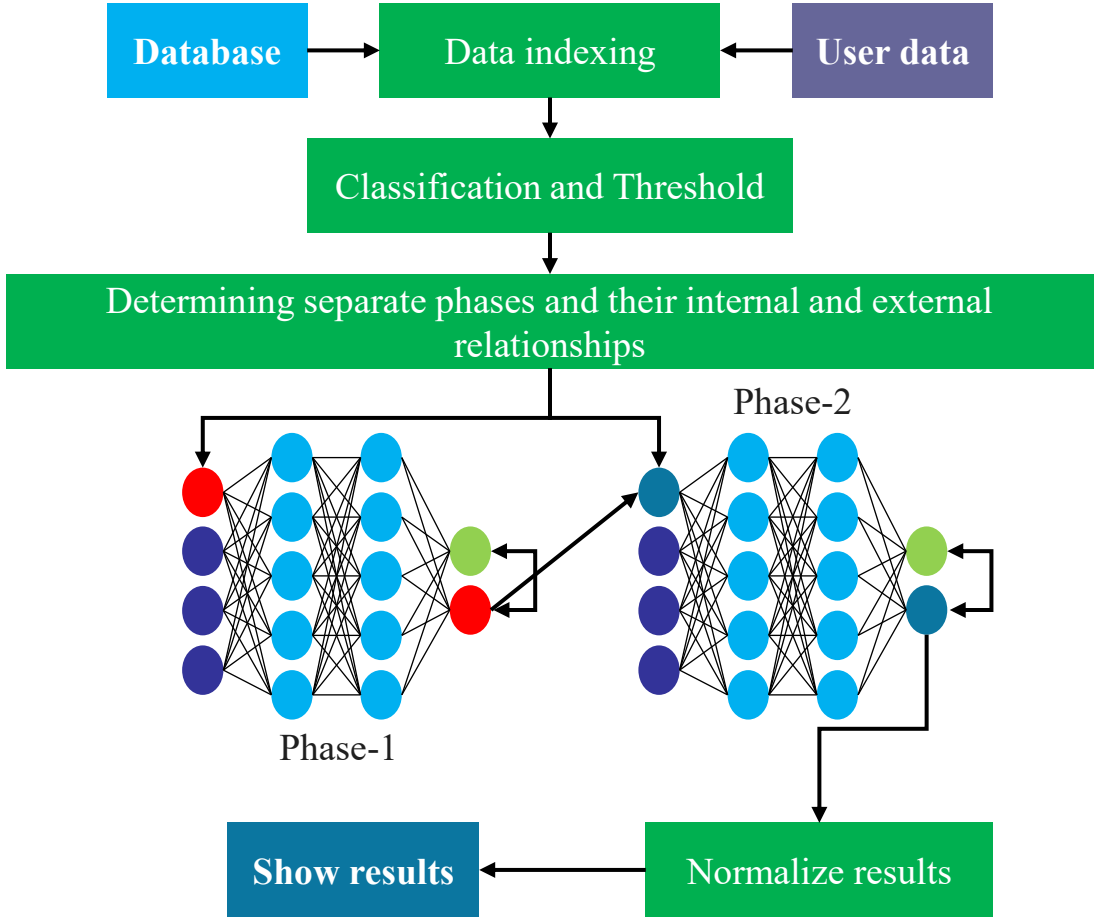
Machine Learning – Evaluation: Accuracy



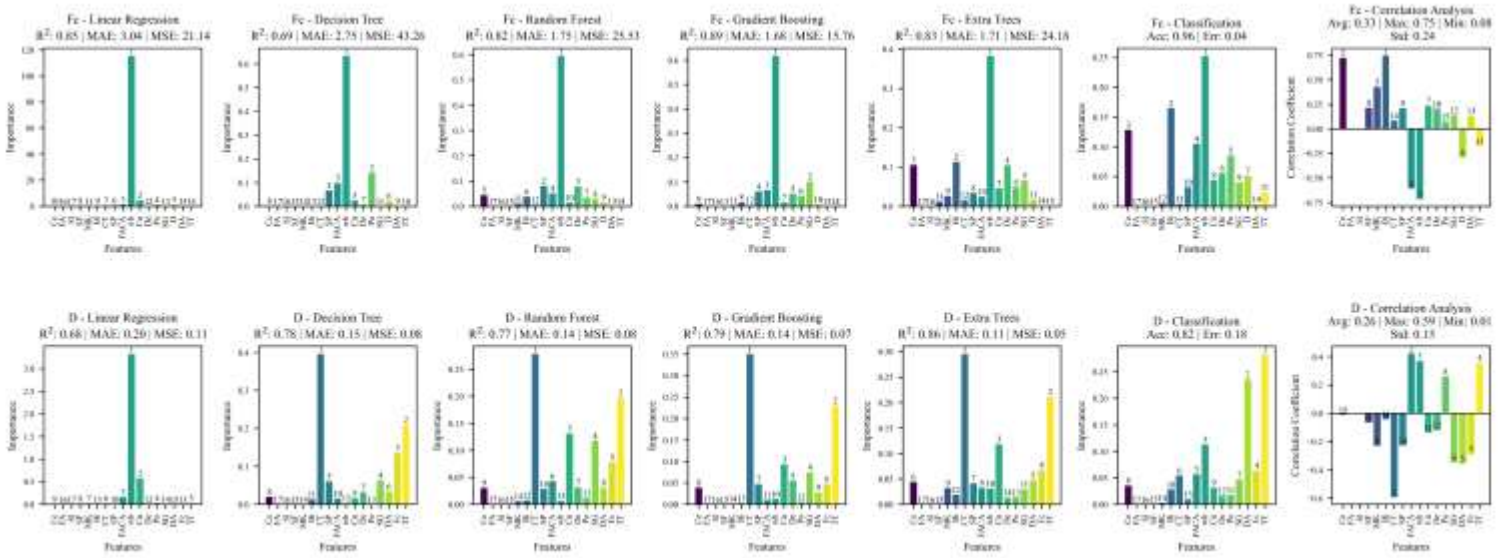


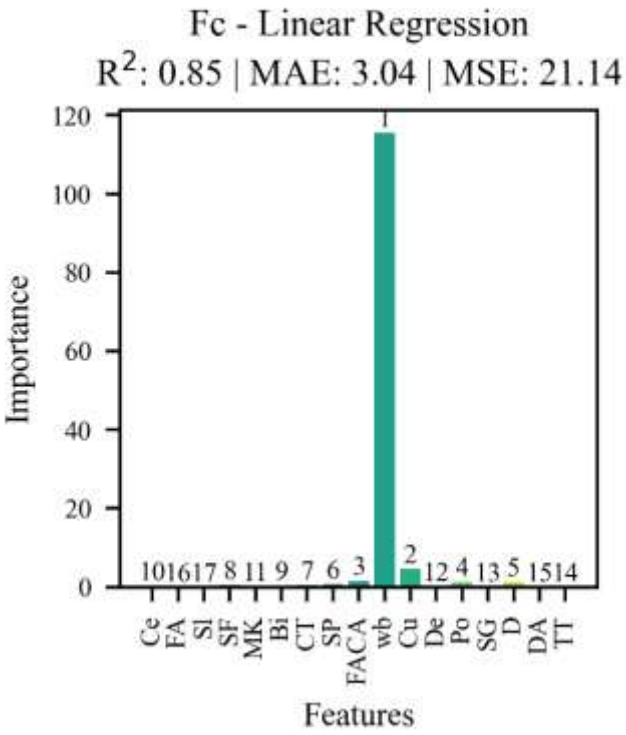
Machine Learning – Optimization: PAMPNet Method

- Prediction Adaptive Multi-Phase Network:
  - Step-1: Determining the most important parameters, processed as a separate phase by ANN or DNN
  - Step-2: Determine the relationship between the selected parameters
  - Step-3: Determining the sensitivity of selected parameters to other indices
  - Step-4: Prioritizing the impact of selected indices on each of the selected parameters
  - Step-5: Using fuzzy logic and thresholding
  - Step-6: Training local relationships and separate review for each group of parameters
  - Step-7: Link the results of each process based on the relationships found between the parameters, or phases, and calculate final result



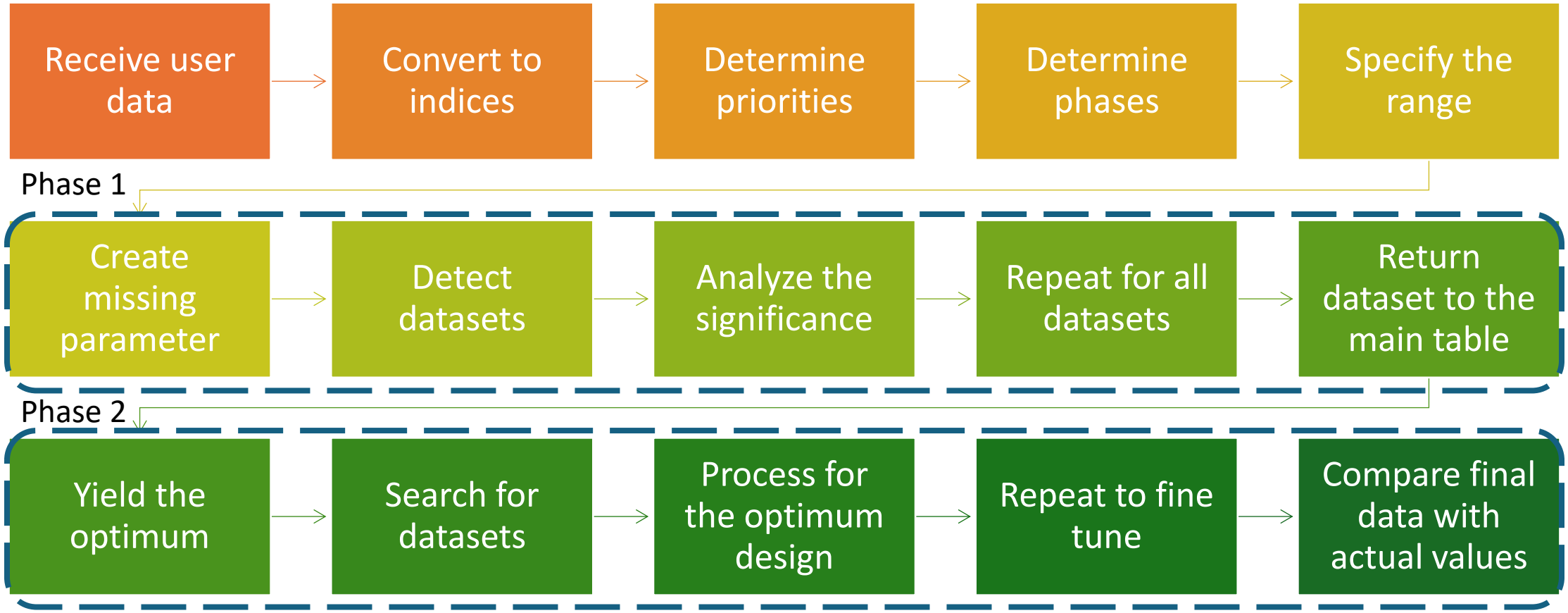
Machine Learning – Optimization: Classification



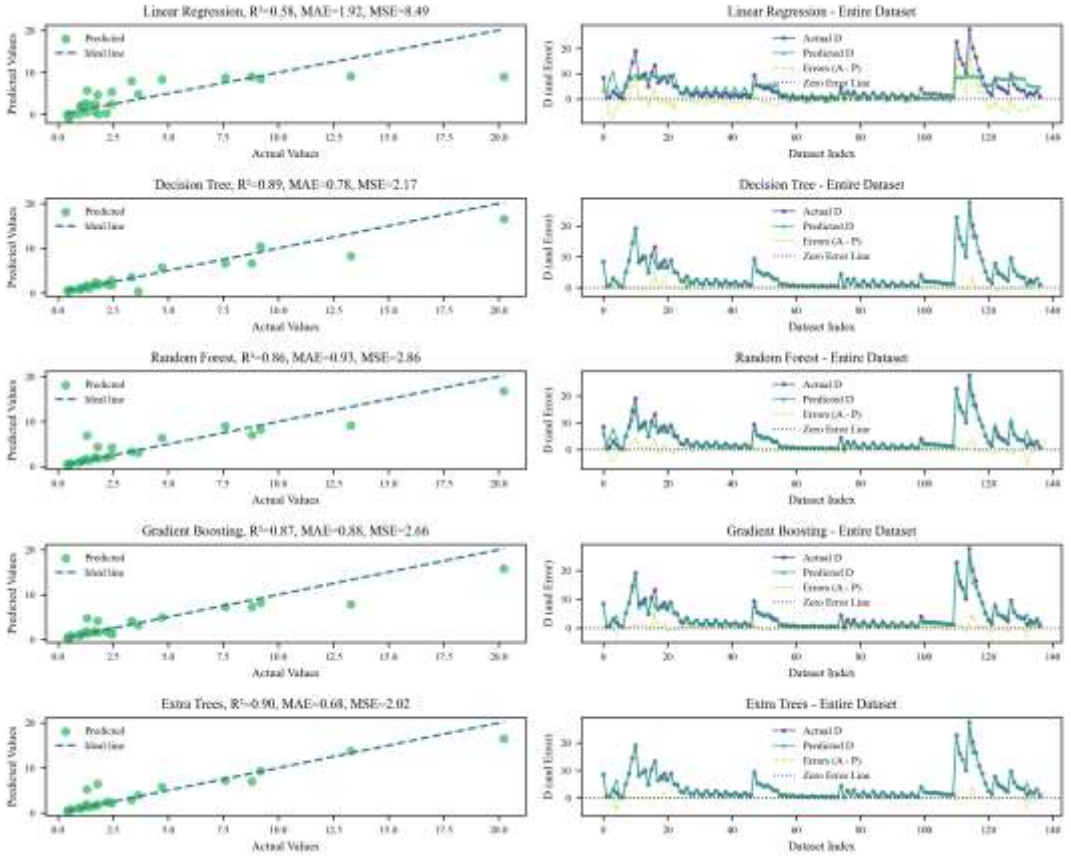


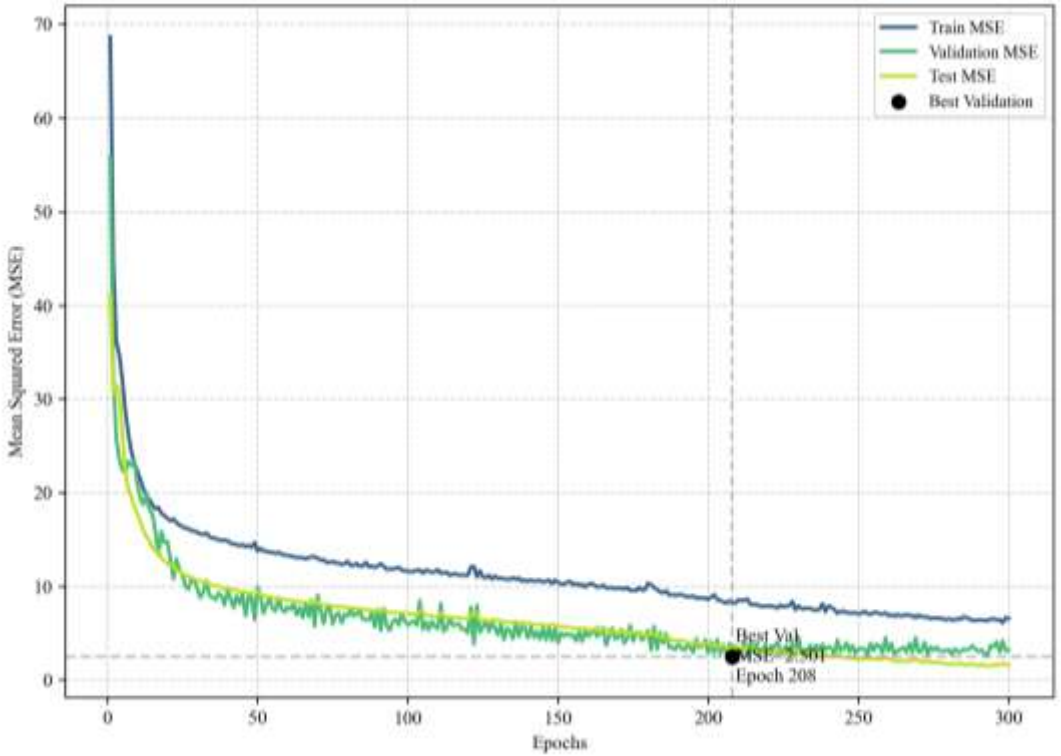
- **Phase I (f'_c)** = w/b | Bi | Cu | Po | De | SG
- **Phase II (D)** = CT | TT | FA/CA | DA | SP

Machine Learning – Optimization: 60-30-10 Train-Verify-Test

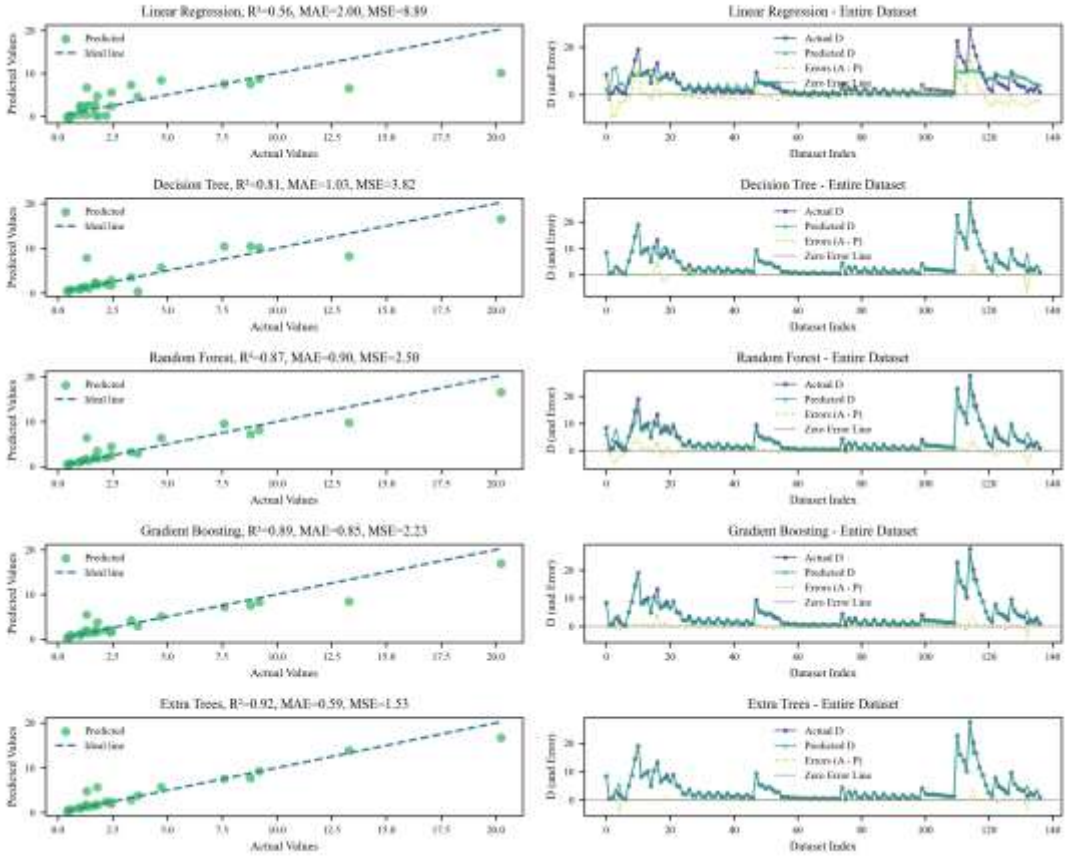


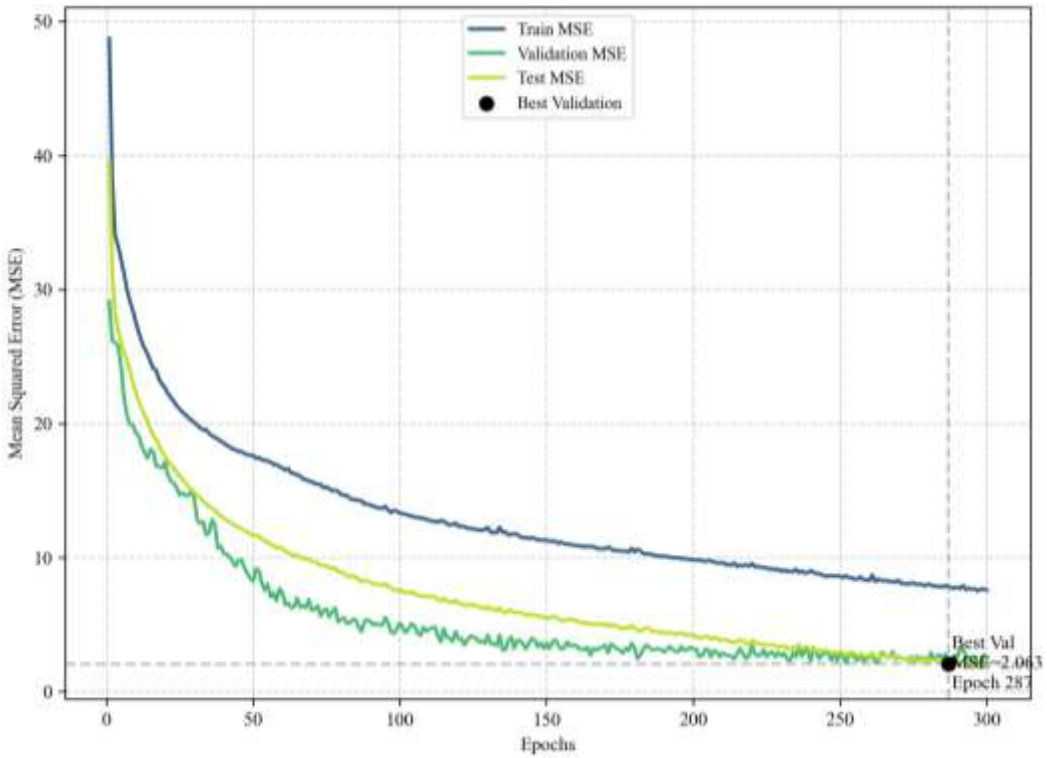
Machine Learning – Optimization: Partitioning 70-15-15 Tr-Ve-Te



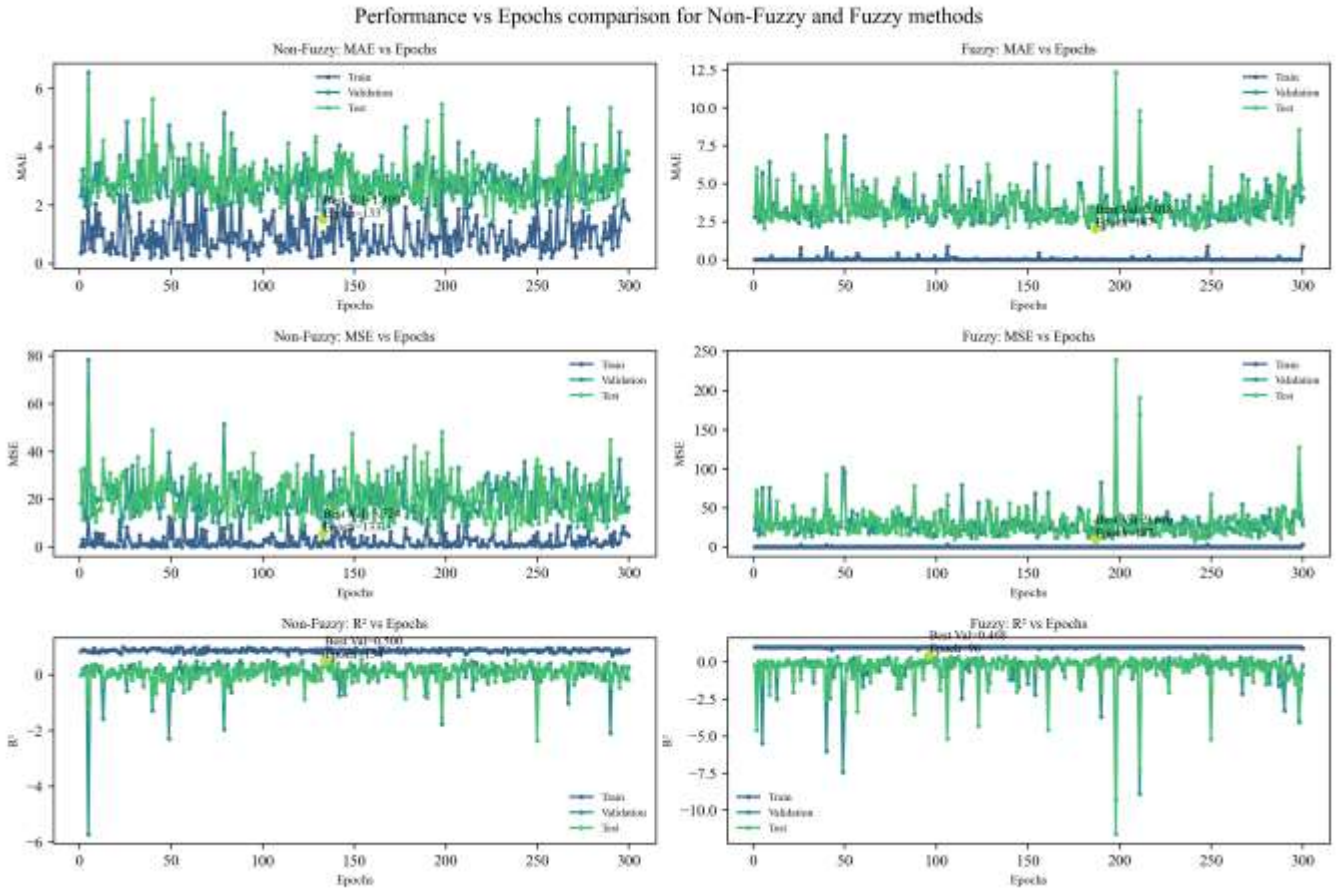


Machine Learning – Optimization: Partitioning 60-30-10 Tr-Ve-Te



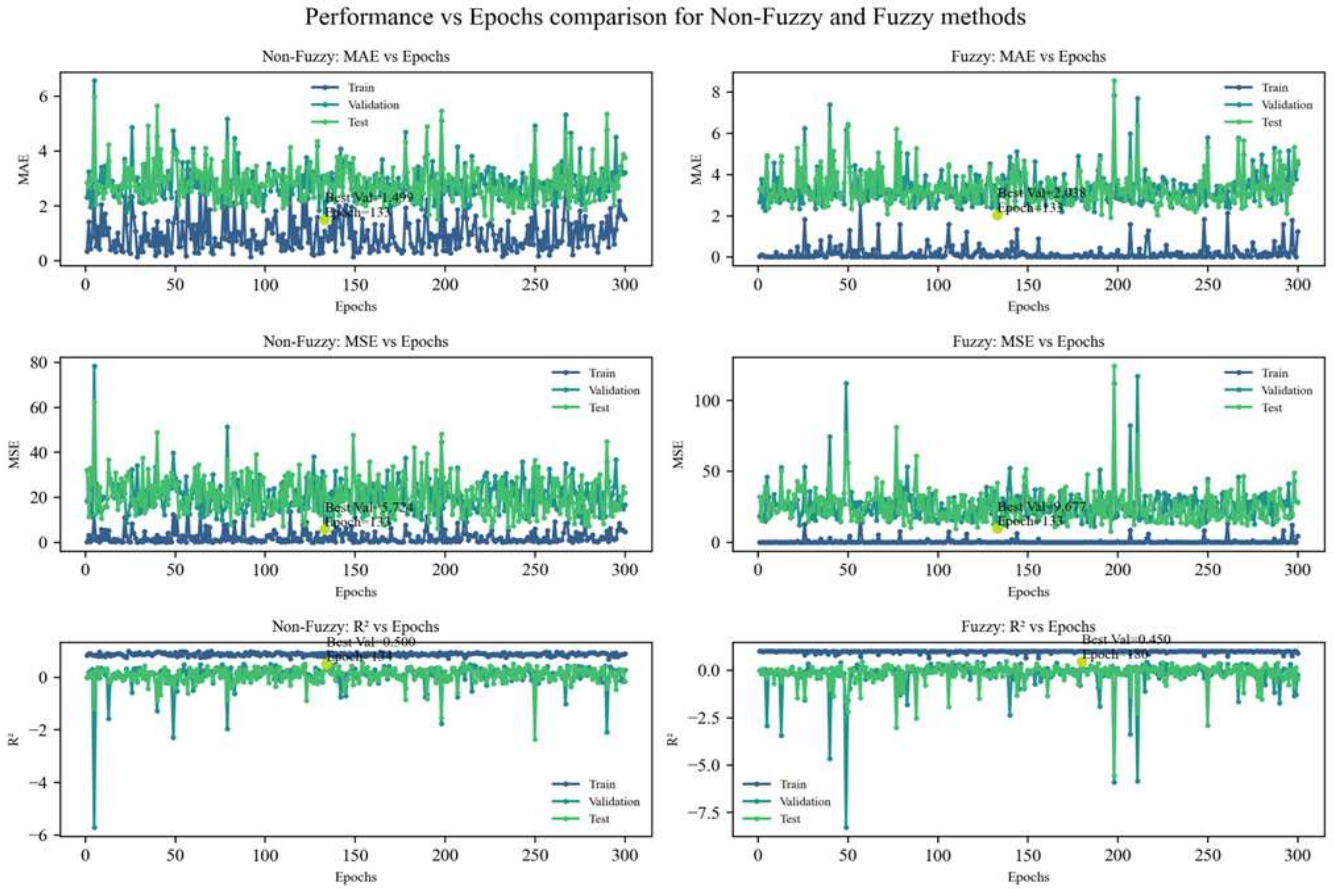


Machine Learning – Optimization: Change in Fuzzy Logic Coefficient



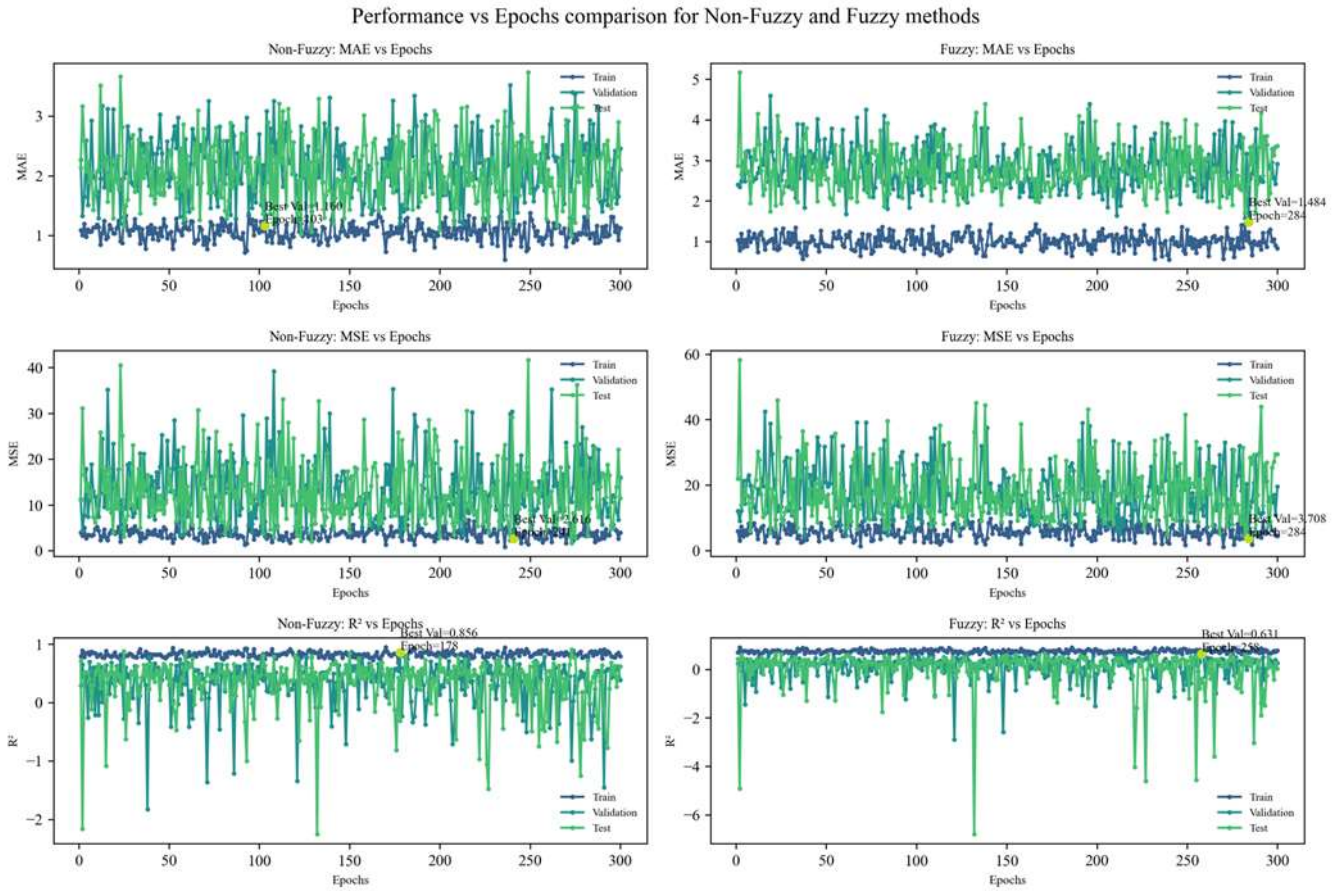
- Change in fuzzy logic coefficient (sigma)
  - Max = 2.00
  - Min = 0.05
  - Average = 1.59
  - Standard deviation = 1.70
  - Fuzzy Logic On
  - ANN model

Machine Learning – Optimization: Change in Fuzzy Logic Coefficient



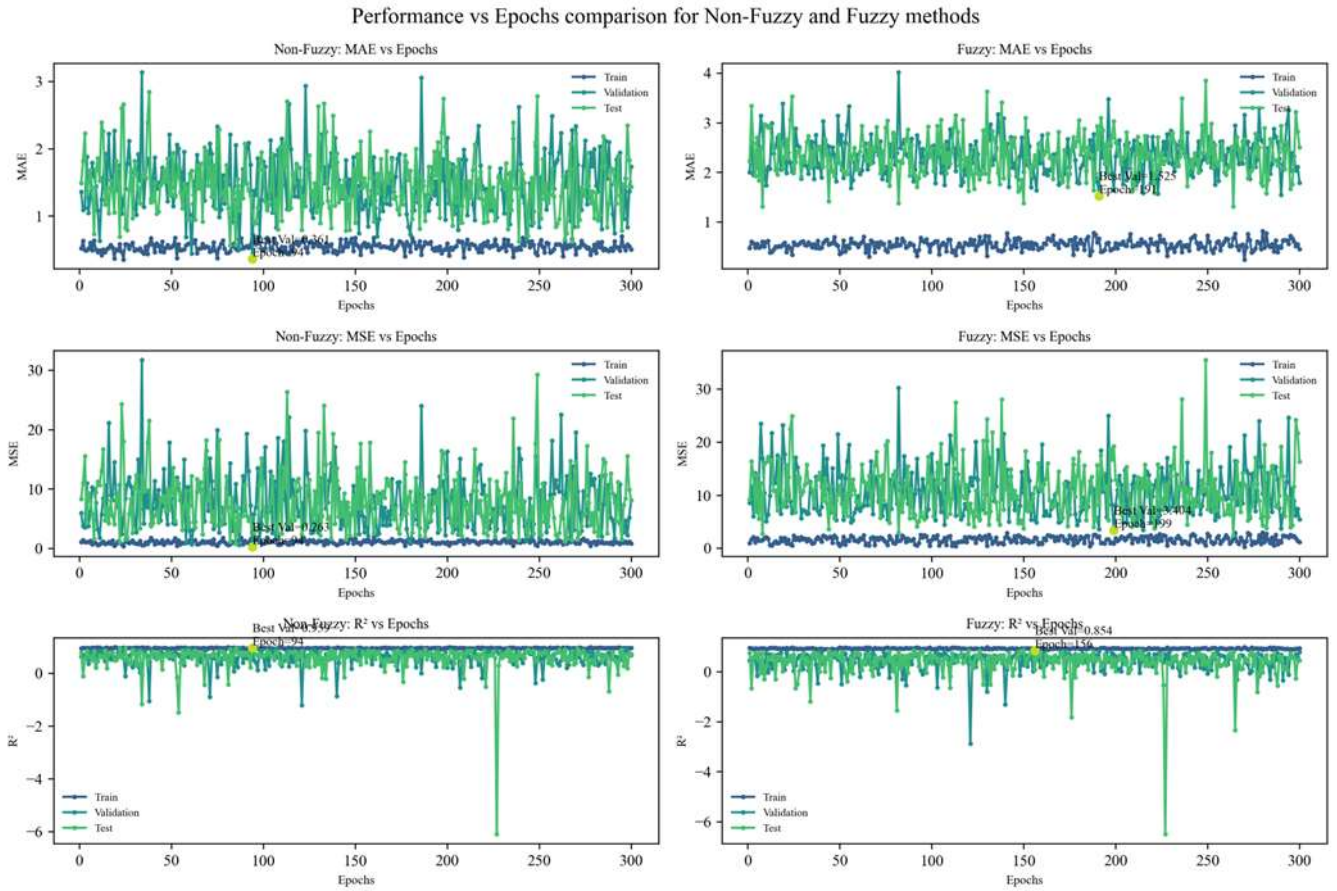
- Change in fuzzy logic coefficient (sigma)
  - Max = 3.00
  - Min = 0.05
  - Average = 1.93
  - Standard deviation = 1.82
  - Fuzzy Logic On
  - ANN model

Machine Learning – Optimization: Change in Fuzzy Logic Coefficient



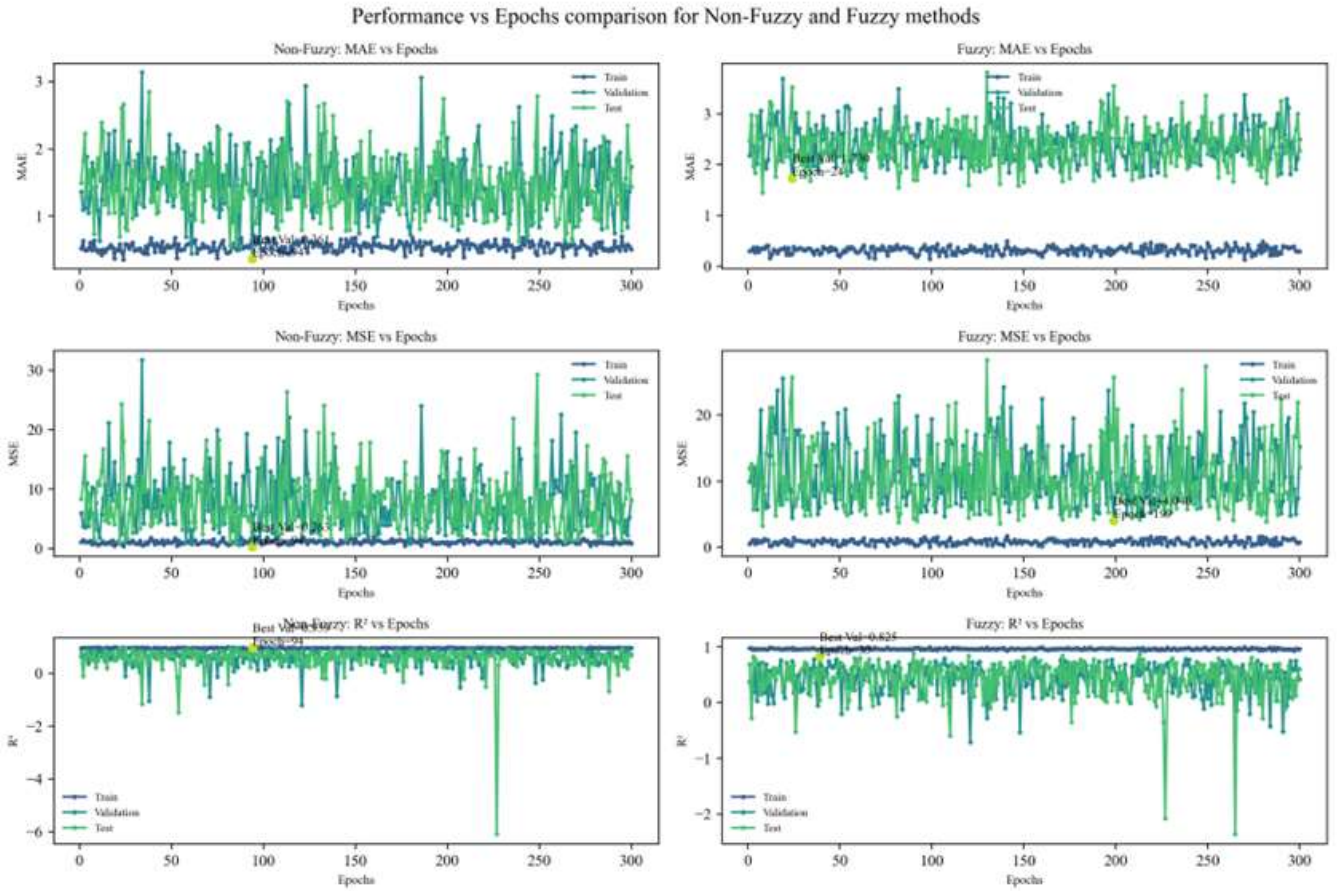
- Change in fuzzy logic coefficient (sigma)
  - Max = 4.00
  - Min = 0.05
  - Average = 2.14
  - Standard deviation = 1.83
  - Fuzzy Logic On
  - ANN model

Machine Learning – Optimization: Change in Fuzzy Logic Coefficient



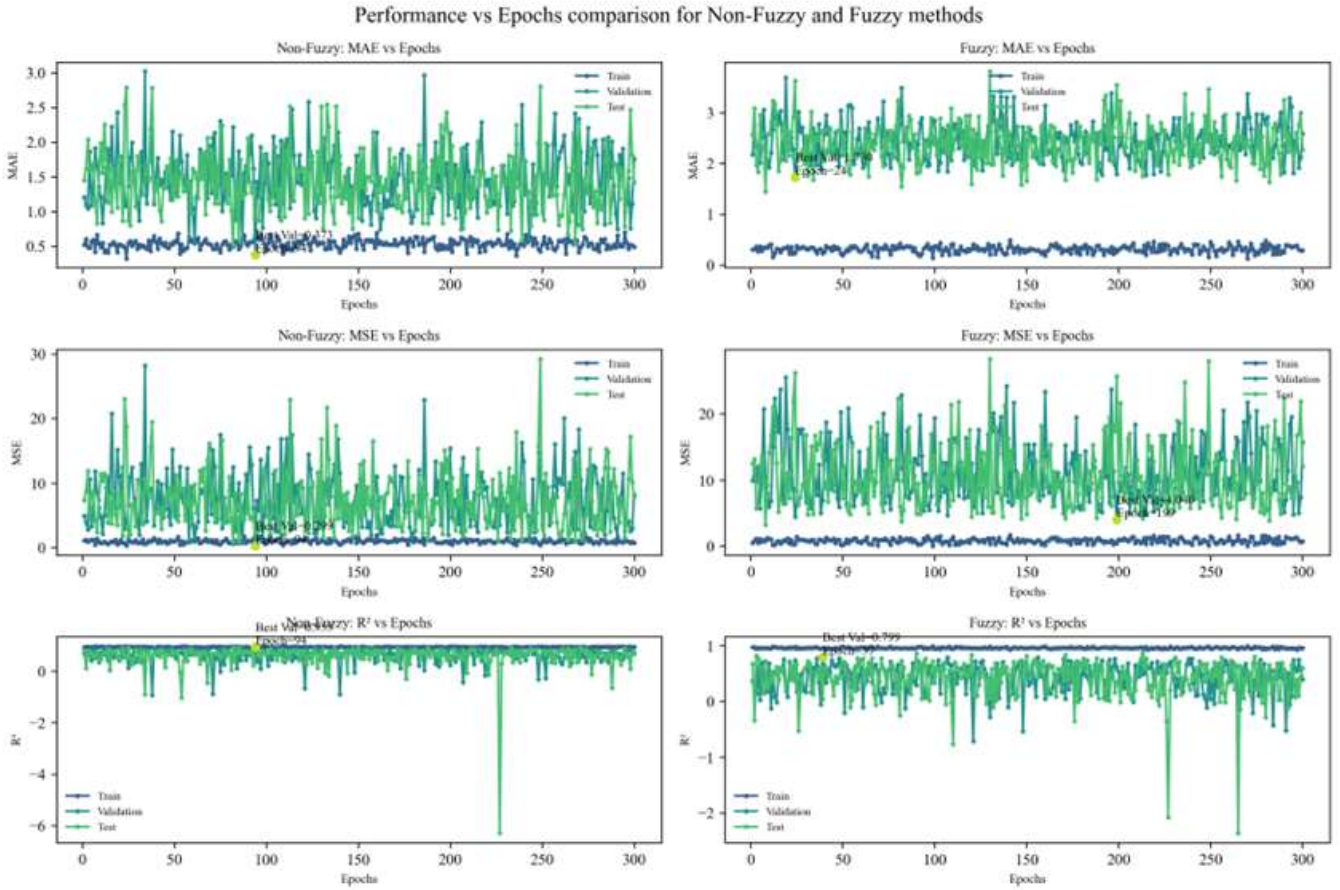
- Change in fuzzy logic coefficient (sigma)
  - Max = 5.00
  - Min = 0.05
  - Average = 2.37
  - Standard deviation = 1.98
  - Fuzzy Logic On
  - ANN model

Machine Learning – Optimization: Change in Fuzzy Logic Coefficient



- Change in fuzzy logic coefficient (sigma)
  - Max = 5.00
  - Min = 0.05
  - Average = 2.60
  - Standard deviation = 2.11
  - Fuzzy Logic On
  - ANN model

Machine Learning – Optimization: Change in Fuzzy Logic Coefficient



- Change in fuzzy logic coefficient (sigma)
  - Max = 7.00
  - Min = 0.06
  - Average = 3.04
  - Standard deviation = 2.66
  - Fuzzy Logic On
  - ANN model

Machine Learning – PAMPNet: Final Model (Optimized)

- Data Processing Steps

Stage 1: Preprocessing and Dynamic Clustering

Feature Clustering (AFC) → Adaptive unsupervised learning

Stage 2: Local Processing with Adaptive Fuzzy Logic and Meta-Learning

Meta-Learning-Driven Attention (MLA) → Feature importance optimization

Stage 3: Adaptive Fusion and Final Prediction

Hybrid Learning Fusion (HLF) → Multi-objective learning paradigm

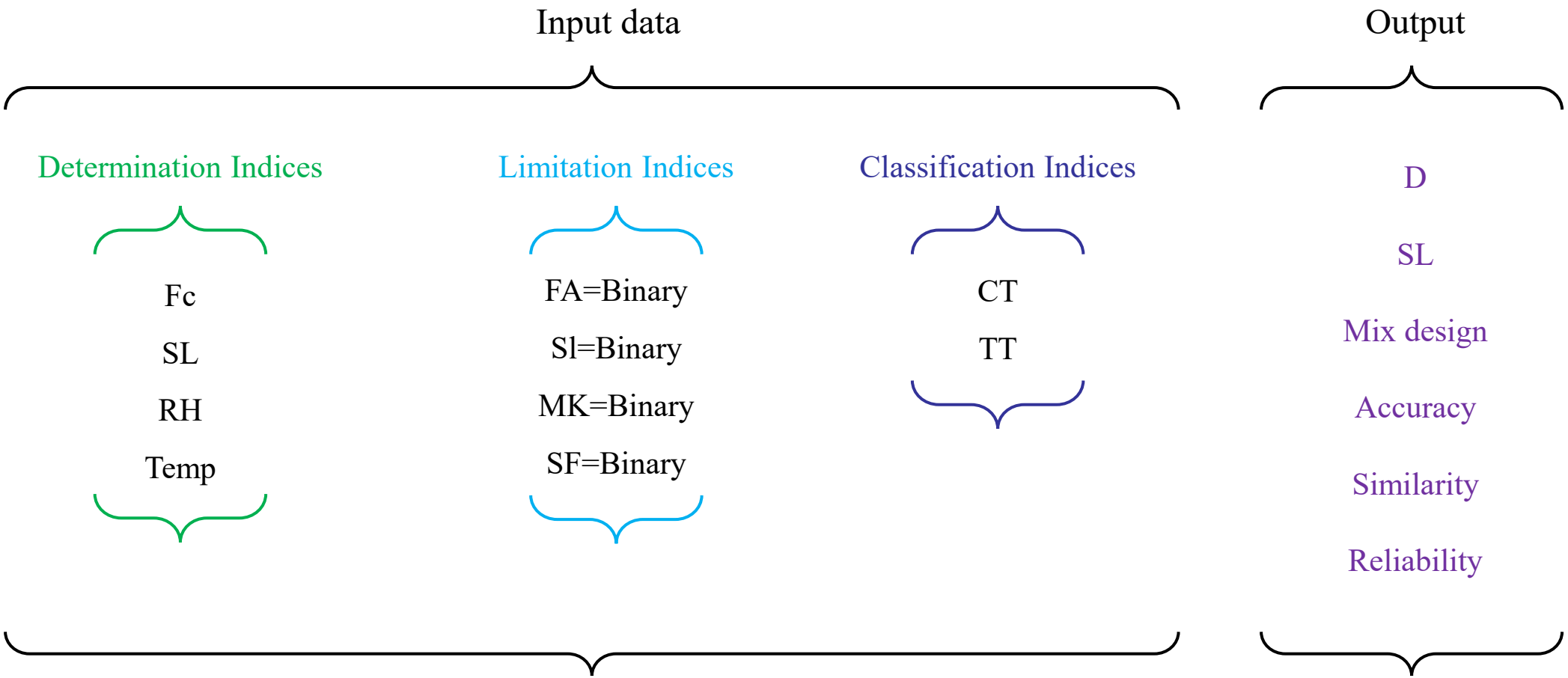
Stage 4: Adaptive Feedback and Continuous Learning

Self-Regulated Learning (SRL) → Auto-tuning of hyperparameters

PAMPNet: Comparison With Other Models

Model	Weight Update Formula	Feature Importance	Adaptability
ANN	$w_{ij} = w_{ij} - \eta\delta_i x_j$	Fixed activation	Fixed learning rate
DNN	$W^{(l)} = W^{(l)} - \eta\delta^{(l)} h^{(l-1)}$	Fixed layer-wise transformation	Fixed structure
GNN	$W^{(l)} = W^{(l)} - \eta \sum_v \delta_v^{(l)} h_v^{(l-1)}$	Fixed graph aggregation	Fixed neighbor influence
Transformer	$W = W - \eta\delta$	Learned attention weights	Fixed attention mechanism
CNN	$W^{(l)} = W^{(l)} - \eta \sum_{i,j} \delta_{i,j}^{(l)} h_{i,j}^{(l-1)}$	Fixed convolutional features	Fixed spatial weighting
PAMPNet	$\boldsymbol{w_{ij}^{t+1} = w_{ij}^{t} - \eta\lambda_{ij}\delta_i x_j}$	**Dynamic self-adapting weighting**	**Self-regulating learning & feature selection**

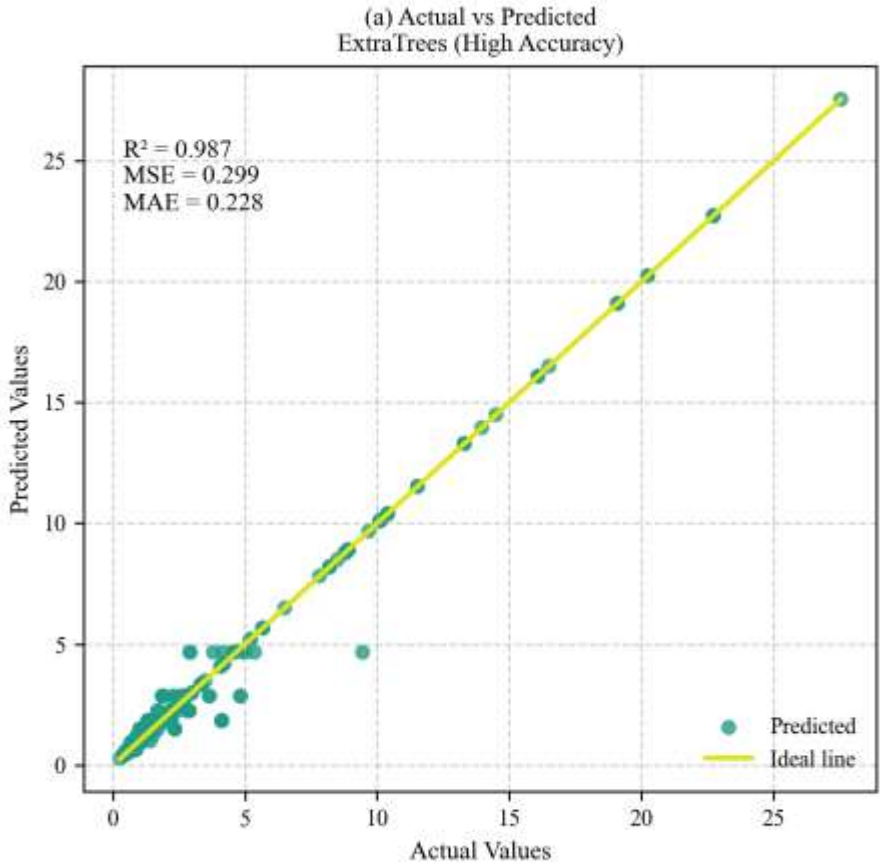
PAMPNet: Data Types

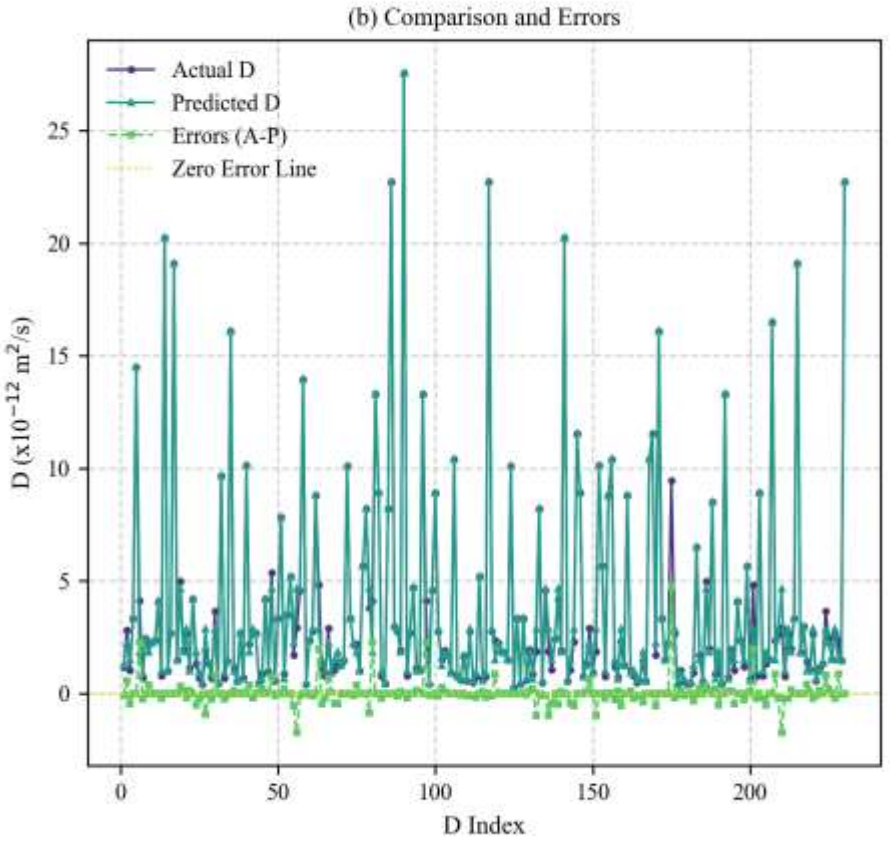


PAMPNet: AFC-MLA

$$SL \propto \left(D_{CT,TT,\frac{FA}{CA},DA,SP,\left(\boldsymbol{FC}_{\frac{w}{b}},Ce,Bi,Cu,De,SG,\underbrace{\left(\boldsymbol{Po}_{FA,SF,Sl,MK} \right)}_{\text{Cluster 3}} \right)}_{\text{Cluster 2}} \right)_{\text{Cluster 1 (Main)}}$$

PAMPNet: Results Accuracy and Reliability





PAMPNet: Outcome Demonstration

- User data

f'c	RH	Temp	SL	SF	MK	Sl	FA	CT	TT
25	30	31	6	1	0	0	0	Any	3% NaCL

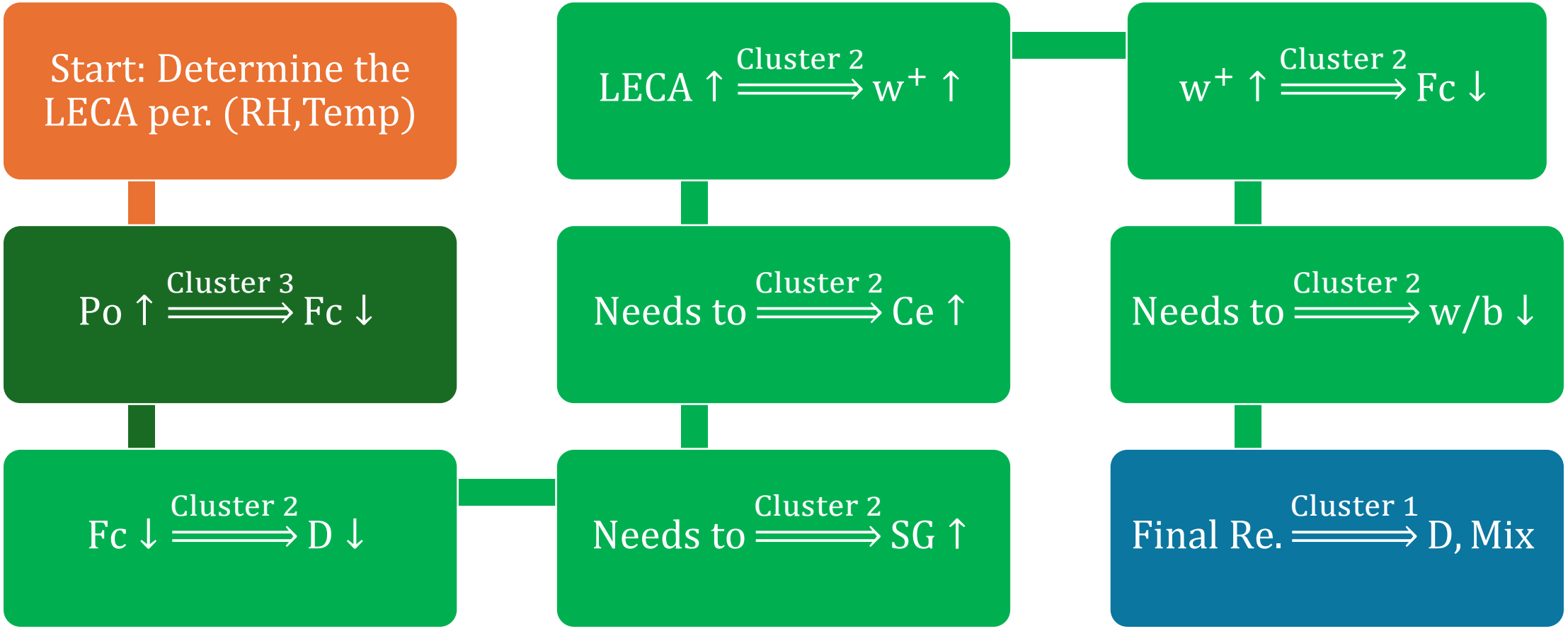
- Predicted by PAMPNet

Ce	SF	Bi	CT	SP	FA/CA	w/b	LECA	De	Po	SG	D	DA	Fc	SL
390	50	440	CEM II	2	0.75	0.45	15%	2370	5.2	2180	4.2E-12	28	25	6

- The most similar real data

Ce	SF	Bi	CT	SP	FA/CA	w/b	Cu	De	Po	SG	D	DA	Fc	SL
350	50	400	CEM II	2	0.81	0.5	28	2380	4.4	2200	4.5E-12	28	24.7	5.98

PAMPNet: Outcome Analysis



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