

Failure Detection for Pharmaceutical Cold Chain Logistics

Client

Envirotainer®

The Active Cold Chain

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Problem Statement



“Pharmaceutical manufacturers
lose 15 billion per year due to
cold chain failure”



Reducing the failed shipment ratio is a long-sought objective for pharmaceutical cold chain industry



Find solutions that can ultimately help to predict and mitigate failures during a shipment

What is a safe delivery of shipment?



- 01 Pharmaceuticals do not experience temperature deviation
- 02 Container has no critical parts failure
- 03 Container is performing according to design



Goal of Analysis



Failure Risk Profile

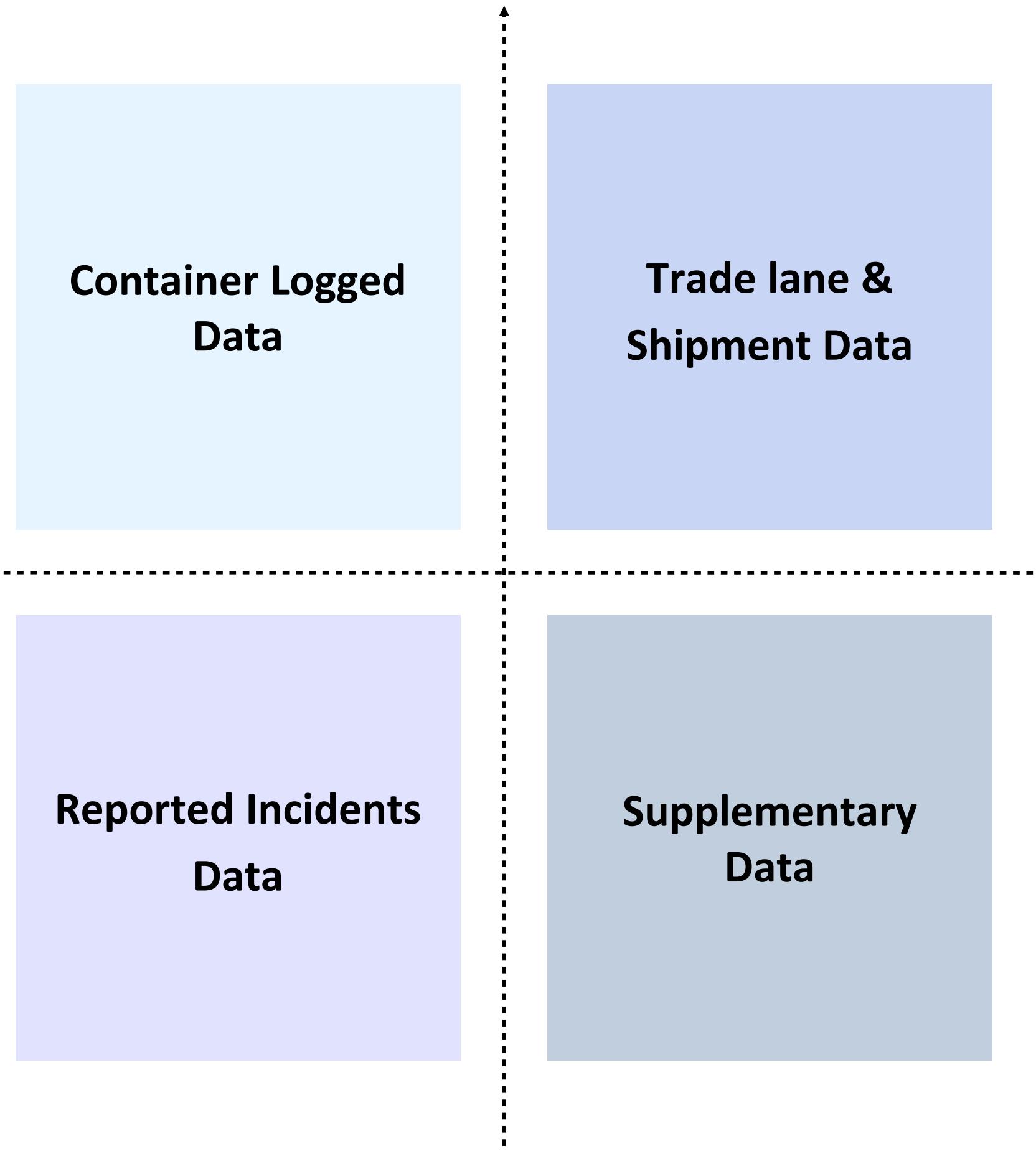
- Identify failure root causes to different types of failures
 - Identify major container handling behaviors that lead to high failure rate
 - Understand the circumstances when failure happens

Predictive Model

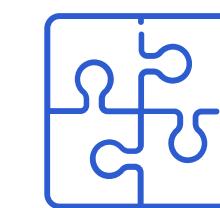
- Predict the likelihood of temperature deviation given certain order information
- Help the company to give pin-pointed handling instructions, or reconsider flight routes for a shipment when a prediction of high likelihood of failure is given



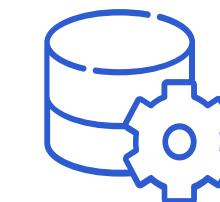
Data Overview



Jan 2018 - Feb 2021



Integrated using container number and order number

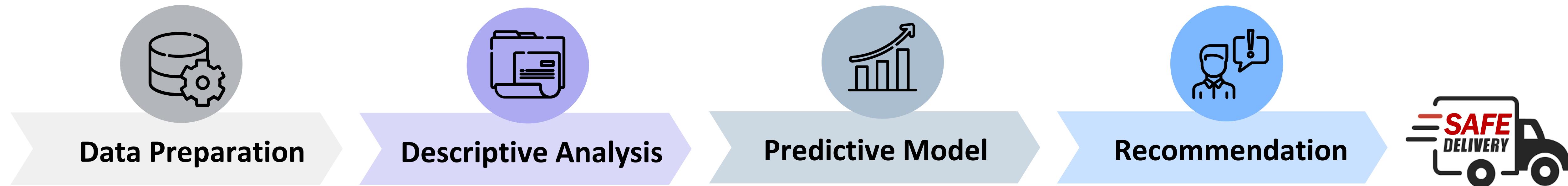


Each observation contains information regarding a unique container movement from origin to destination

70k+

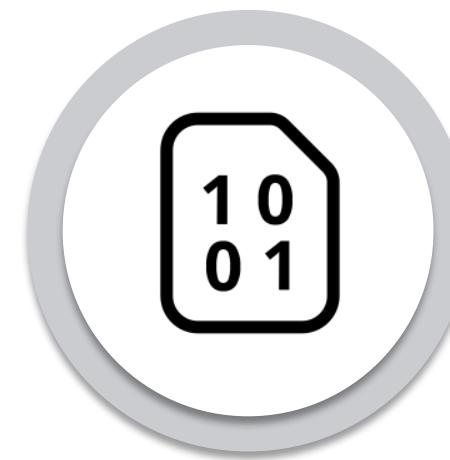
Container movement for 3 years

Analytics Workflow



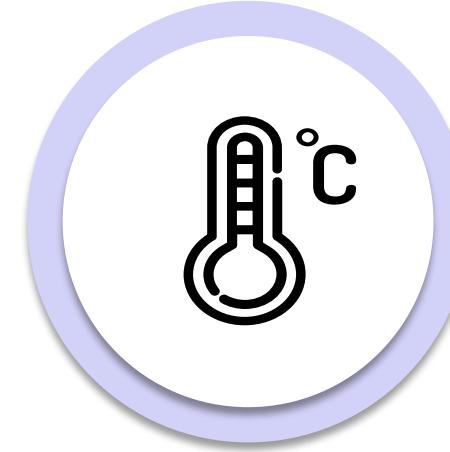
- Failure (Label) Definition
- Variable Aggregation
- Row Selection
- Failure Risk Profile
- Colinearity Analysis
- Feature Engineering
- Imbalanced Data Handling
- Model Implementation
- Model Evaluation

Failure Definition



Label

- Binary: Failure (1) vs. Normal (0)



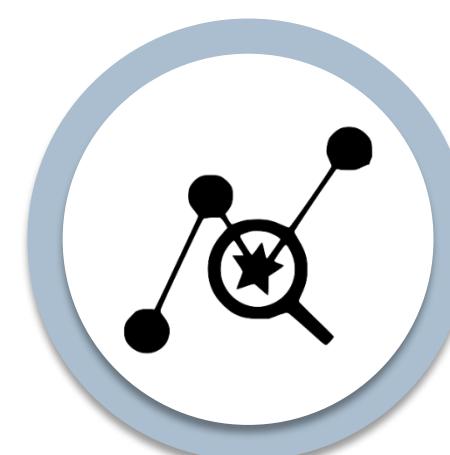
Temperature Deviation

- Average container inside temperature deviates from the set temperature range
 - **This definition of temperature deviation(TD) was validated using actual reported TD data**



Parts Failure Alarms

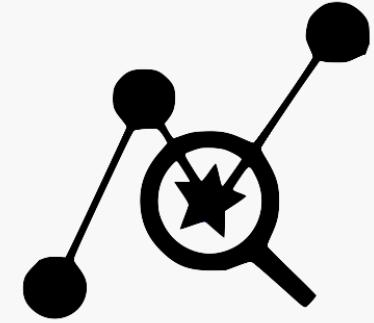
- Essential parts alarms are triggered



Compressor Performance Anomalies

- Container compressor is not functioning properly
 - Compressor is a critical part and more frequently utilized

Failure Definition - Compressor Performance Anomalies

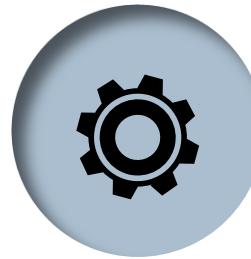


Extract **1,673** anomaly observations using Copula Quantile Regression



Distribution

Compressor Power Step vs. Delta



Method

Copula quantile regression 5% and 95%



Definition

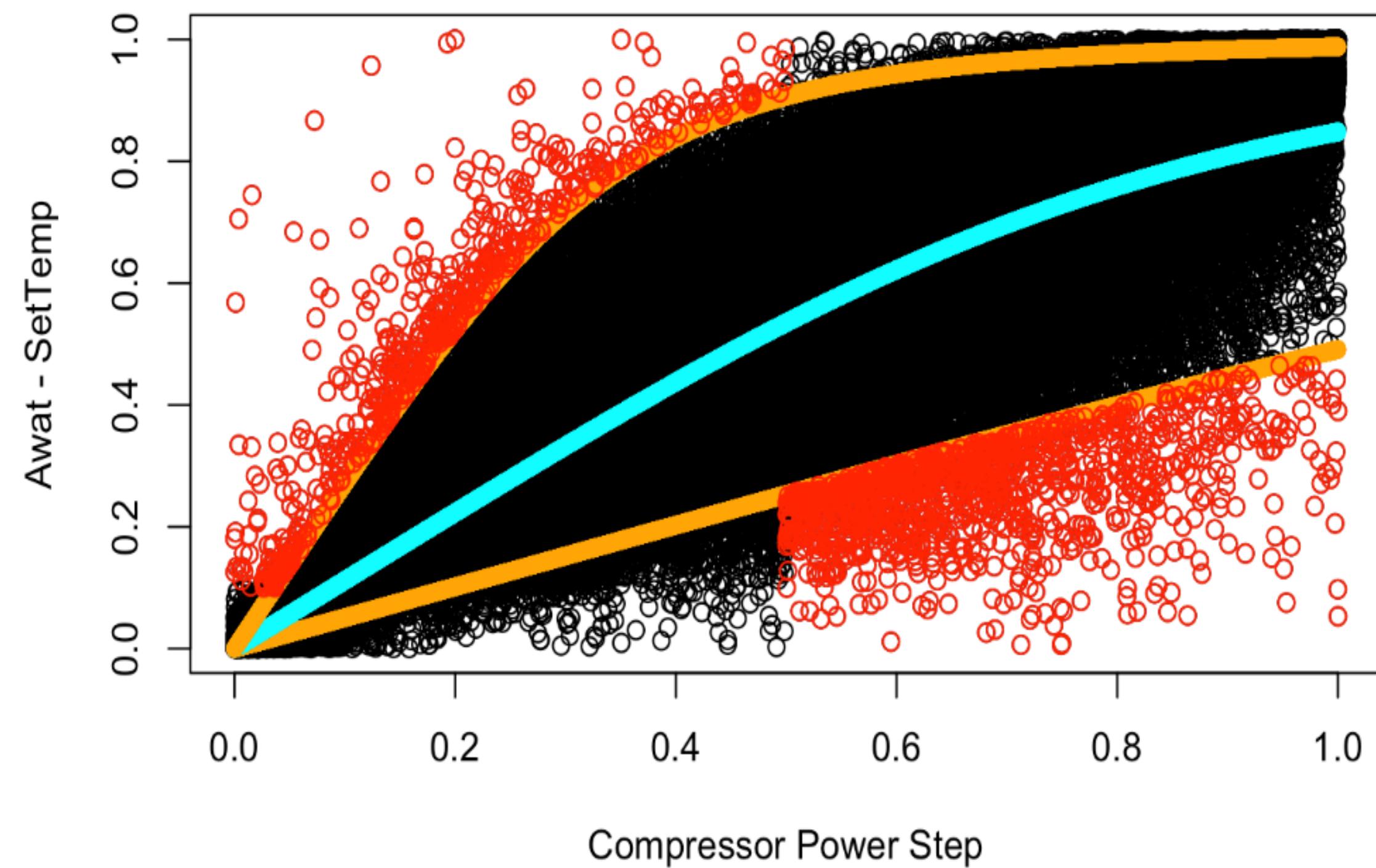
Over-performing: Delta is low, but compressor power step is high

Under-performing: Delta is high, but compressor power step is low



Total Anomaly

1673 observations



Variable Aggregation & Row Selection



Variable Aggregation

- Out of Design Temperature Exposure Duration (ODTD)
- Average Weighted Ambient Temperature (AWAT)
- Delta (AWAT - Set Temperature)



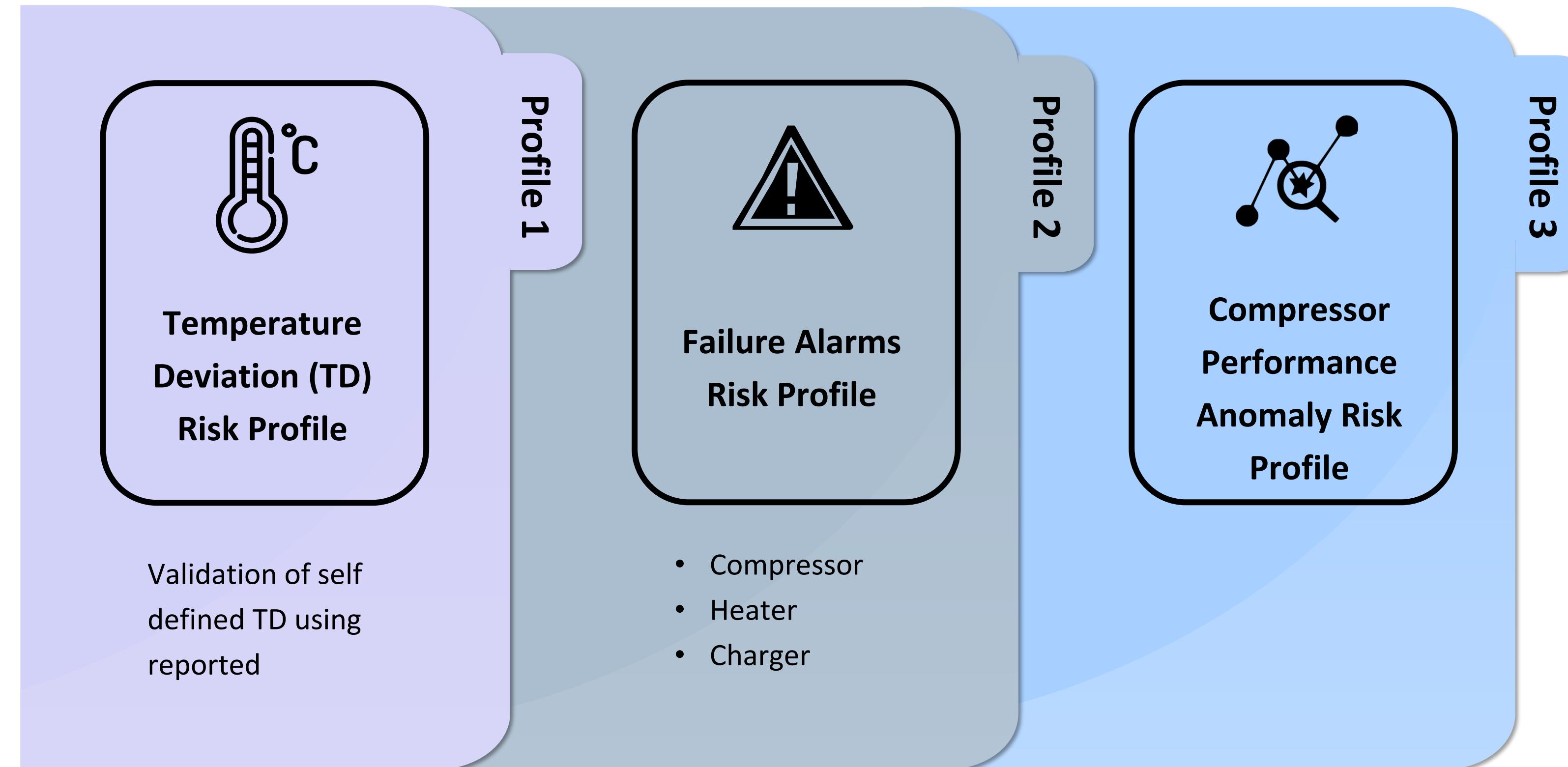
Row Selection

- Only records with container logged information are selected
- Only shipments with operational log time duration larger than 8 hours are chosen to avoid average inside temperature values being over influenced by container's preconditioning period

Descriptive Analysis



Failure Risk Profile



Temperature Deviation (TD) Risk Profile



Higher ambient temperature and longer exposure to extreme temperature increase TD rate



Season

- Summer has the highest TD rate, taking up **39%** of the total TD



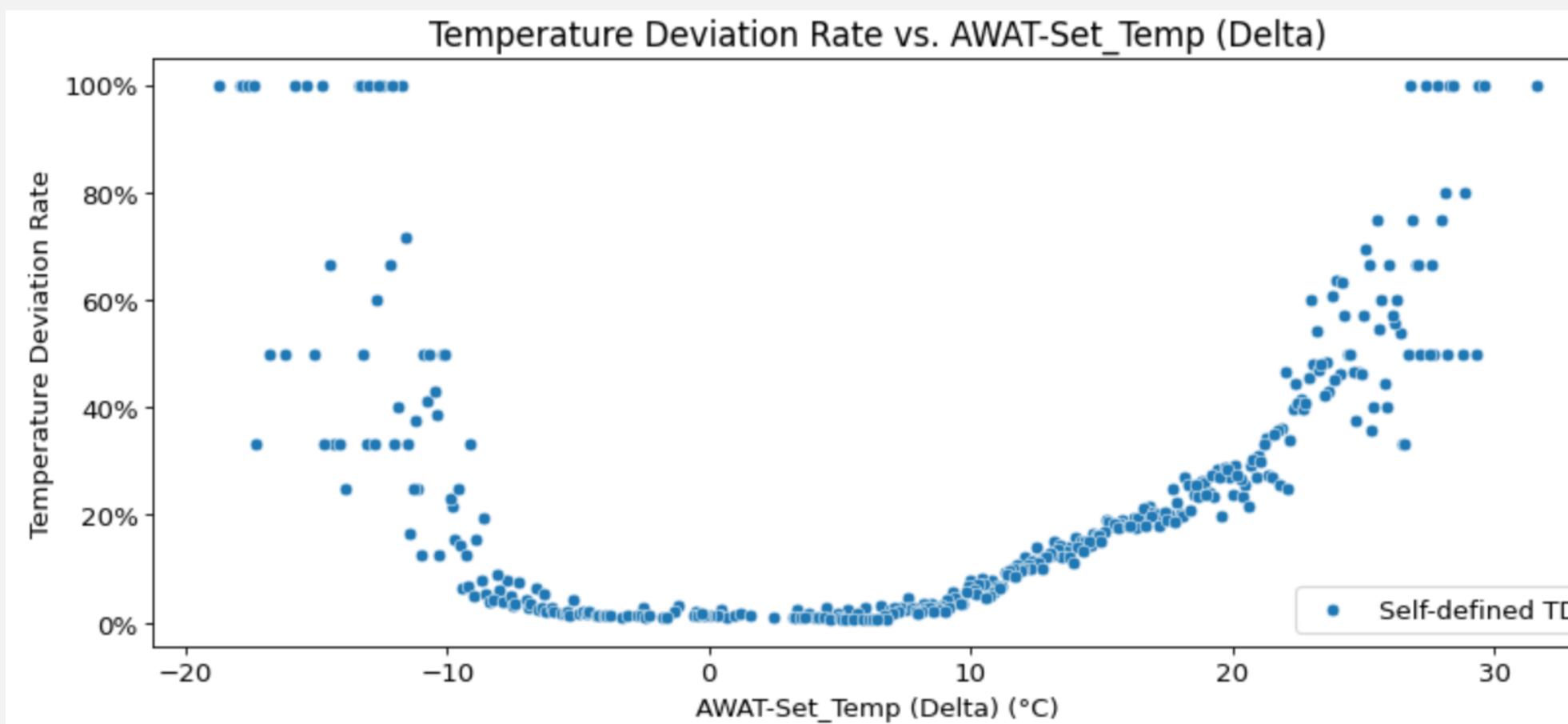
Shipment Duration

- The longer the shipment duration, the higher the TD rate



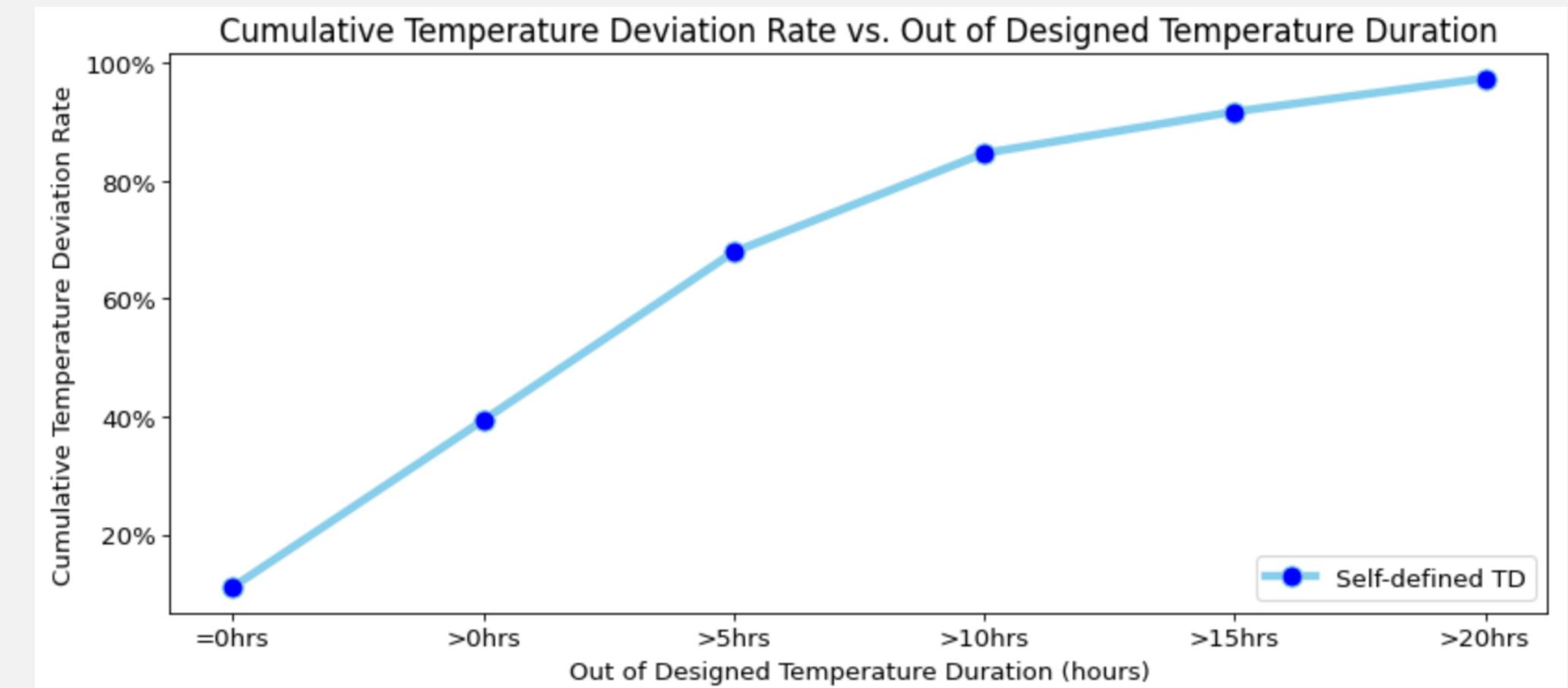
Delta

- TD rate increases exponentially when $|\Delta|$ is above **10°C**



Out of designed temperature exposure duration (ODTD)

- TD rate reaches **70%** when ODTD is above 5 hours



Temperature Deviation (TD) Risk Profile

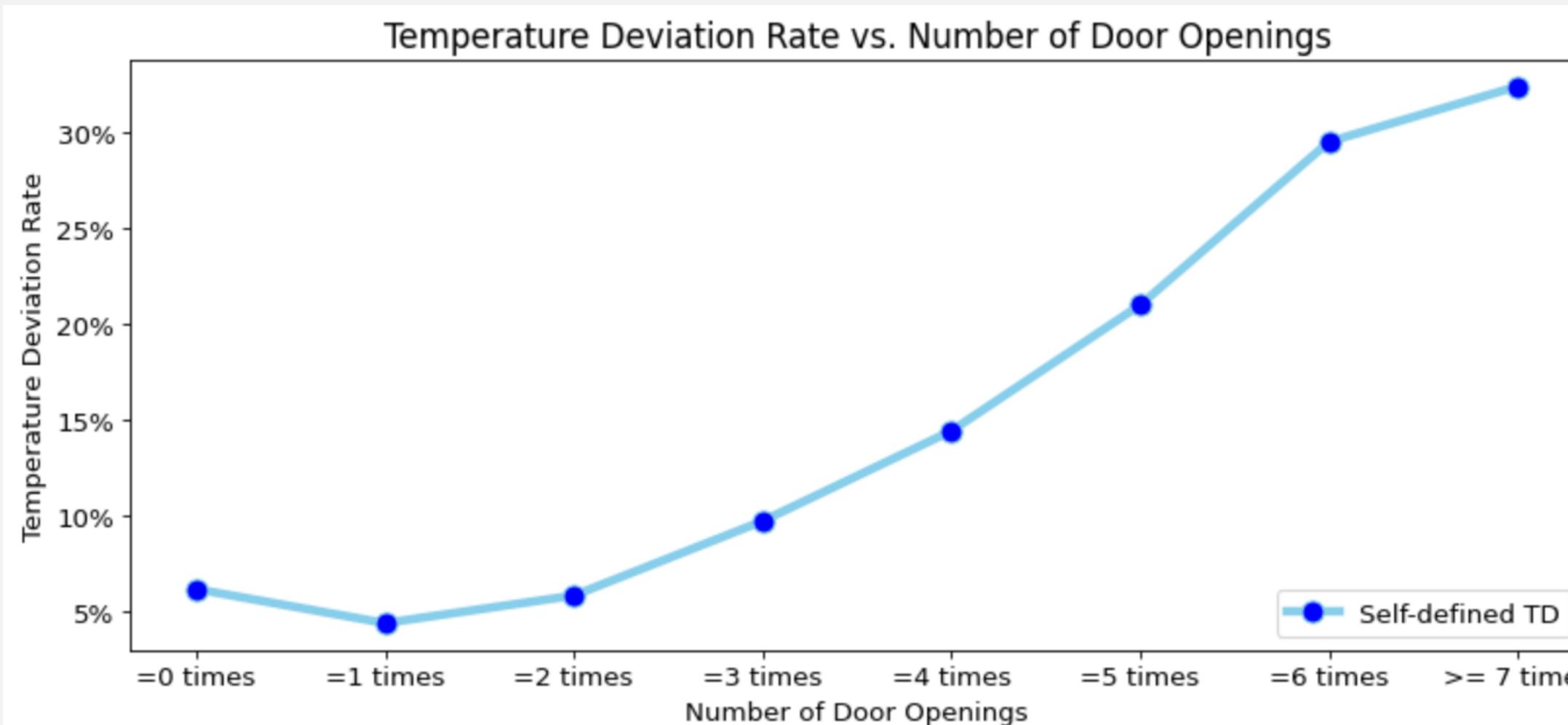


More door openings and lower battery mean increase TD rate



Number of door openings

- TD rate climbs after **3** times of door openings



Battery Mean

- TD rate increases when battery mean is below **70%**



Economic Status of origin and destination countries

- TD increases when the origin is developing country

10.6%

Developed → Developed

9.6%

Developed → Developing

16.1%

Developing → Developed

17.2%

Developing → Developing

Failure Alarms Risk Profile



Compressor & Heater Alarms

Higher ambient temp., longer exposure to extreme temp., and more door openings increase alarm rate

Season

- Summer takes up **39%** of total compressor alarms and **56%** of total heater alarms

Alarm Rate	Spring	Summer	Autumn	Winter
Compressor	0.21%	0.44%	0.25%	0.28%
Heater	0.06%	0.20%	0.04%	0.06%

Shipment Duration

- The longer the shipment duration, the higher the compressor & heater alarm rate

Delta

- Compressor alarm rate increases as Delta gets larger



Out of designed temperature exposure duration (ODTD)

- Compressor alarm rate jumps after **4 hrs** of ODTD
- Heater alarm rate increases sharply after **10 hrs** of ODTD

Number of door openings

- Compressor & heater rate increases after **6 times** of door openings

Failure Alarms Risk Profile



Charger Alarms

Supply voltage of 100V-127V and incorrect charging behavior increase charger alarm rate



Supply Voltage

- Charger alarm rate peaks when the supply voltage is **100V-127V** in origin and destination

0.65%

Origin Voltage

100V-127V

0.32%

220V-240V

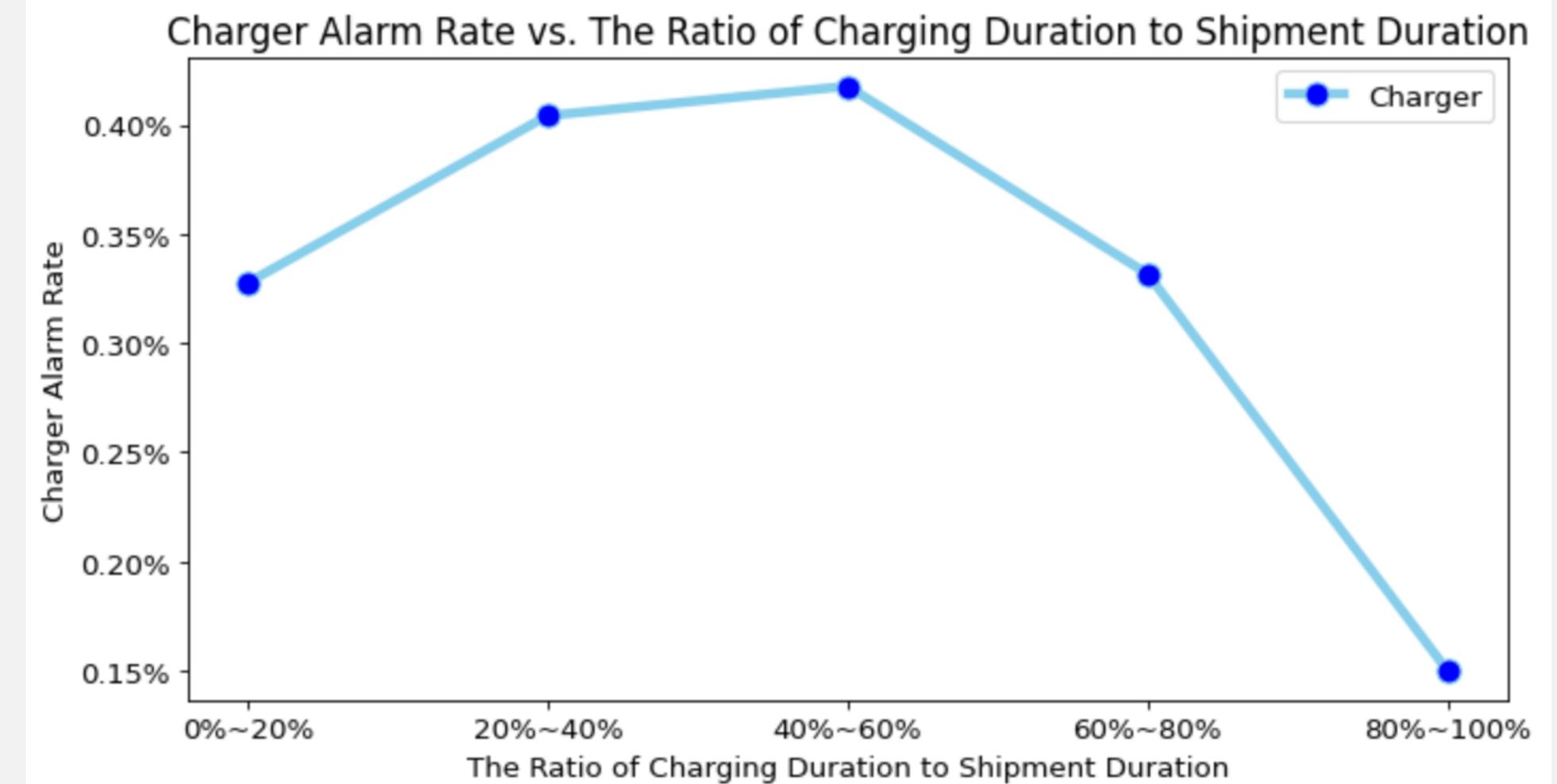
Destination Voltage

100V-127V



Charging Behavior

- Not continuously charging the container
- Frequently alternating between charging and no charging



Compressor Performance Anomalies Risk Profile



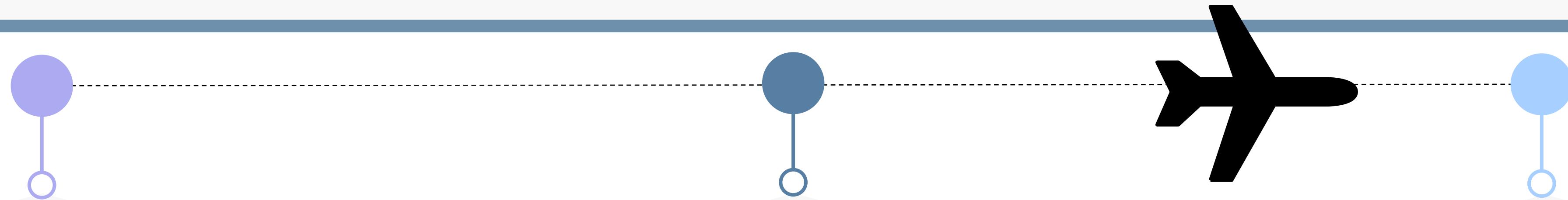
Containers with compressor performance issue tend to have more compressor alarm rate & TD rate

	Compressor Alarm Rate	Temperature Deviation Rate	Out of Designed Temperature Exposure (hrs)	Mean Battery Level	Mean Number of Door Openings	Charging Time Ratio
Normal	0.3%	13%	0.045	80%	3.5	47%
Abnormal	1.1%	35%	0.119	71%	4.4	40%

Predictive Model



Feature Engineering



Label Selection

Temperature deviation (TD)

- **Reason:** The ultimate objective is to avoid temperature deviation during a shipment

Predictors Selection

Features whose values are given or can be estimated at the beginning of each shipment

- Season
- Set Temperature
- Estimated Shipment Duration
- Estimated AWAT
- Usage
- Origins and Destinations
- Airlines

Recategorization

To avoid over dimensionalities of following categorical features

- Origins and Destinations – Recategorized into 4 groups by economic status
- Airlines- Recategorized into 3 groups by number of container shipments with Envirotainer

Imbalanced Data Handling

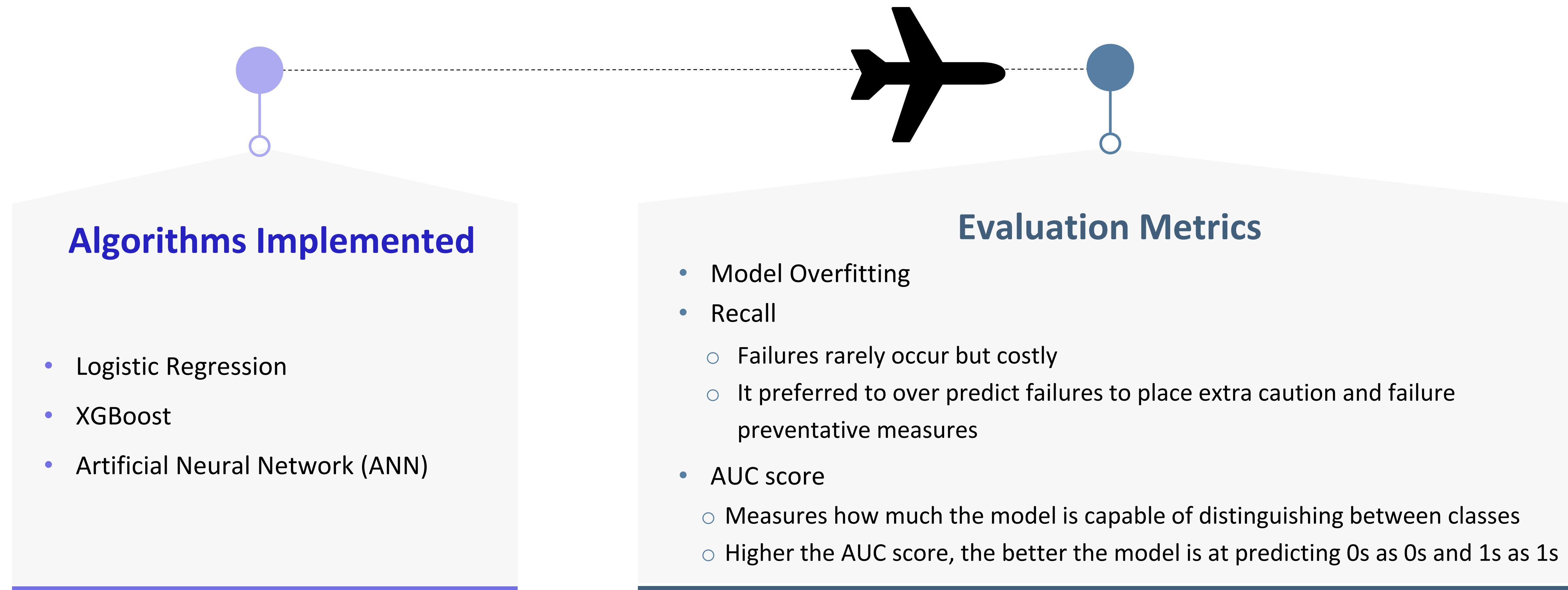


Main reason to create balanced dataset: Give equal priority to each class

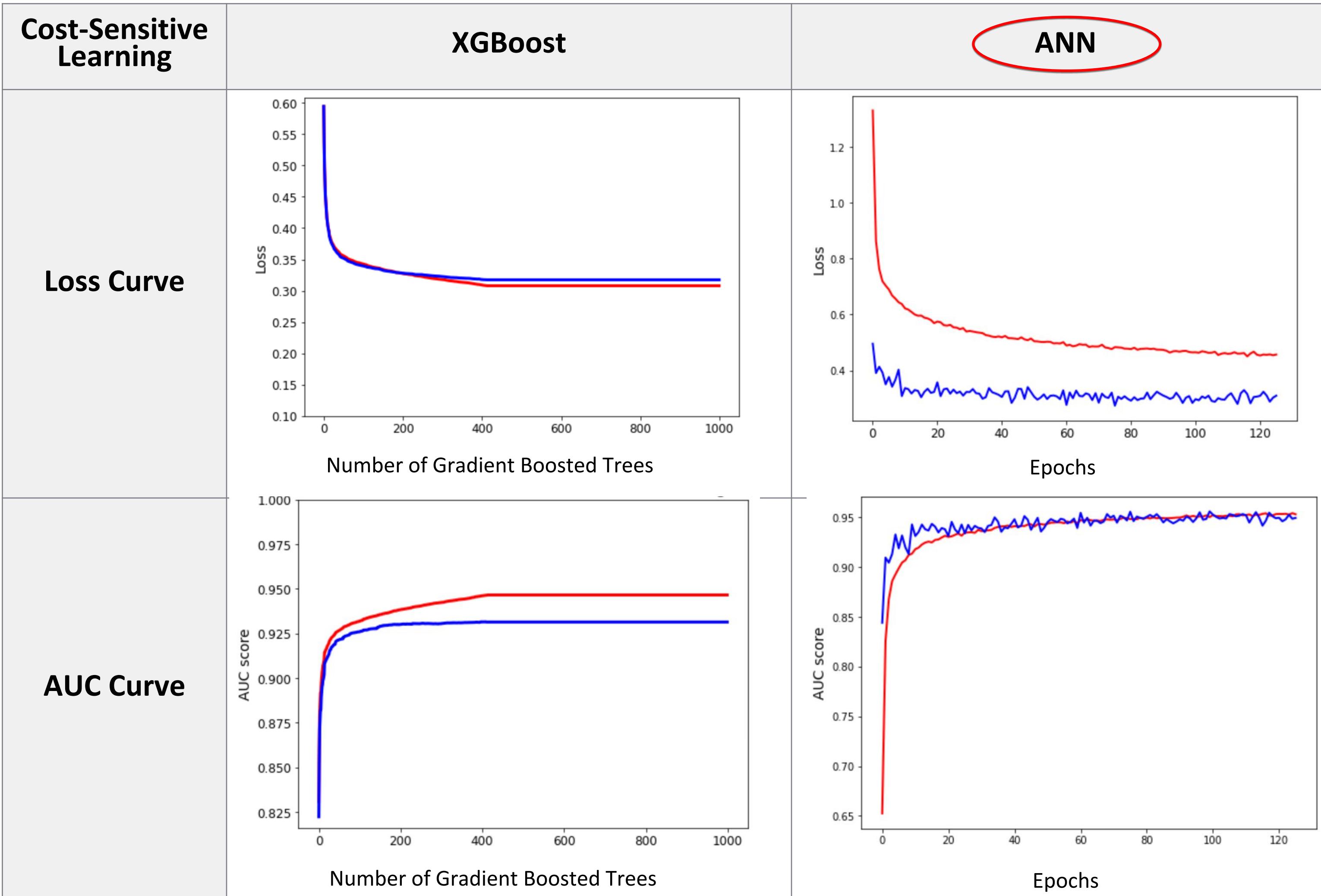
	Adaptive Resampling									
	Oversampling		Down-sampling		Cost-sensitive learning					
Concept	No TD	TD	SMOTE 	TD	No TD	Random down-sampling 	No TD	TD	88% : 12% = 7.3 : 1	Weights for cost function
Advantage	no loss of information		reduce run-time and memory		no loss of information					
Disadvantage	prone to overfit than down-sampling		lose critical information and create bias							

Model Implementation & Evaluation

Data was split into train (67.5%), validation (22.5%), and test (10%) sets



Model Implementation – Overfitting Analysis



- Cost sensitive learning performed best for both XGBoost and ANN
- However, **ANN with cost-sensitive learning** performed much better in the convergence progression between train and validation AUC scores than XGBoost.

AUC & Recall Scores



- Highest Recall with Good AUC Scores

Validation set

Recall Score	Logistic Regression	XGBoost	ANN
Original data	0.298	0.486	0.484
Oversampling with SMOTE	0.821	0.590	0.825
Random down-sampling	0.820	0.878	0.891
Cost sensitive learning	0.821	0.878	0.891

AUC Score	Logistic Regression	XGBoost	ANN
Original data	0.876	0.931	0.936
Oversampling with SMOTE	0.889	0.920	0.930
Random down-sampling	0.887	0.927	0.928
Cost sensitive learning	0.888	0.931	0.936



Winning Model

Artificial Neural Network with cost-sensitive learning

Test Set

Accuracy: 0.8641

Precision: 0.472

Recall Score: 0.891

F1 Score: 0.61

AUC score 0.936

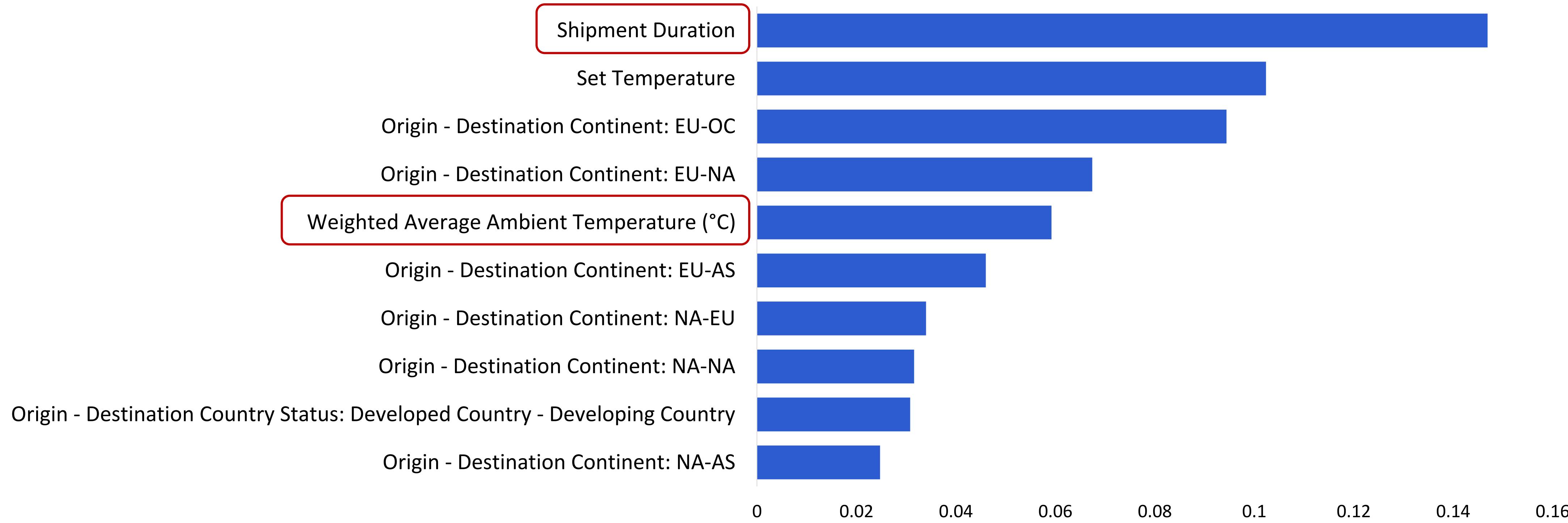
22

Model Interpretability



- XGBoost is more interpretable than ANN
- **Shipment Duration** and **Delta (AWAT-Set Temp)** have the most impact on failure occurrence.

Top 10 Predictors of XGBoost with Cost-sensitive Learning



Recommendation



Recommendation



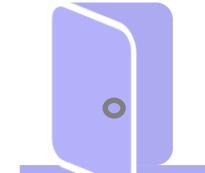
01

Place containers into **temperature-controlled storages** during transition

02

Turn on the container no more than **2 hours** before placing the product inside

03

Minimize the  during a shipment, under **5 times** if possible

04

Continuously charge  and maintained the battery level above **70%** if possible

05

Use **voltage transformers** when the supply voltage is between **100V - 127V** or consider a charger design modification

Demo



Predictive Model

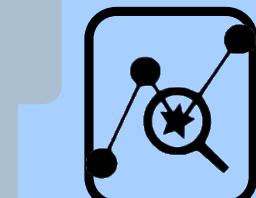
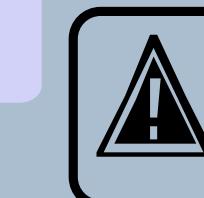
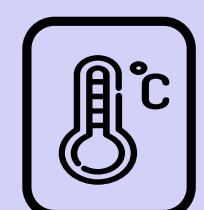
Release Month	May
Set Temp (°C)	5 °C
Average Ambient Temperature(°C)	22 °C
Shipment duration	200hrs
Origin - Destination	ATL - DEL
Airlines	Delta Air Lines (Big Airlines)



Place an Order



The classification
is TD



Recommended Preventative Measures

Future Works



01

Utilizing historical and streaming data to give **real time or near real time predictions** on different types of failures

02

Establishing a **resource/logistic allocation system** based on the derived insights on shippers, airlines, routes and transfer hubs

03

Generating **real time/near real time solutions, i.e. maintenance, repair or replacement**, using both real time failure prediction and resource allocation systems

04

Developing **demand related analytics and forecast** based on historical ordering data, order back-log data and real time health events.



Thank You!

Appendix

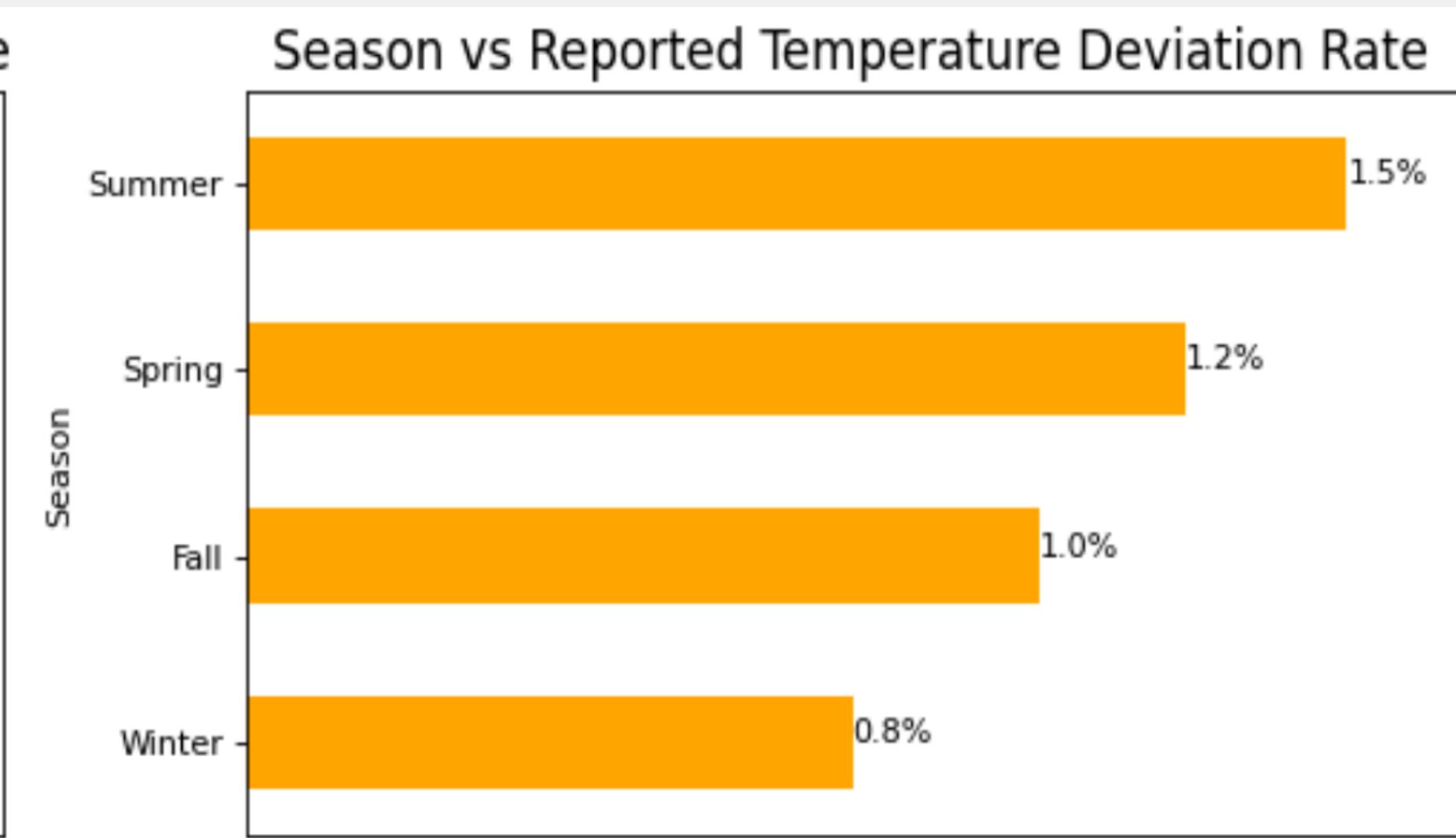
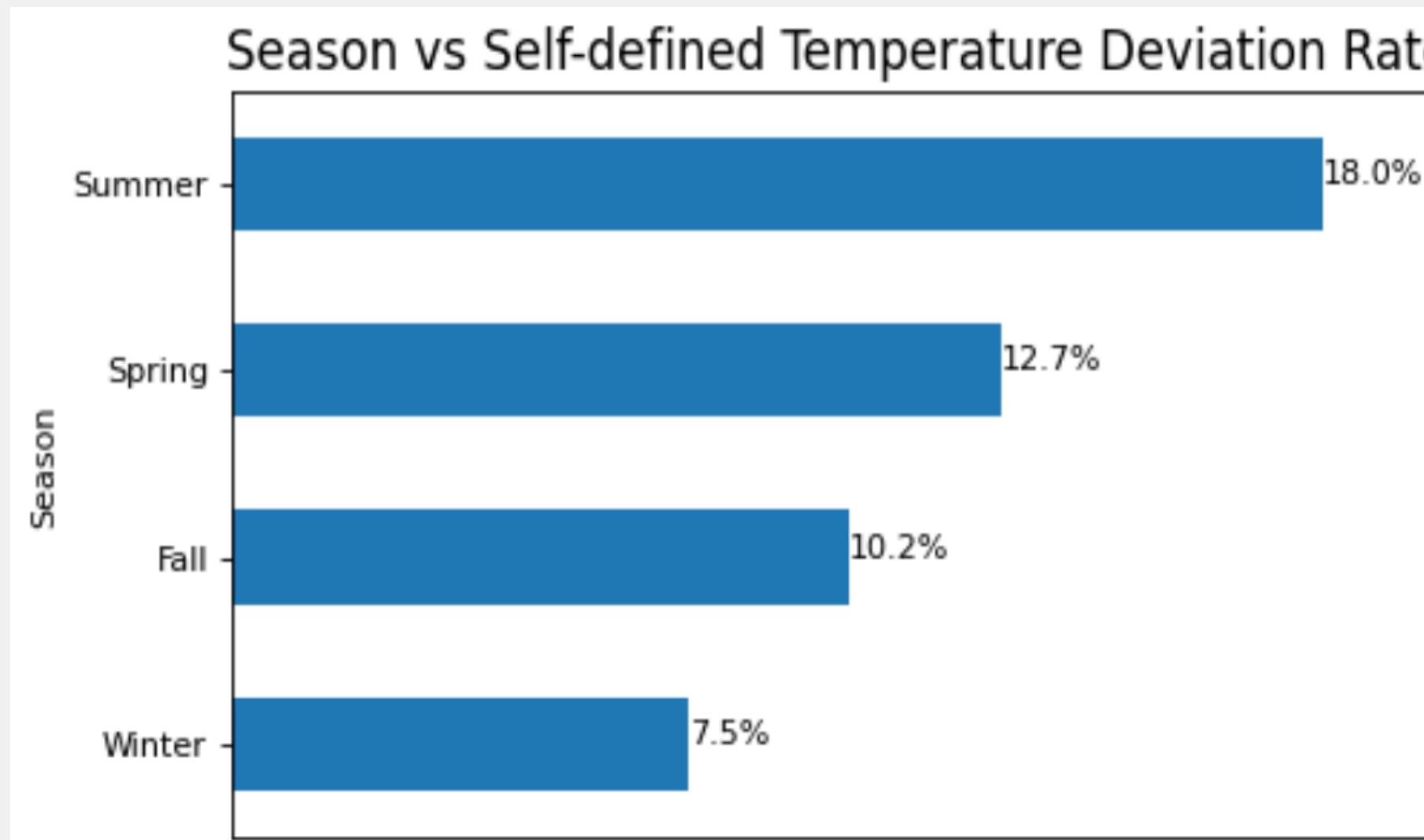


Temperature Deviation Findings



Season vs. Temperature Deviation Rate

- Temperature deviation often happens in summer
- Reported temperature deviations show the same trend against the season factor

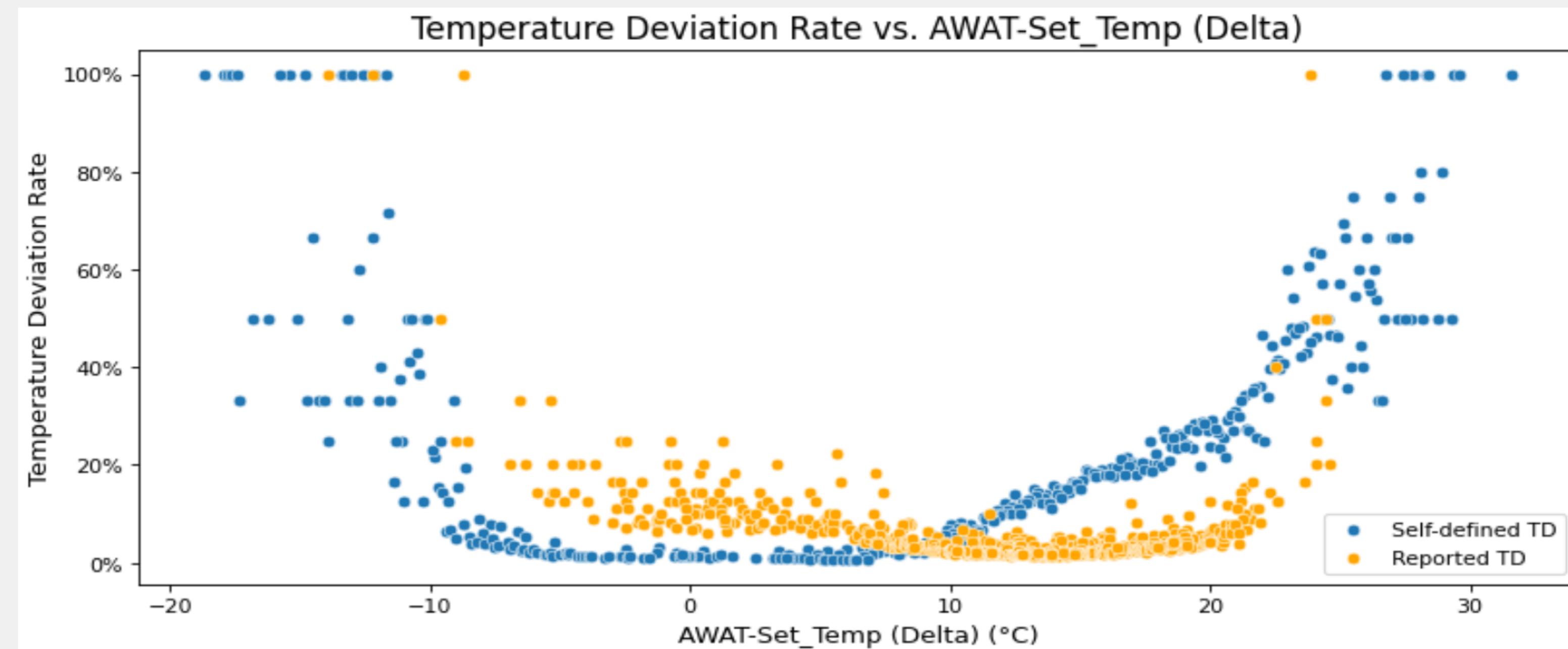


Temperature Deviation Findings



Delta vs. Temperature Deviation Rate

- When the Delta is extremely high or low, the temperature deviation rate is 100%
- The temperature deviation rate minimizes when Delta is between -10°C and 10°C and starts to exponentially increase when Delta is over 10°C or below -10°C.

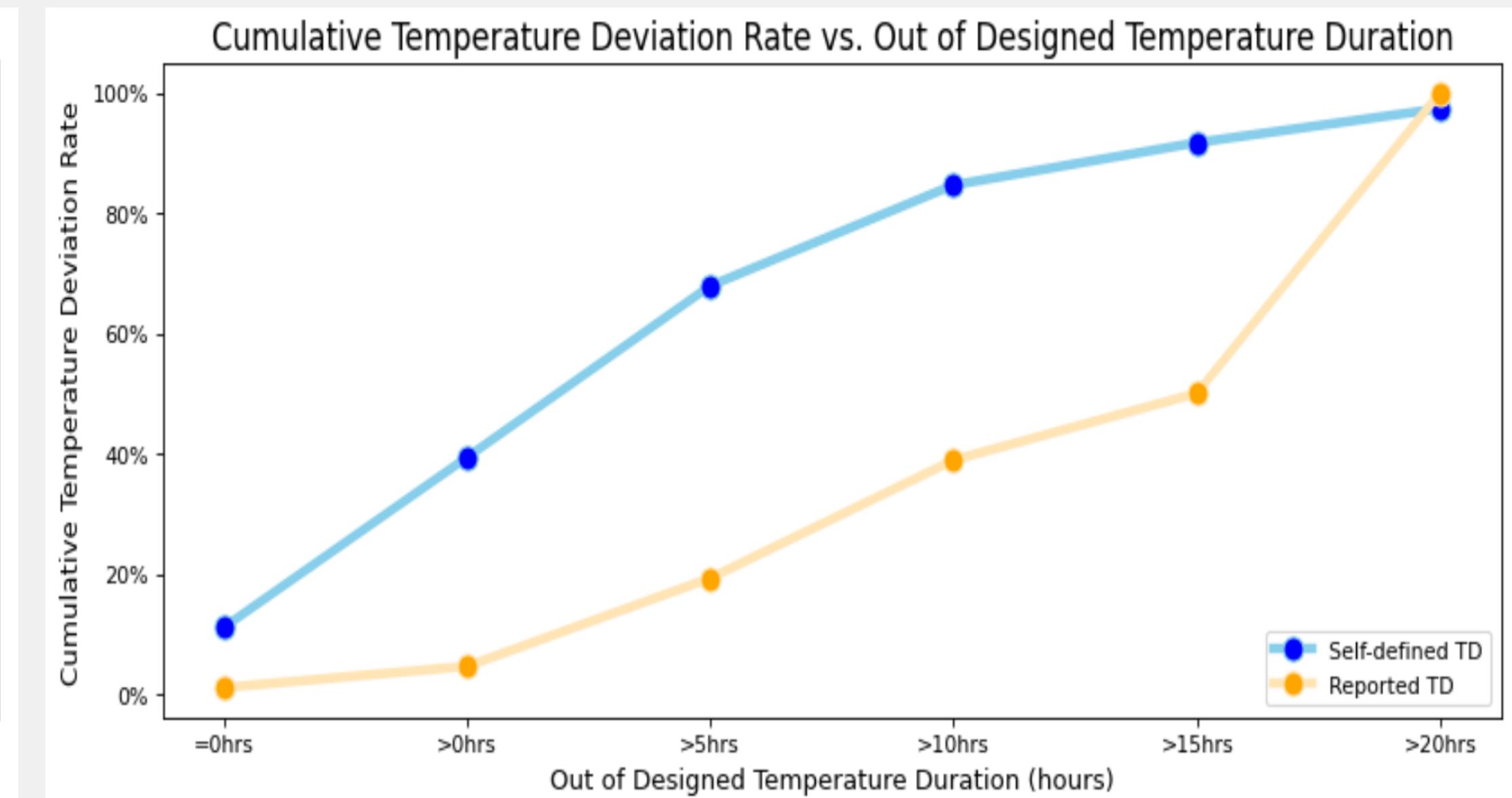
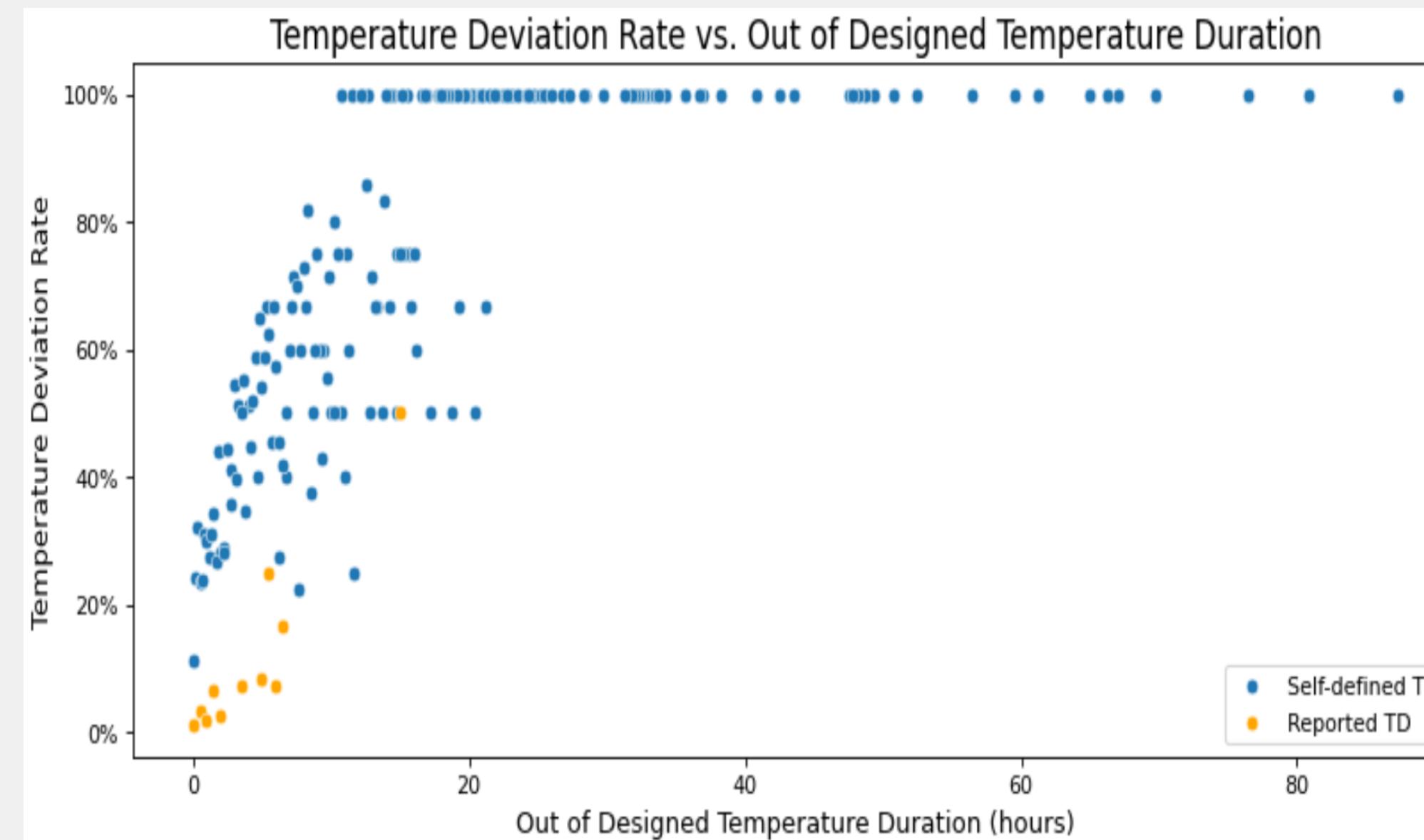


Temperature Deviation Findings



Out of Designed Temperature Duration vs. Temperature Deviation

- When the ODTD increases from 0 hour to 10 hours, the cumulative temperature deviation rate significantly increases from 0.11 to 0.87.

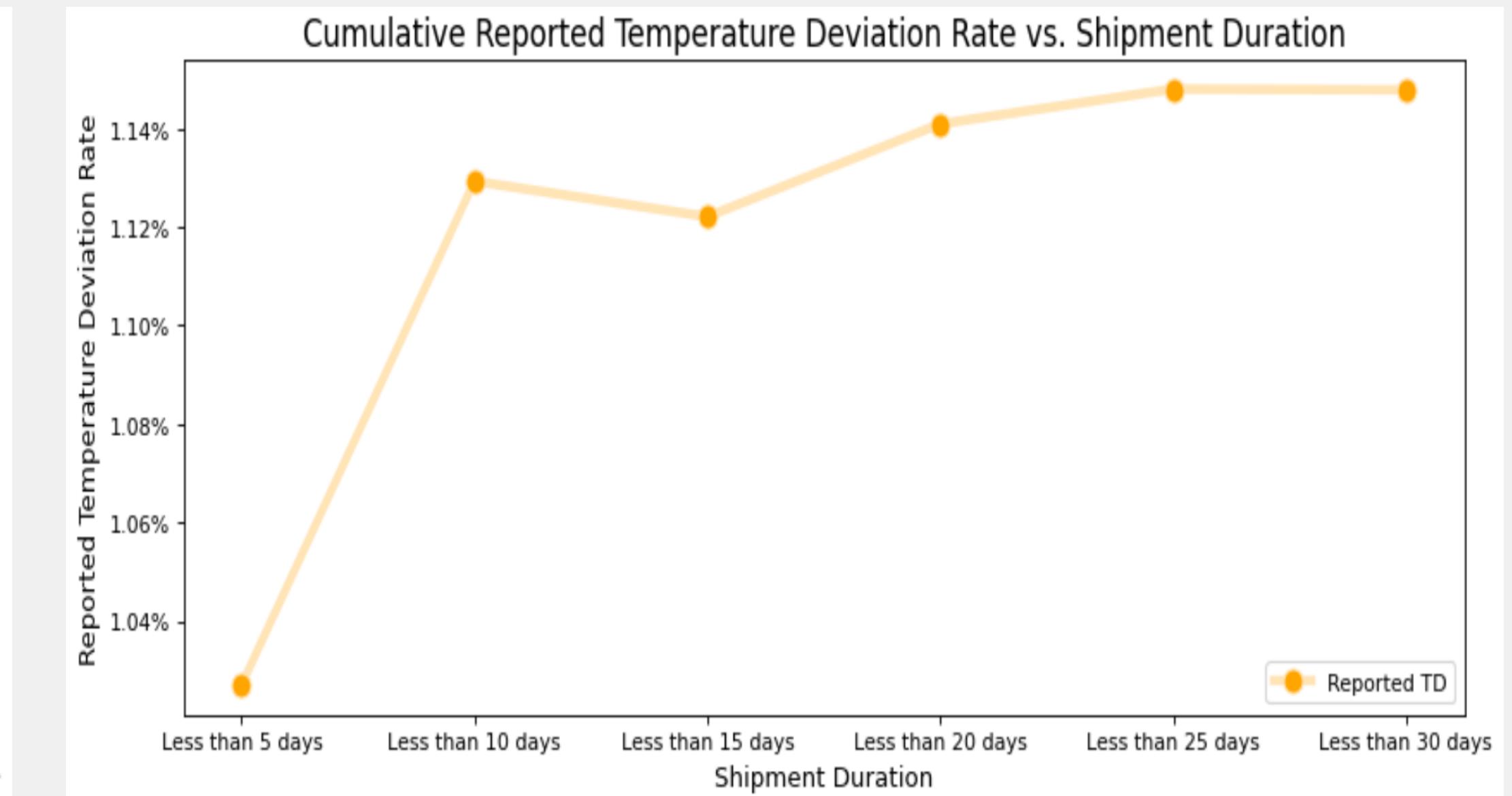
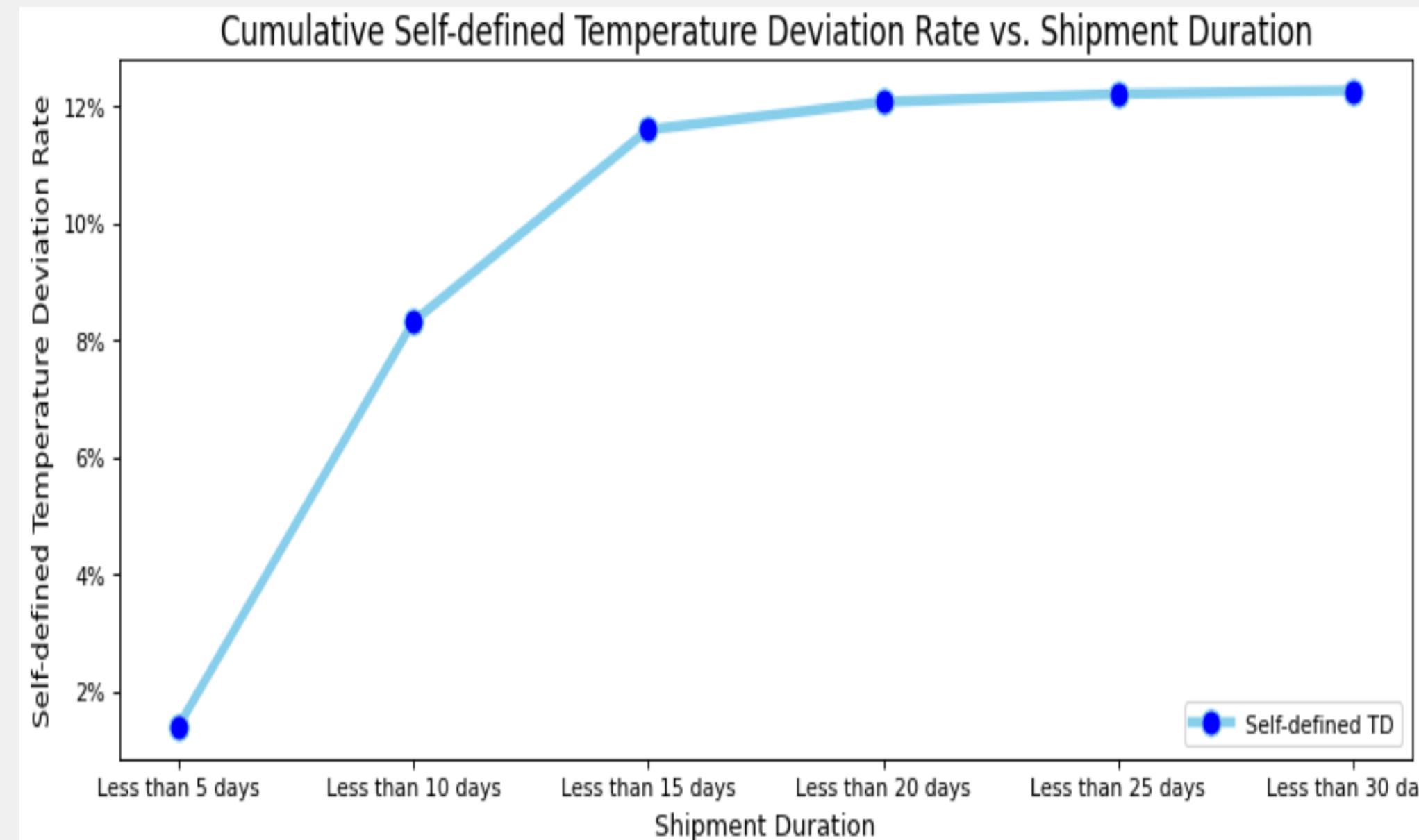


Temperature Deviation Findings



Shipment Duration vs. Temperature Deviation

- Temperature deviation rate increases from 0.01 to 0.08 when the shipment duration changes from less than 5 days to less than 10 days

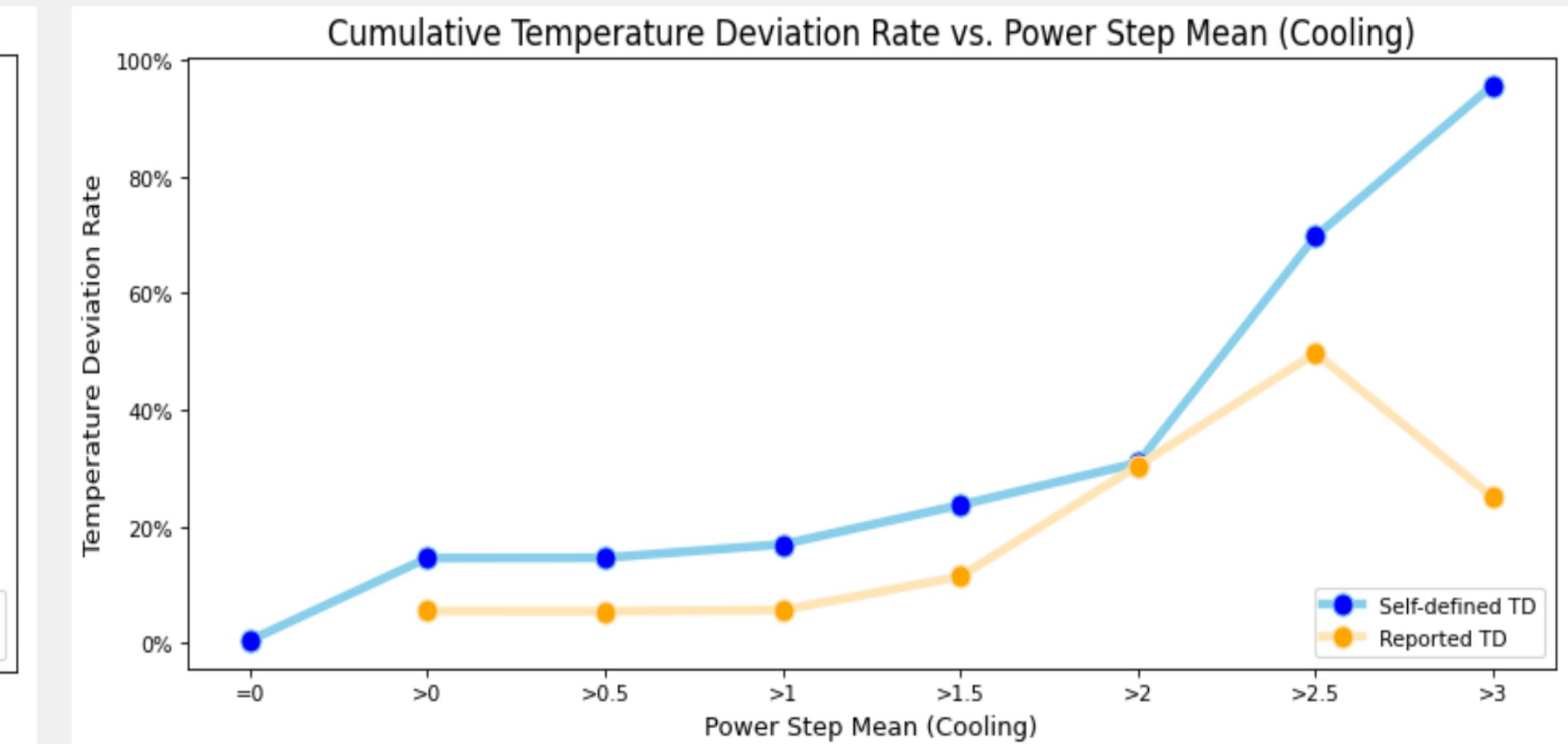
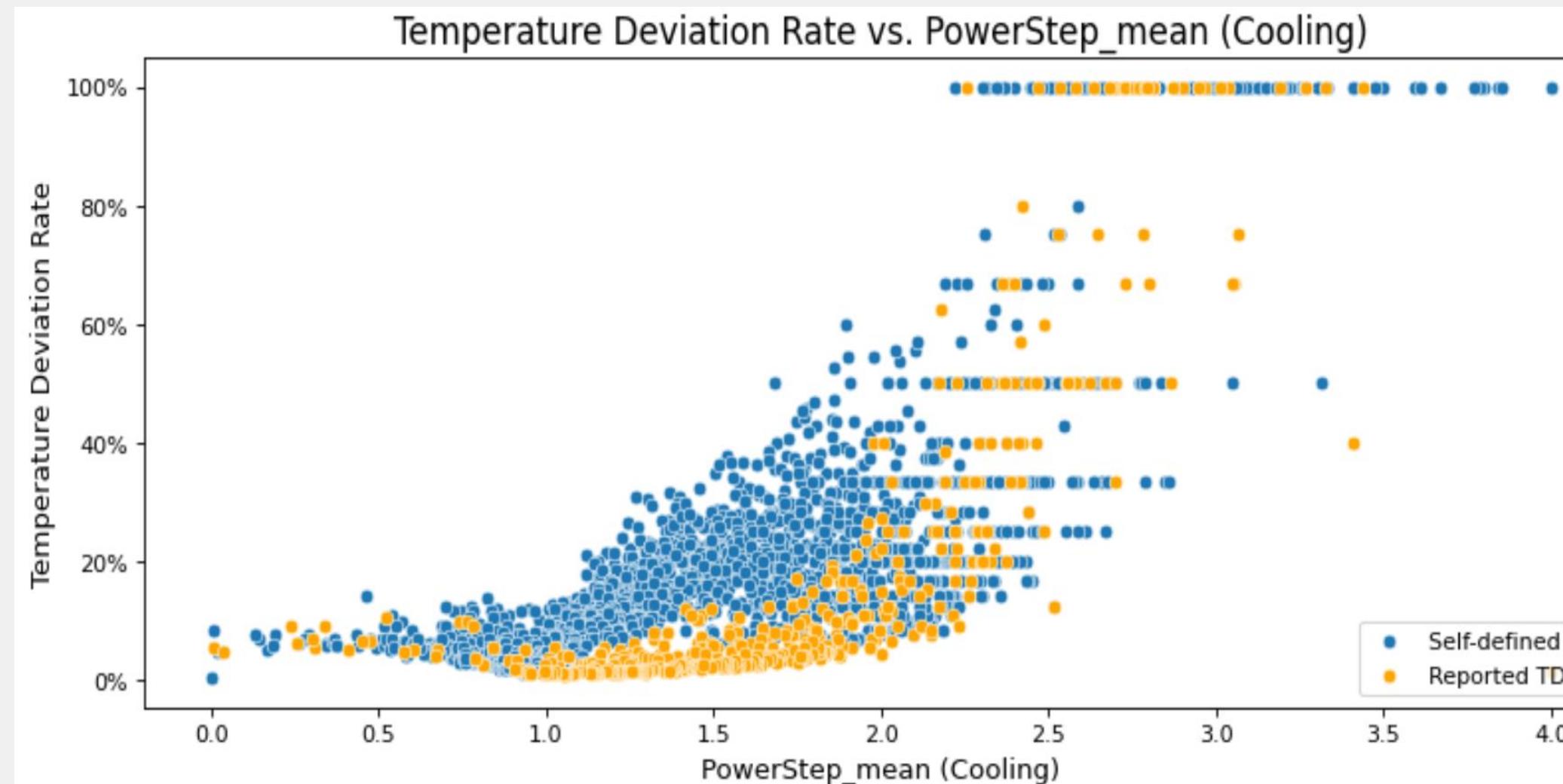


Temperature Deviation Findings



Compressor Power Step vs. Temperature Deviation

- Containers experience higher temperature deviation rate when power step used for compressor (workload) increase
- The reported temperature deviation rate demonstrates a very similar trend as its self-defined counterpart when plotted against mean compressor power step.

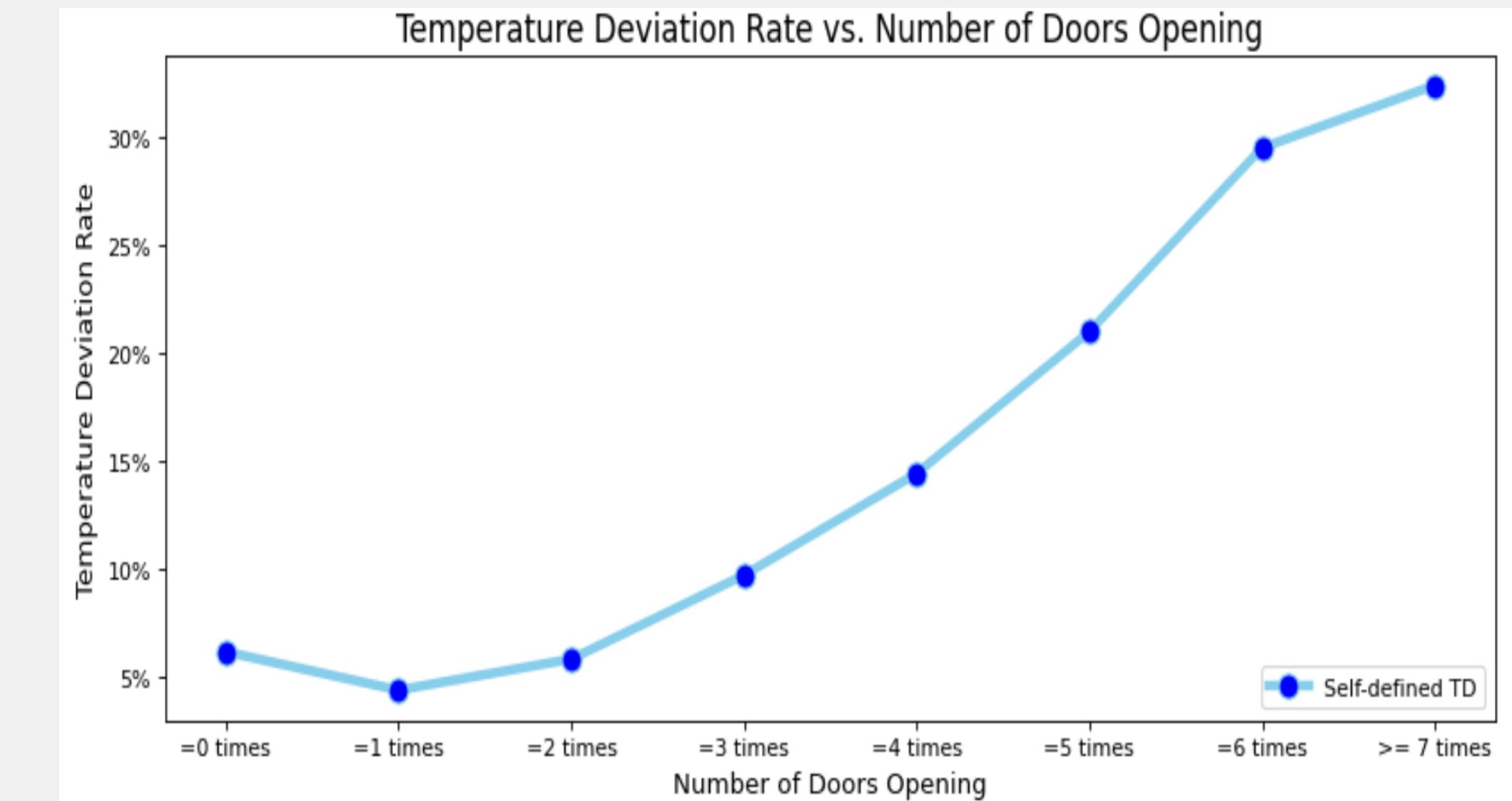
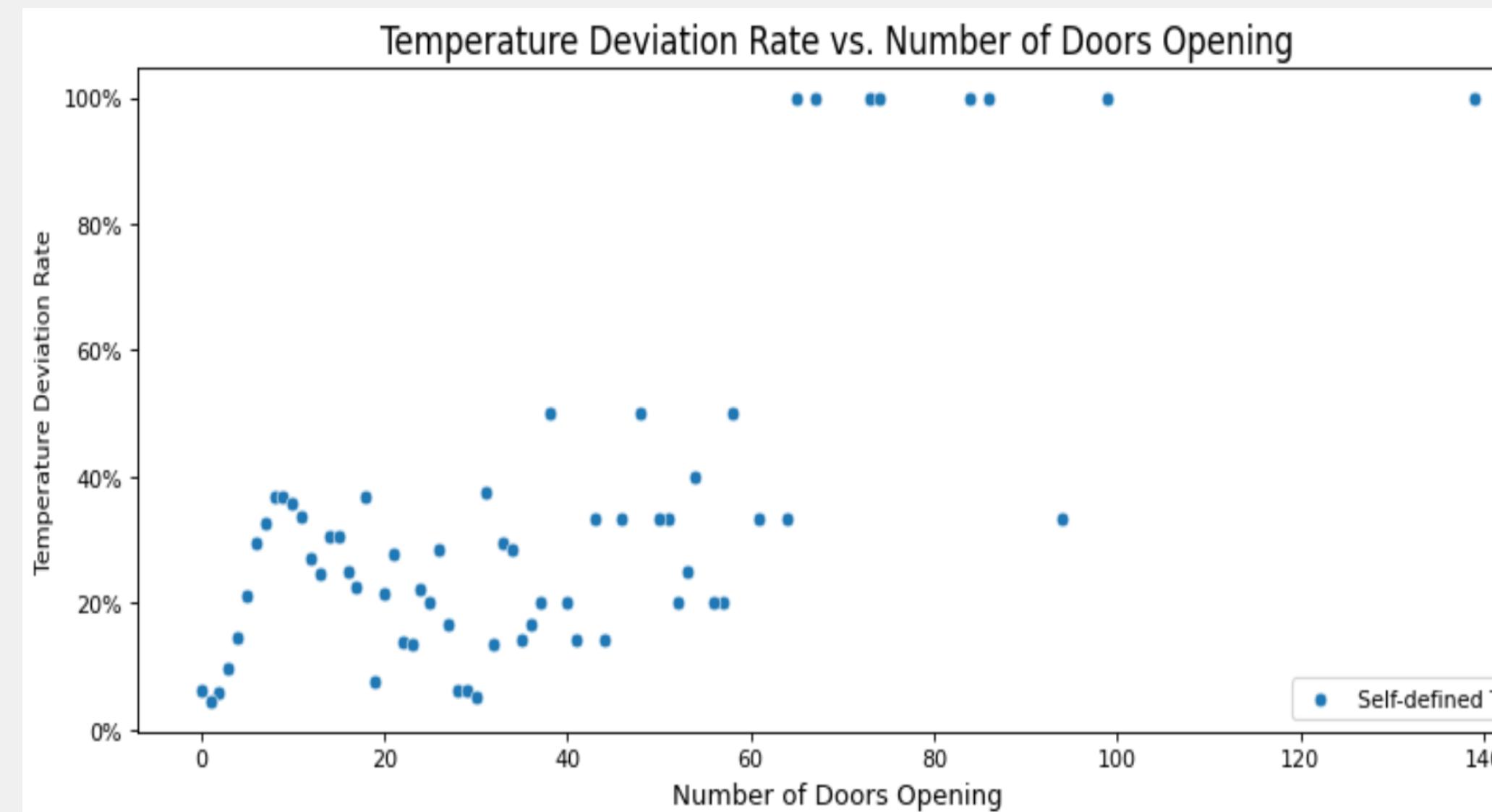


Temperature Deviation Findings



Number of Door Openings vs. Temperature Deviation

- The number of door openings between 0 to 7 times, the temperature deviation rate increases from 0.06 to 0.32
- The temperature deviation rate climbs significantly when the number of door openings is above 3 times during a shipment.

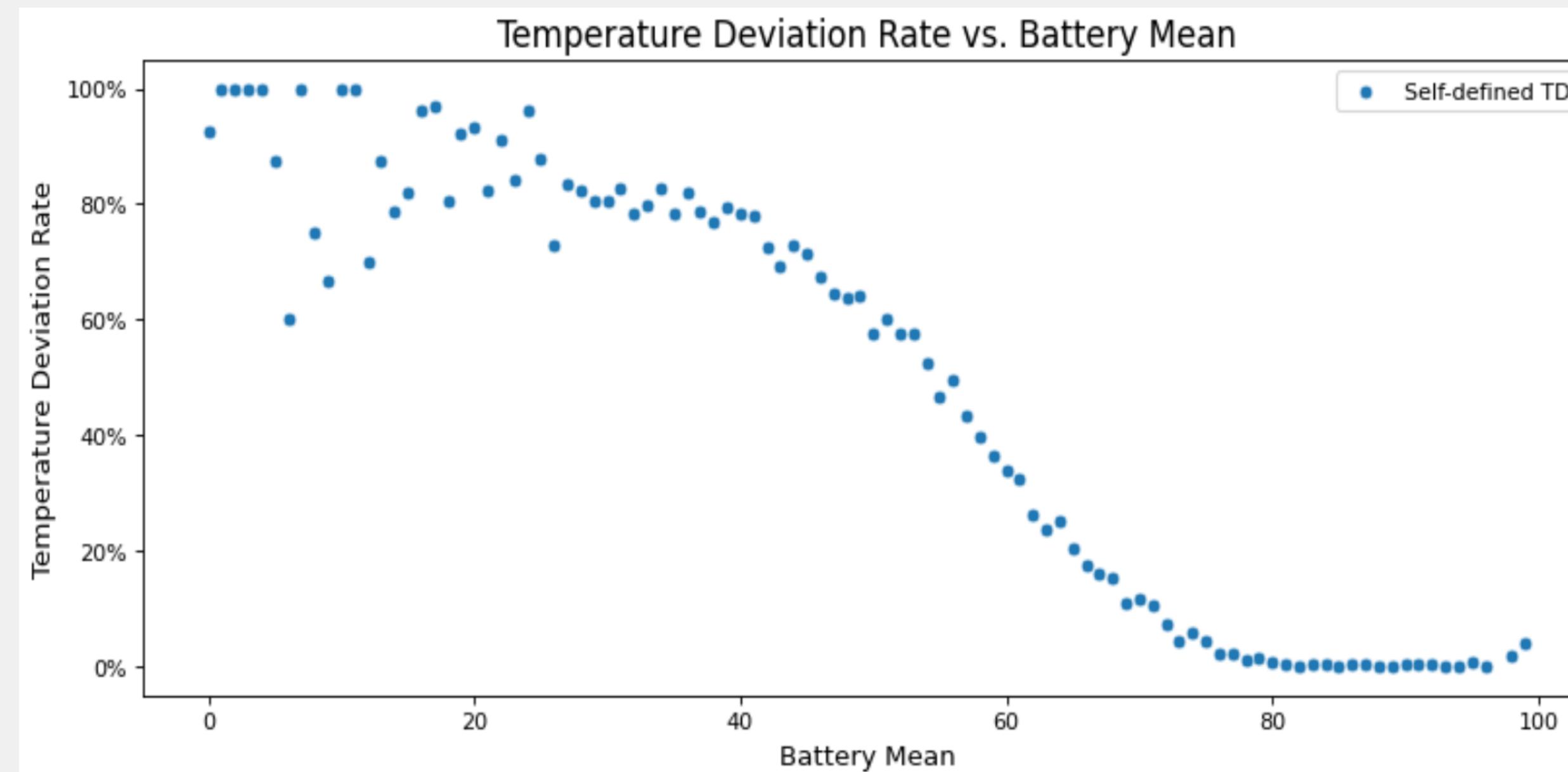


Temperature Deviation Findings



Battery Mean vs. Temperature Deviation

- The non-temperature deviation shipments' battery mean is 83.82%, and temperature deviated shipments' battery mean is 46.19%
- Temperature deviation rate decreases as the battery mean increases

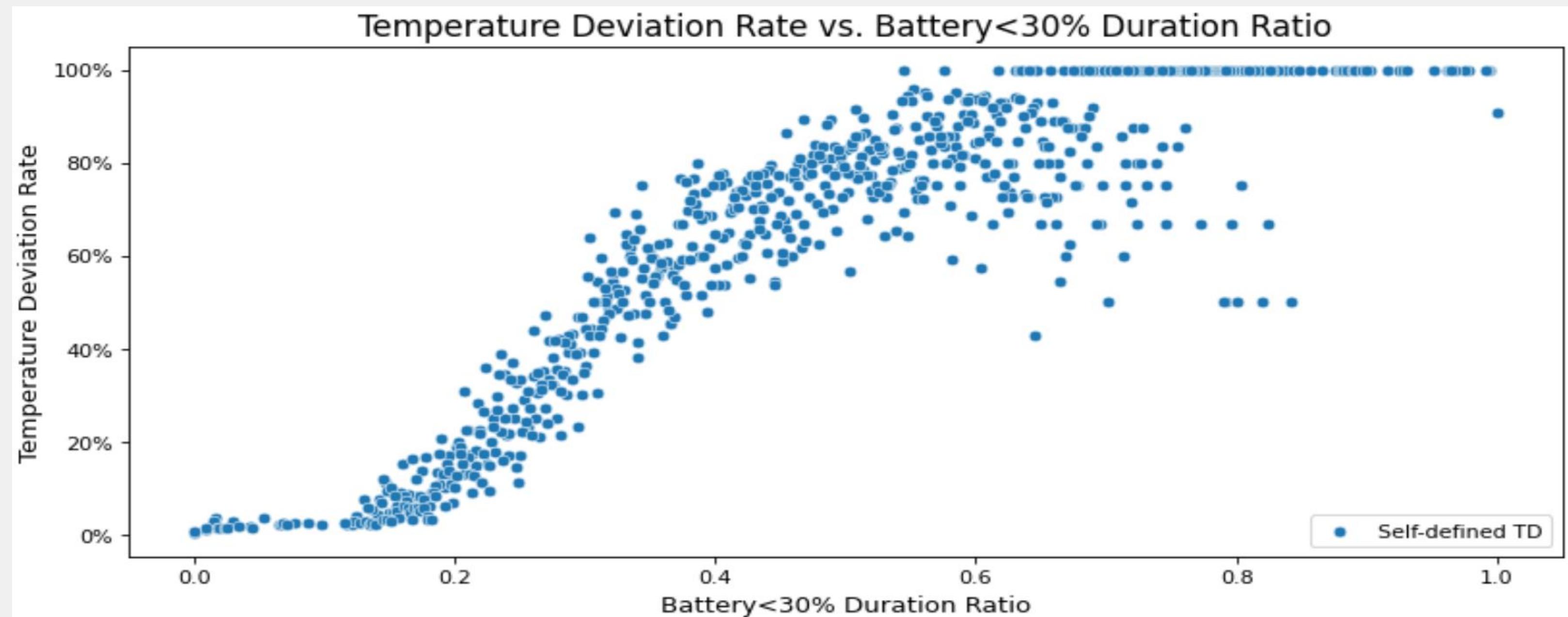


Temperature Deviation Findings



Battery < 30% vs. Temperature Deviation

- As the duration ratio of battery less than 30% increases, the temperature deviation rate will also increase
- It is suggested not to keep the container battery less than 30%.

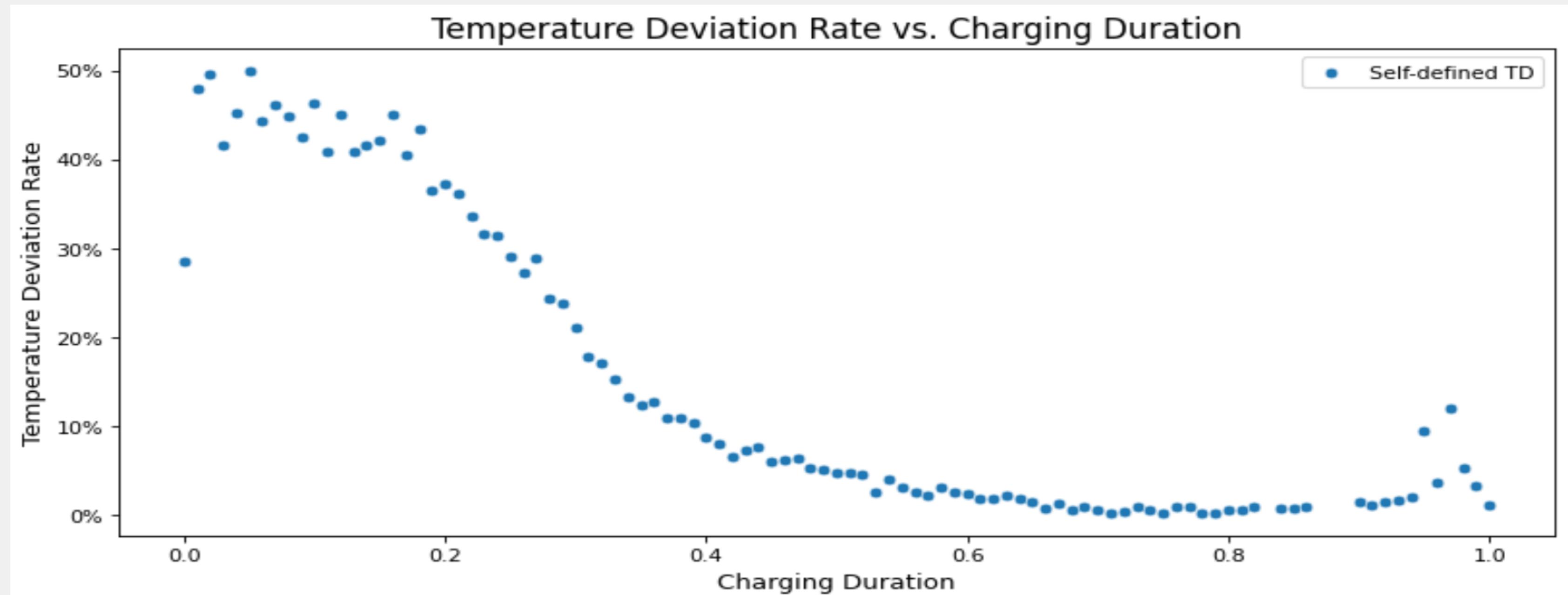


Temperature Deviation Findings



Charging Duration vs. Cumulative Temperature Deviation Rate

- The longer we charge containers during a shipment, the lower temperature deviation rate will be



Temperature Deviation Findings



Economic Status vs. Temperature Deviation

- Economic status of origin countries has a higher impact on temperature deviation ratio as the airline that handles the shipment tend to come from the origin country
- Developed country airlines tend to handle containers better and produce smaller TD ratios

Temperature Deviation						
Origin - Destination Countries	Observed Value					Total
	Developed-Developed	Developed-Developing	Developing - Developed	Developing - Developing		
# of temp deviation	4,357	719	3,029	583	8,688	
# of temp deviation	36,776	6,794	15,740	2,811	62,121	
Total	41,133	7,513	18,769	3,394	70,809	
Ratio of temp deviation	10.59%	9.57%	16.14%	17.18%	12.27%	
Ratio of temp deviation	89.41%	90.43%	83.86%	82.82%	87.73%	

Chi-squared Test	495.264	Critical value (0.95)	7.815
df	3		
p_value	0		

Airlines with High Temperature Deviation Rate



Top 3 Airline vs. Container Handling Behaviors

- The top 3 temperature deviation rate airlines have a lower battery mean than non-temperature deviated shipments
- The battery less than 30% and 0% duration are higher, while the charging duration rate is lower than non-temperature deviation shipments
- The average number of door openings is higher for those airlines than the non-temperature deviation shipments.

	Battery mean	Battery < 30 duration ratio	Battery = 0 duration ratio	Charging duration ratio	Number of door openings mean
Non-Temp Deviation	83.821543	0.043385	0.020093	0.498377	3.342965
Temp Deviation	46.193959	0.452953	0.381411	0.252690	4.967364
Airline78	52.309369	0.380164	0.306721	0.244777	3.845466
Airline8	56.229293	0.335765	0.241829	0.279544	3.842679
Airline46	59.434520	0.295381	0.244963	0.296757	5.324763

Trade Lanes with High Temperature Deviation Rate



Top 3 Trade Lanes vs. External Uncontrollable Factors

- Shipment trade lanes with the highest temperature deviation rate tend to have a much larger average Delta than trade lanes with low temperature deviation rate
- Containers in those high TD rate trade lanes experience much longer ODTD

	Delta Mean	ODTD Ratio
Non-Temp deviation	10.946935	0.066960
Temp deviation	15.691380	0.834061
ORD_FCO	15.853284	0.089730
BSL_JFK	11.030490	0.375570
LUX_HSV	15.436840	0.500845

Failure Alarms Findings



Charger Alarms vs. Voltage

- Voltage has an effect on the number of charger alarms
- When the supply voltage of both origin and destination countries are between 100V and 127V, the charger alarm rate is the highest (0.65%)
- When the supply voltage of both origin and destination countries are between 220V and 240V, the charger alarm rate is the lowest (0.32%)
- The container chargers are twice as likely to failure when the supply voltage is between 100V-127V

Observed Value					
Origin - Destination	Group1	Group2	Group3	Group4	Total
#of charger alarm	36	55	121	48	260
#of no charger alarm	5463	15302	35055	14729	70549
Total	5499	15357	35176	14777	70809

Ratio of charger alarm	0.65%	0.36%	0.34%	0.32%	0.37%
Ratio of no charger alarm	99.35%	99.64%	99.66%	99.68%	99.63%

Expected Value					
Origin - Destination	Group1	Group2	Group3	Group4	Total
#of charger alarm	20	56	129	54	260
#of no charger alarm	5479	15301	35047	14723	70549
Total	5499	15357	35176	14777	70809

Chi-squared Test 13.699 Critical Value (0.05) 7.815
df 3
p_value 0.003

Failure Alarms Findings



Compressor Alarms vs. Season

- In the Chi-squared test, we have observed a statistically significant seasonal effect on the compressor alarm rate
- Containers experience more compressor alarms in summer than other seasons
- There is a significantly higher compressor alarm rate of 0.44% in the summer

Observed Value					
Season	Spring	Summer	Autum	Winter	Total
# of compressor alarm	36	83	48	44	211
# of no compressor alarm	16,899	18,692	19,258	15,749	70,598
Total	16,935	18,775	19,306	15,793	70,809

Ratio of compressor alarm	0.21%	0.44%	0.25%	0.28%	0.30%
Ratio of no compressor alarm	99.79%	99.56%	99.75%	99.72%	99.70%

Expected Value					
Seasons	Spring	Summer	Autum	Winter	Total
# of compressor alarm	50	56	58	47	211
# of no compressor alarm	16,885	18,719	19,248	15,746	70,598
Total	16,935	18,775	19,306	15,793	70,809

Chi-squared Test
df
p_value

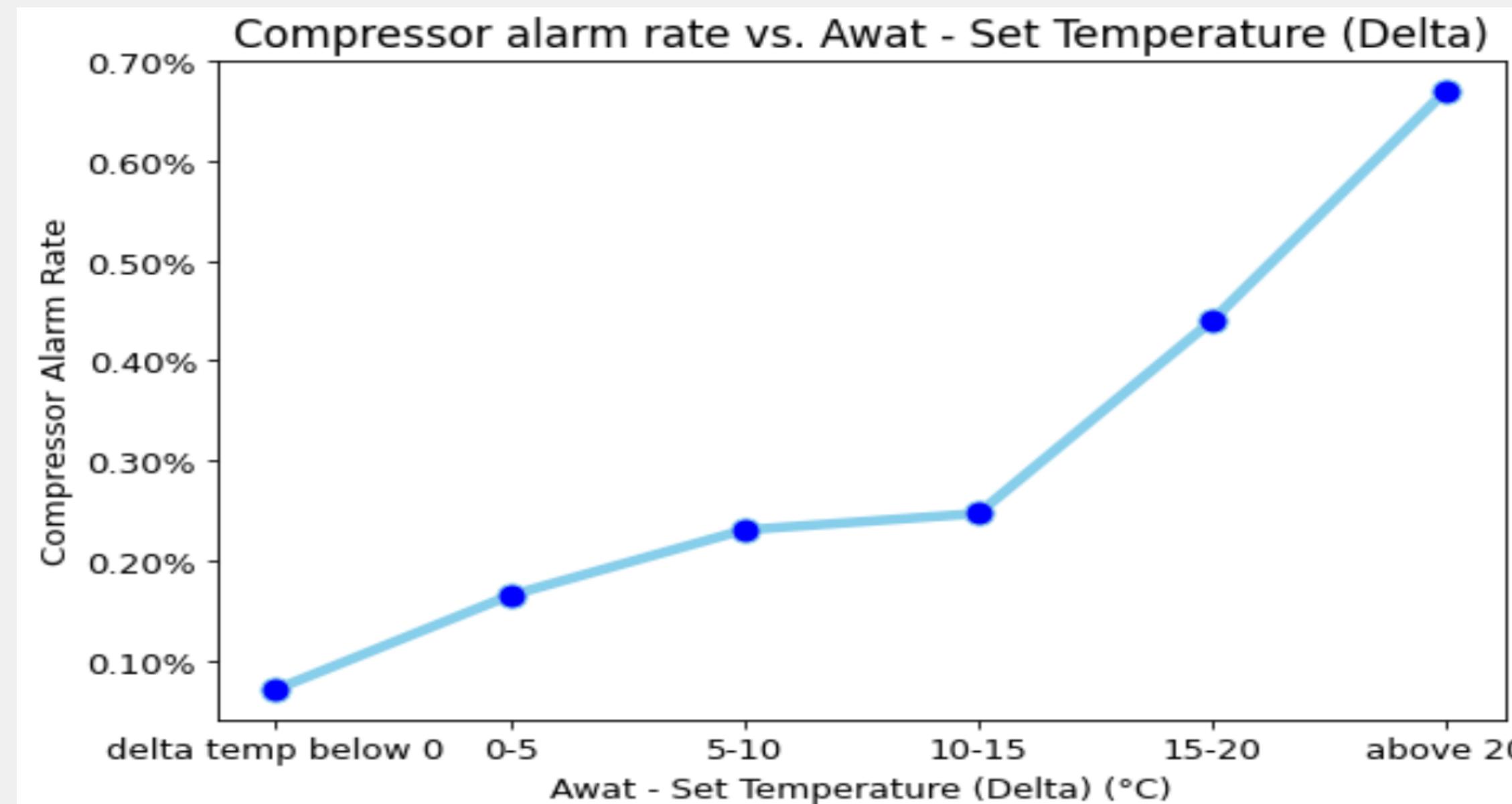
19.06 Critical Value (0.05)
3
0.0002

Failure Alarms Findings



Compressor Alarms Rate vs. Delta Temperature

- Compressor alarm rate goes up as the delta temperature climbs. Especially after the temperature reaches above 15°C, the compressor alarm rate climbs quickly.

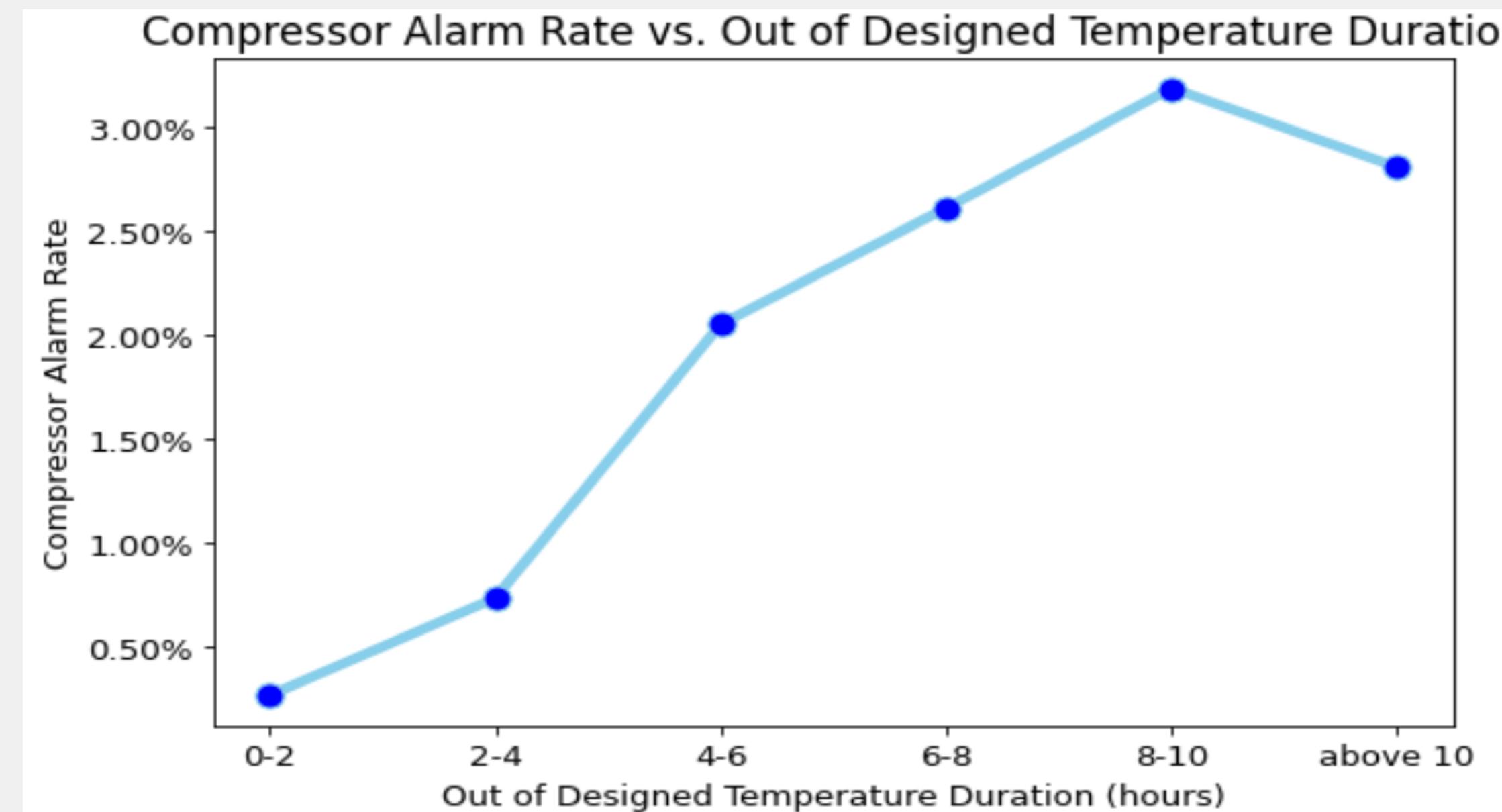


Failure Alarms Findings



Compressor Alarms Rate vs. Out of Designed Temperature Duration

- It seems that after total 4 hours of experiencing out of designed temperature, there is a big jump in the compressor alarm rate

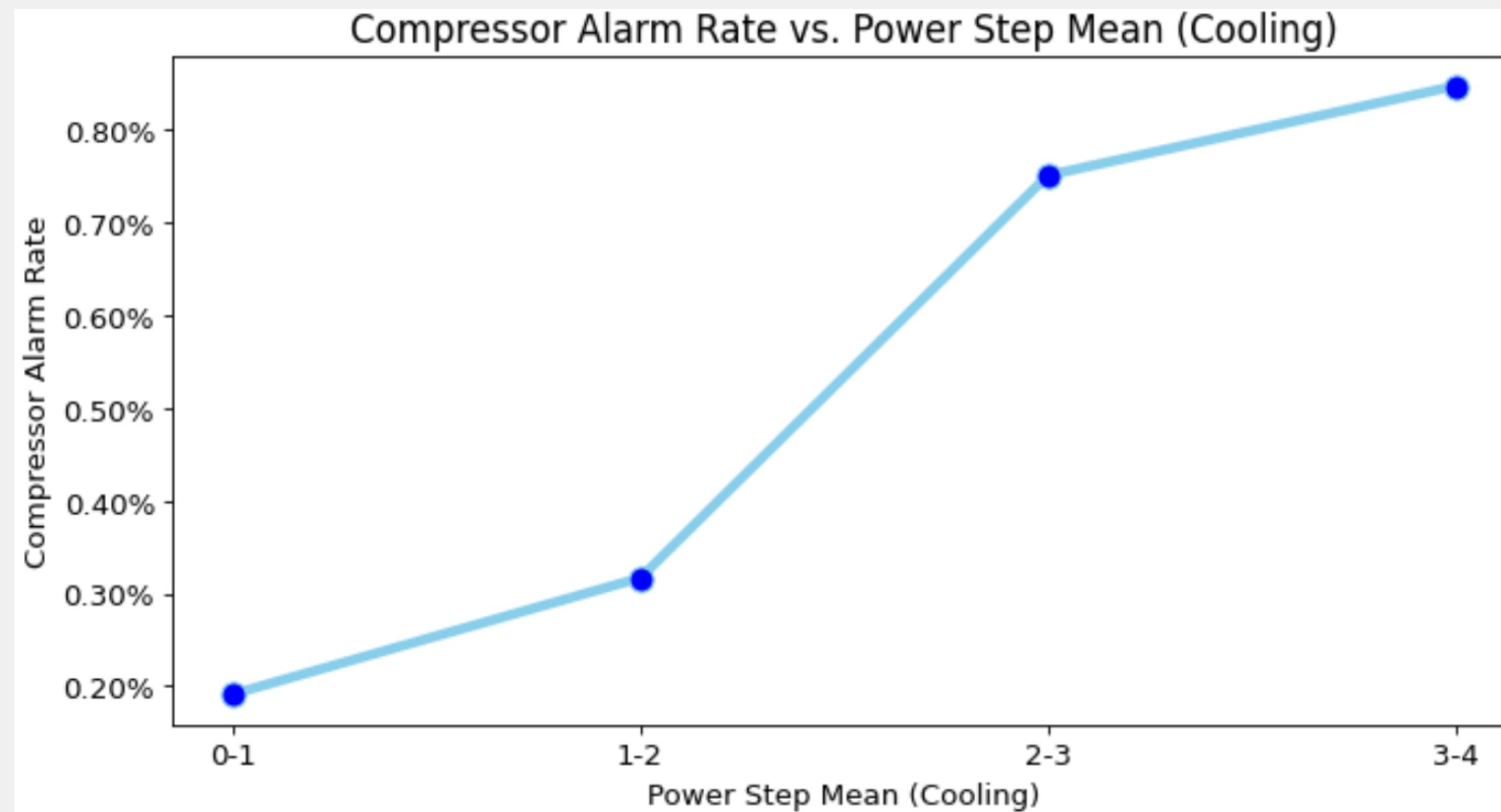


Failure Alarms Findings



Compressor Alarms Rate vs. Power Step Mean (Cooling)

- A critical value of power step mean of 2, after which there is a big jump in the compressor alarm rate, is observed

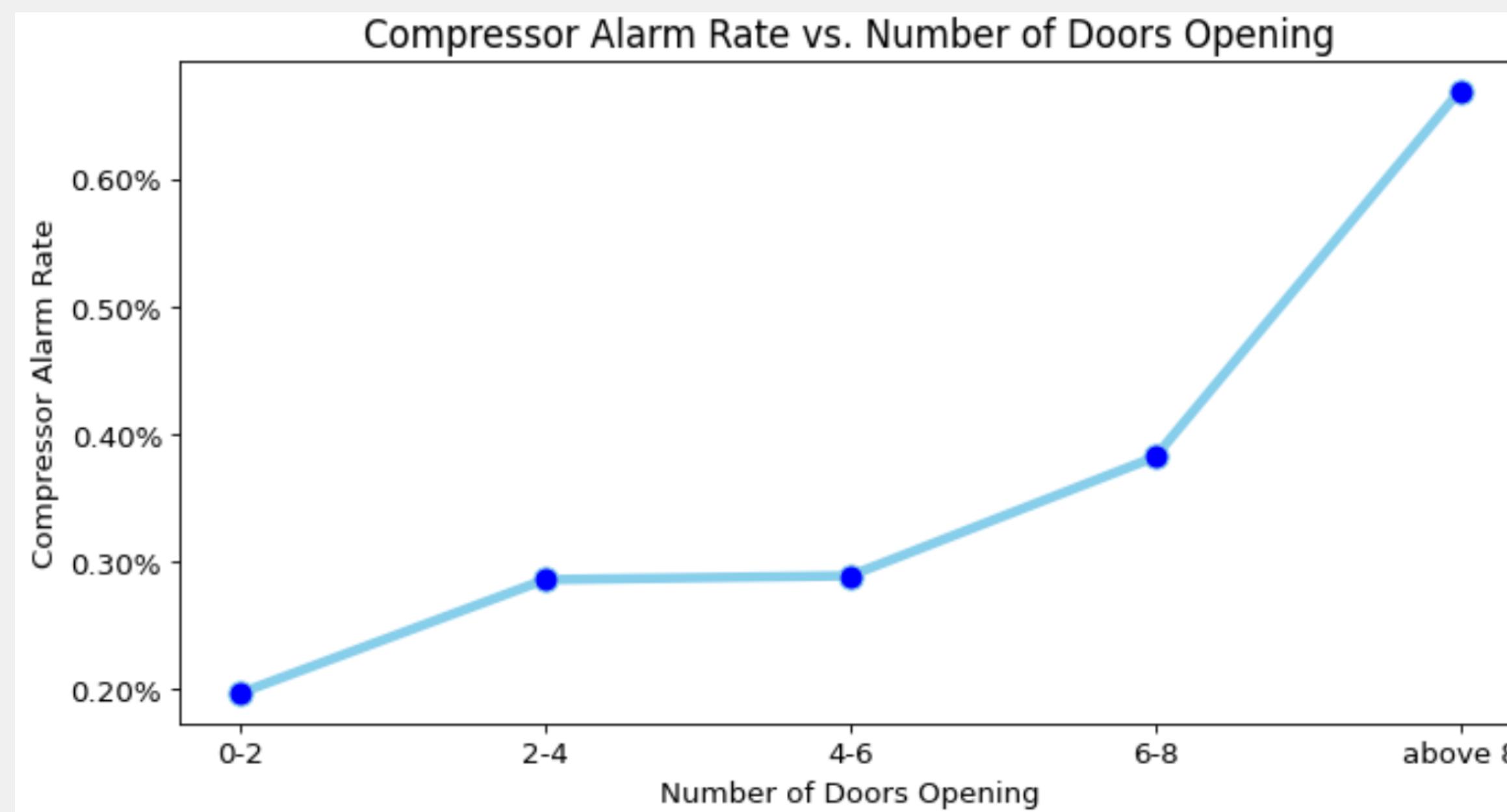


Failure Alarms Findings



Compressor Alarms Rate vs. Power Step Mean (Cooling)

- Especially after the number of door openings reaches 6 time or more, there is a big jump in the compressor alarm rate



Failure Alarms Findings



Heater Alarms vs. Season

- Heater alarms are more likely to occur in summer
- There is a significantly higher heater alarm rate of 0.2% in the summer.

Observed Value					
Season	Spring	Summer	Autum	Winter	Total
# of heater alarm	11	37	8	10	66
# of no heater alarm	16924	18738	19298	15783	70743
Total	16935	18775	19306	15793	70809

Ratio of heater alarm	0.06%	0.20%	0.04%	0.06%	0.09%
Ratio of no heater alarm	99.94%	99.80%	99.96%	99.94%	99.91%

Chi-squared Test
df
p_value

30.273 Critical Value (0.95)

3

7.815

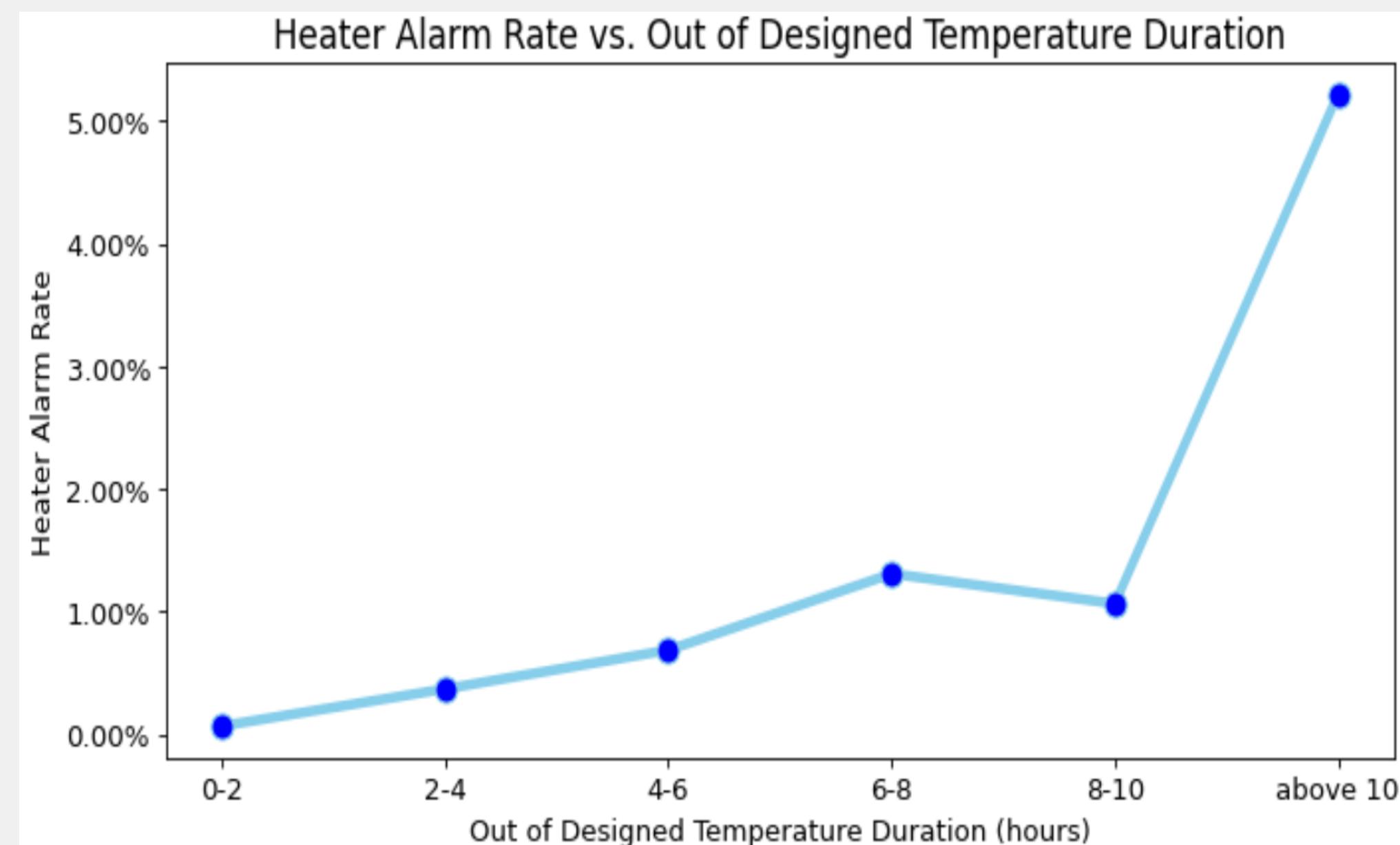
Expected Value					
Seasons	Spring	Summer	Autum	Winter	Total
# of heater alarm	16	17	18	15	66
# of no heater alarm	16919	18758	19288	15778	70743
Total	16935	18775	19306	15793	70809

Failure Alarms Findings



Heater Alarms vs. ODTD

- It seems that after total 10 hours of experiencing out of designed temperature, there is a big jump in the heater alarm rate

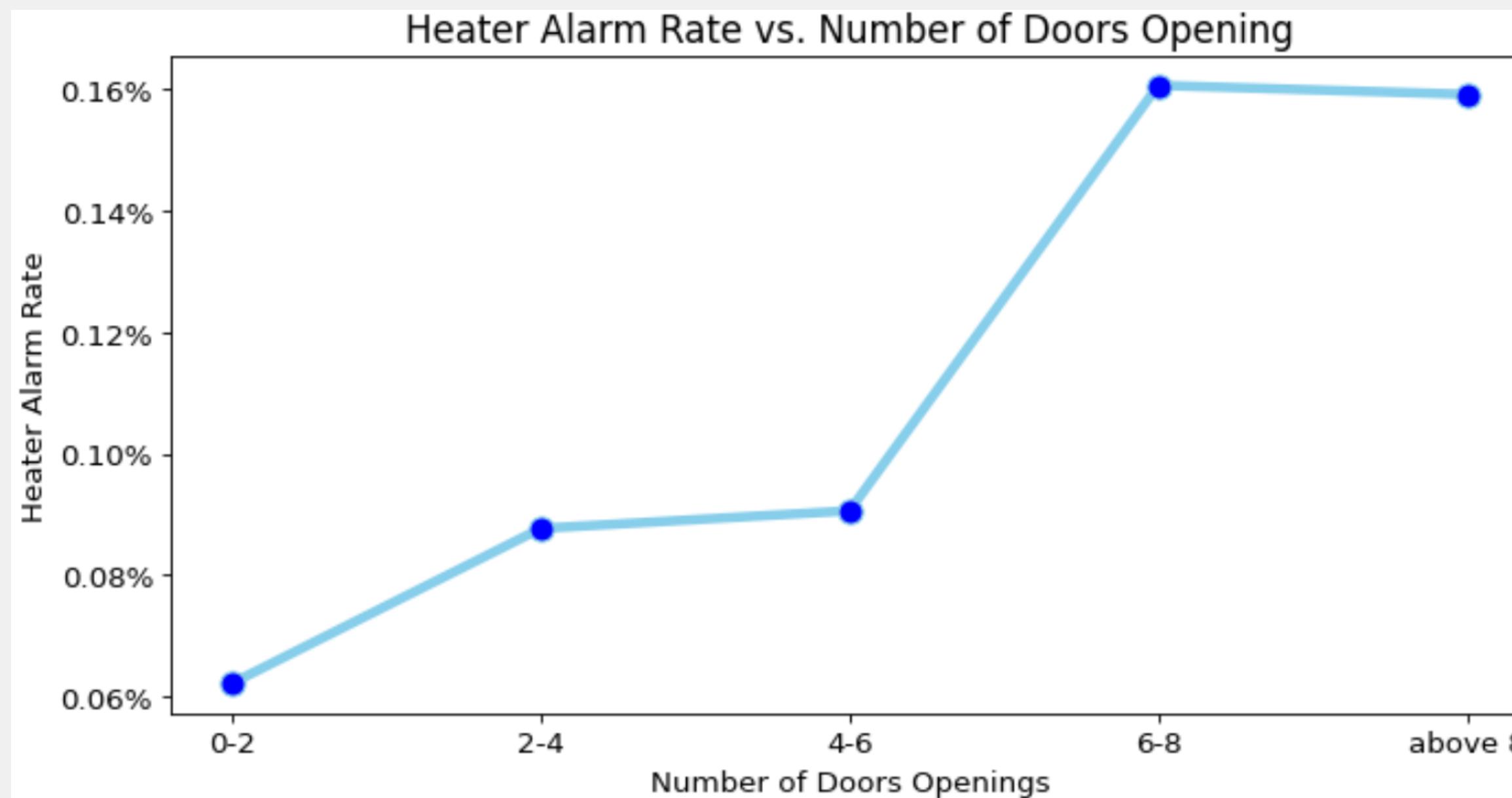


Failure Alarms Findings



Heater Alarms vs. Number of Door Openings

- As the number of door openings increases, the heater alarm rate tends to climb, and when the number of door openings pass 4, there is big jump of the heater alarm rate

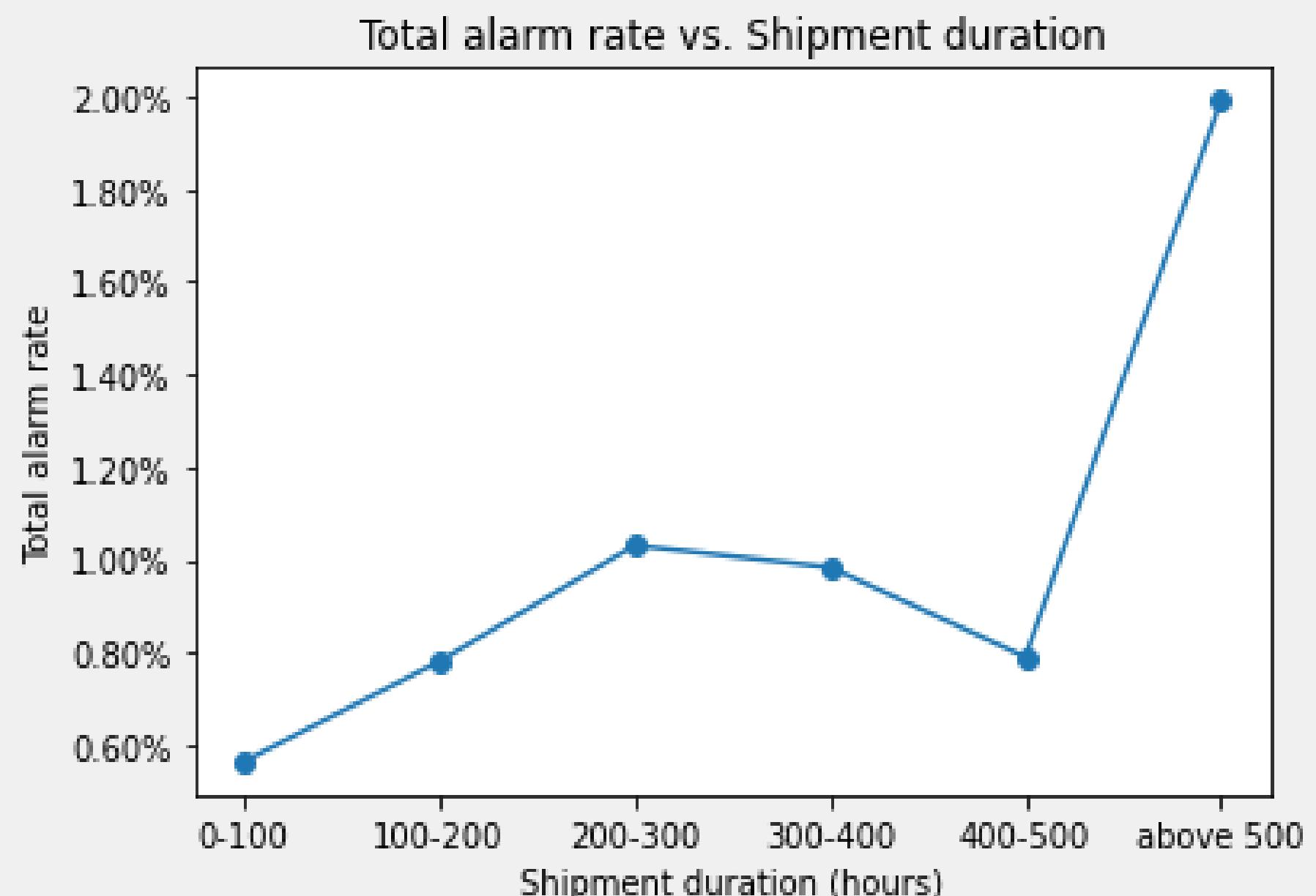


Failure Alarms Findings



Total Failure Alarms vs. Shipment Duration

- The longer the shipment duration is, the higher the compressor total alarm rate is especially after the shipment duration is above 500 hours.

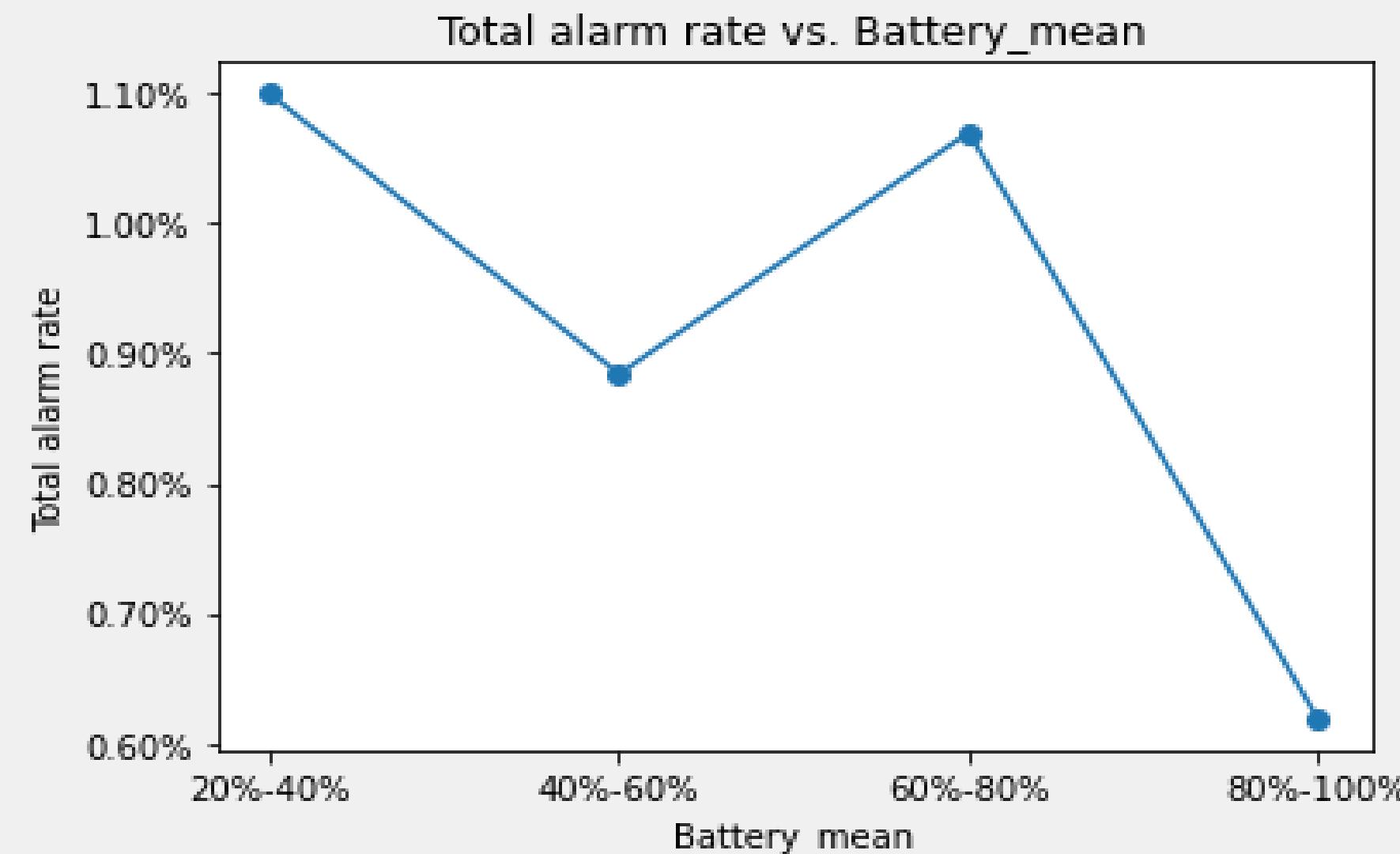


Failure Alarms Findings



Total Failure Alarms vs. Battery Level

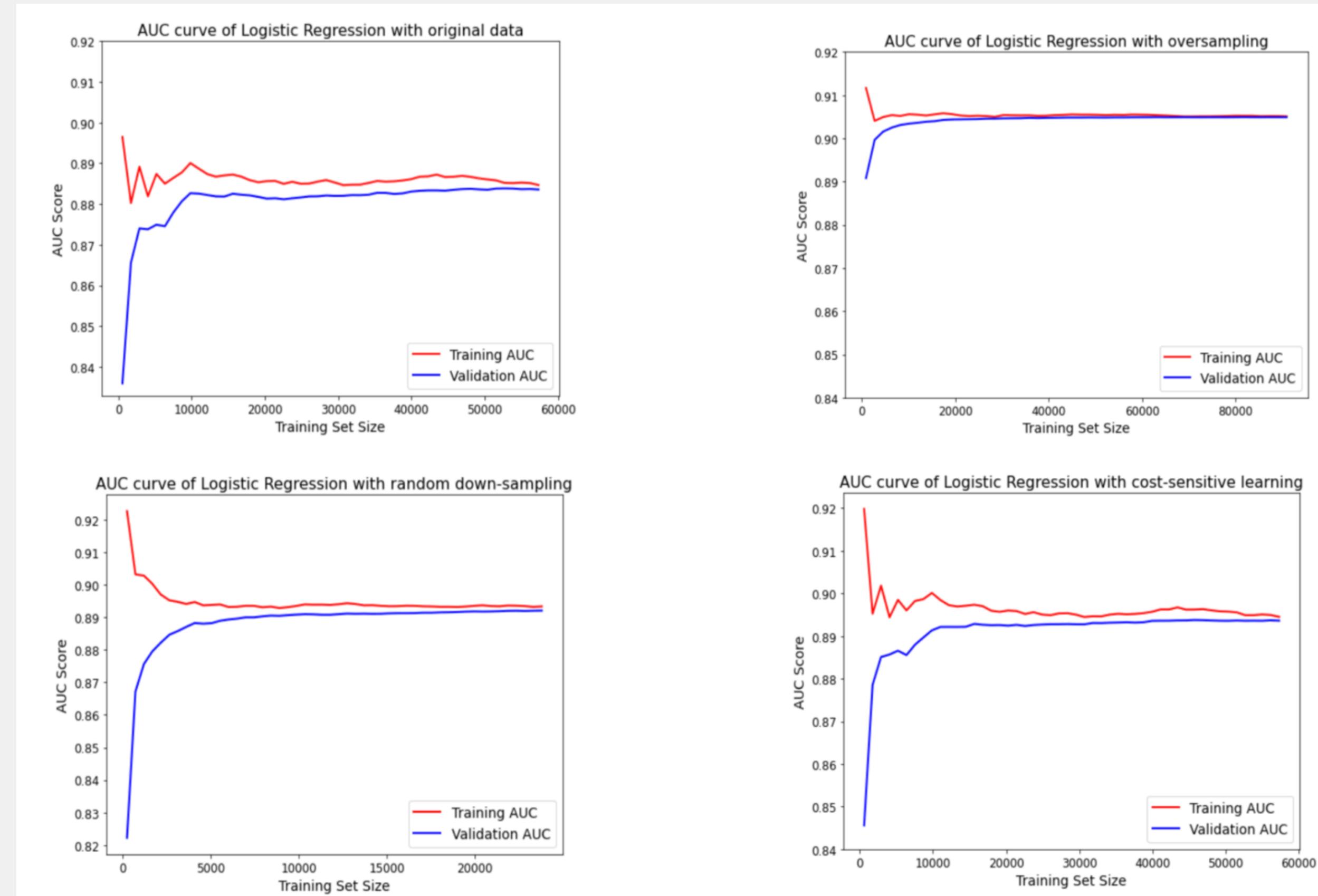
- Total alarm rate tends decreases as the battery increases
- Maintaining a high battery level throughout the shipments can help to decrease total parts failure alarms rate



Predictive Model Findings



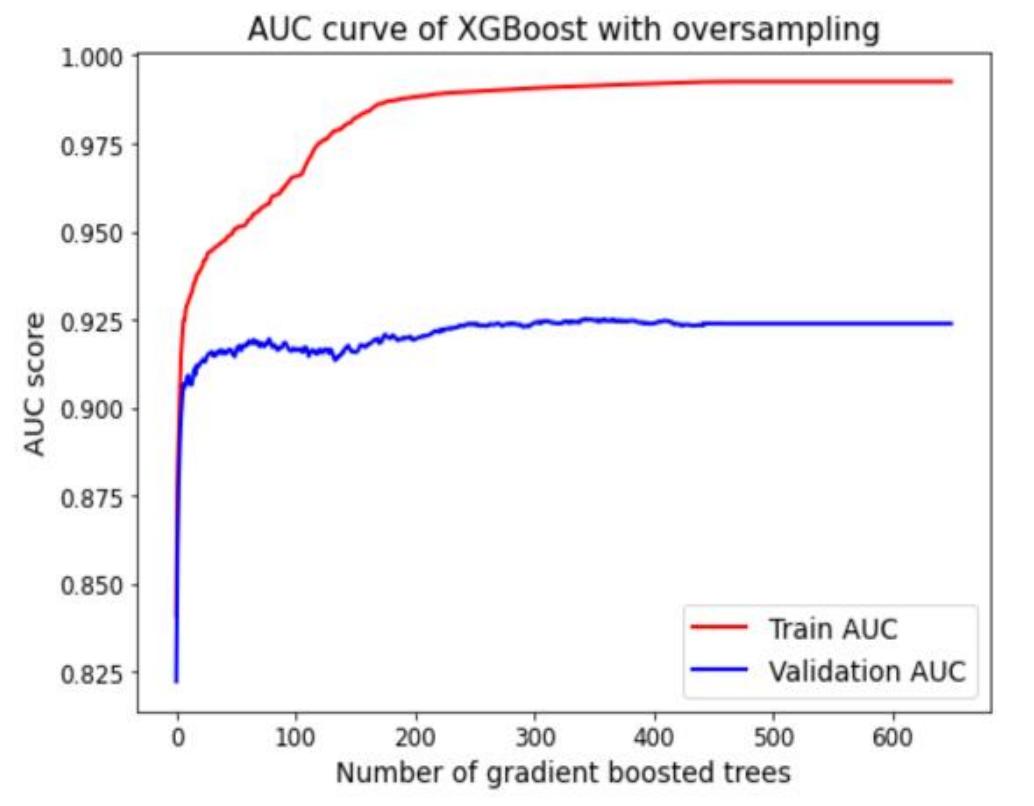
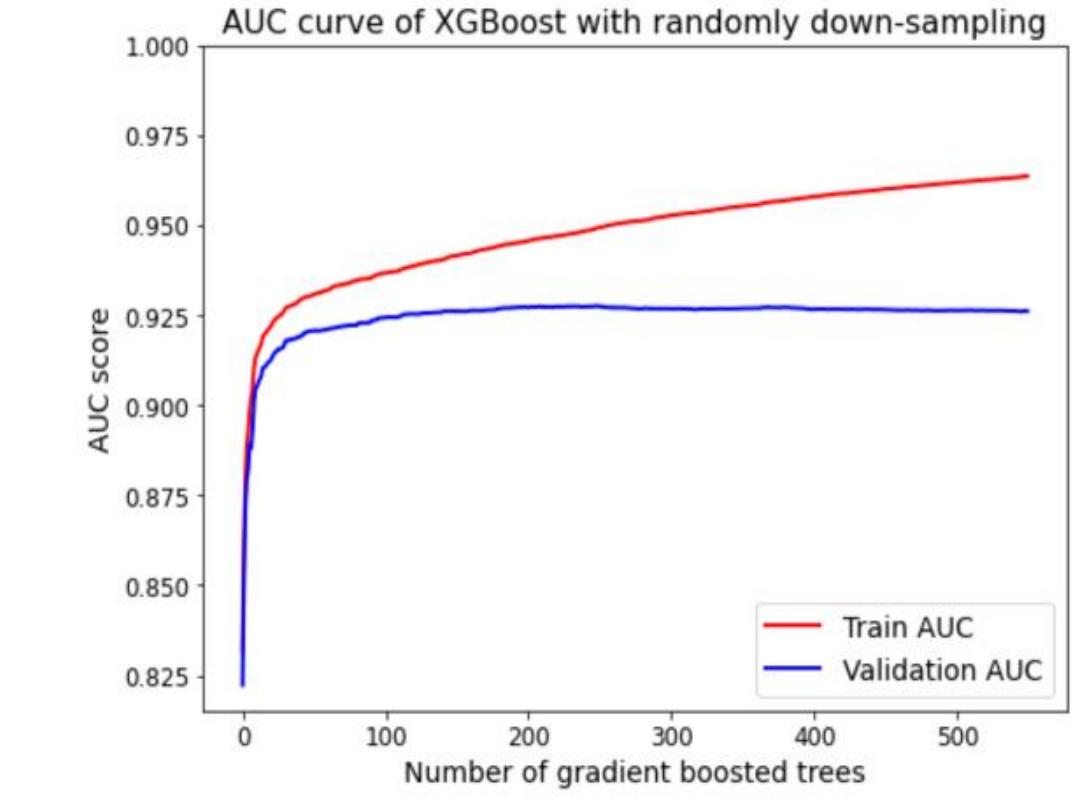
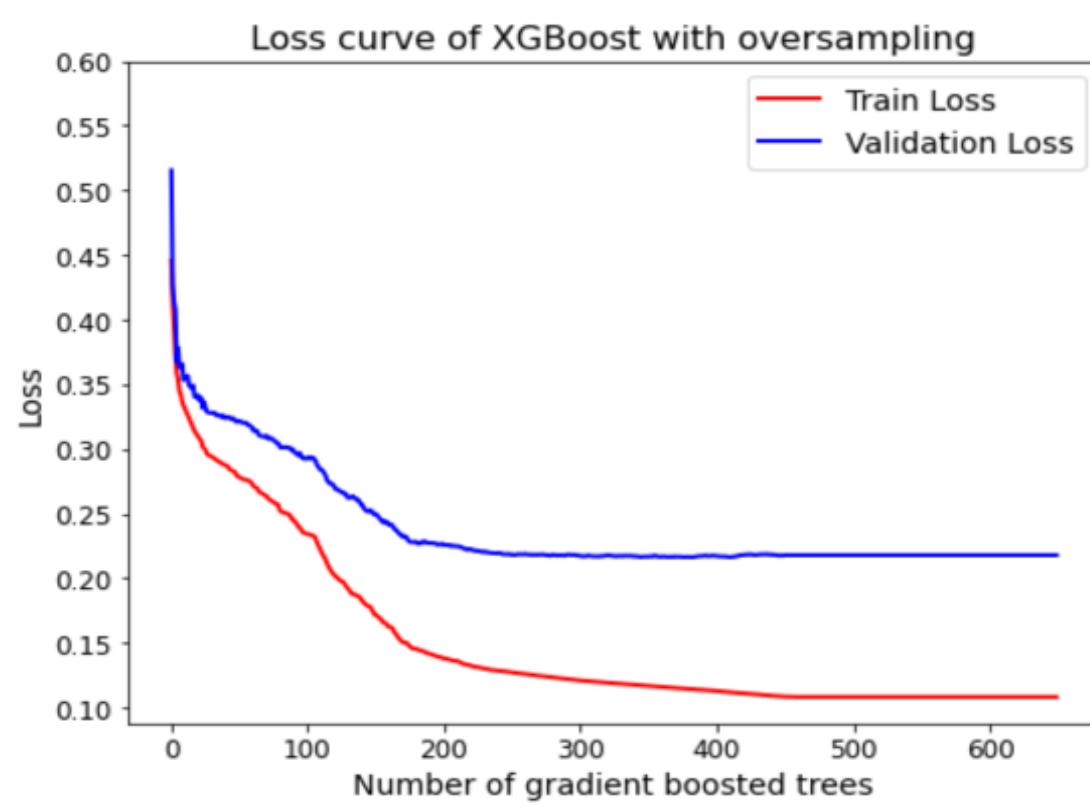
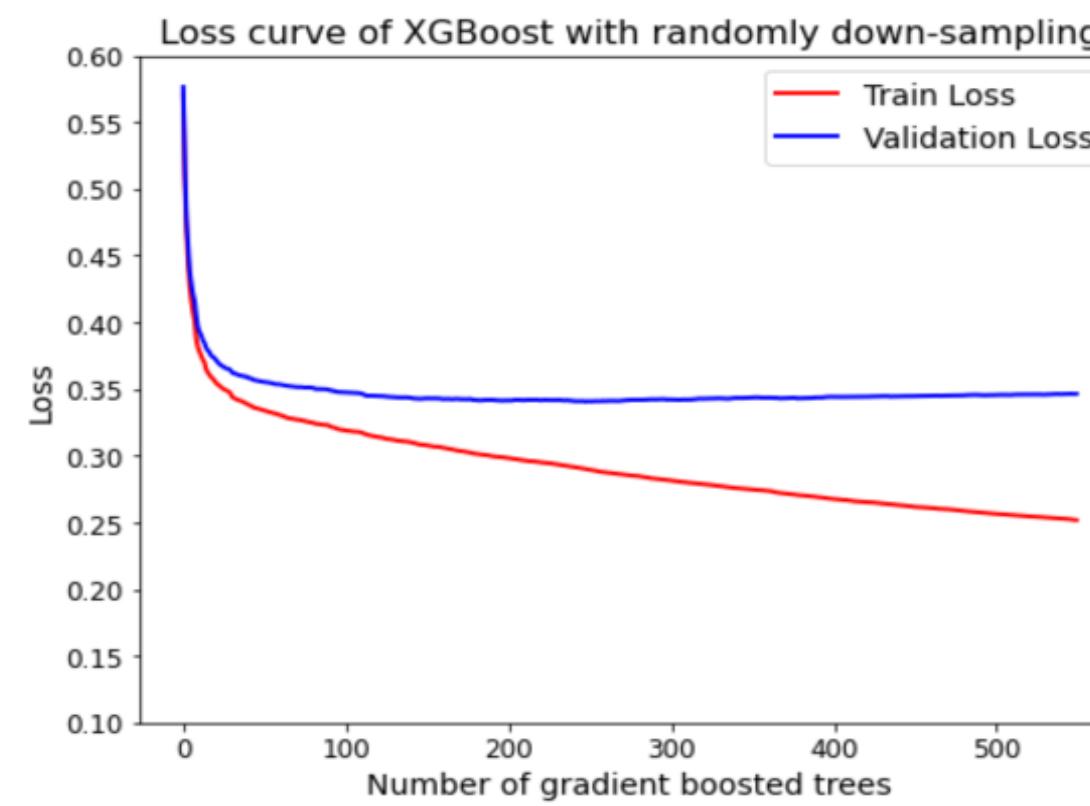
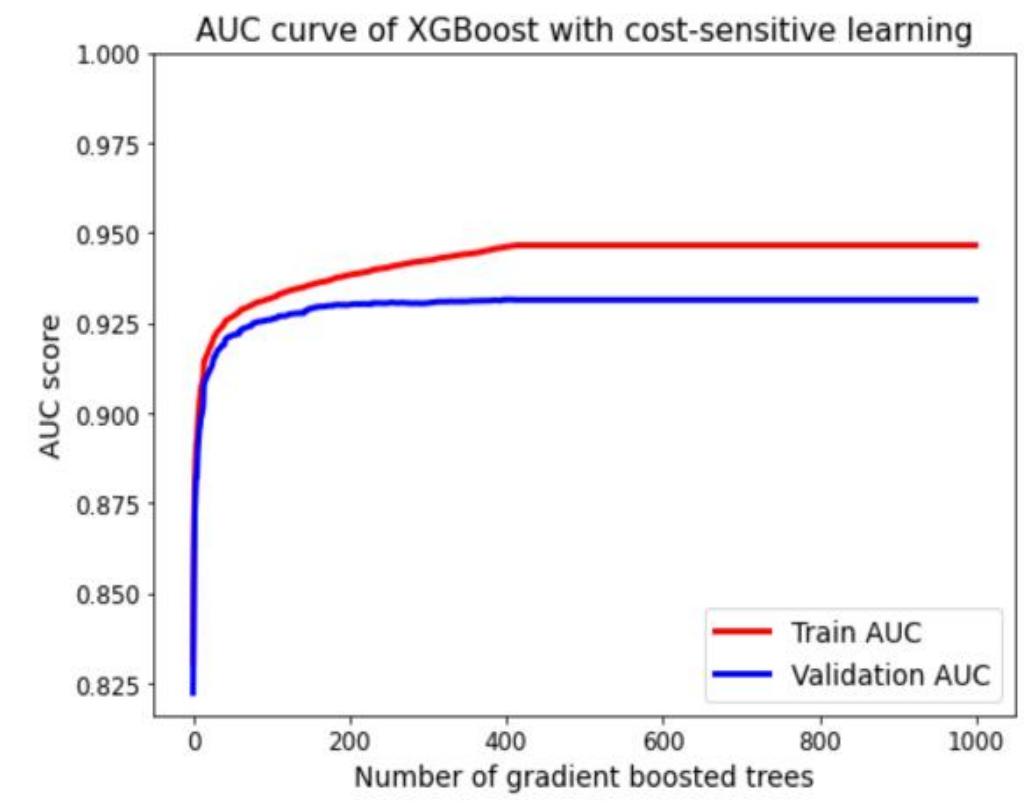
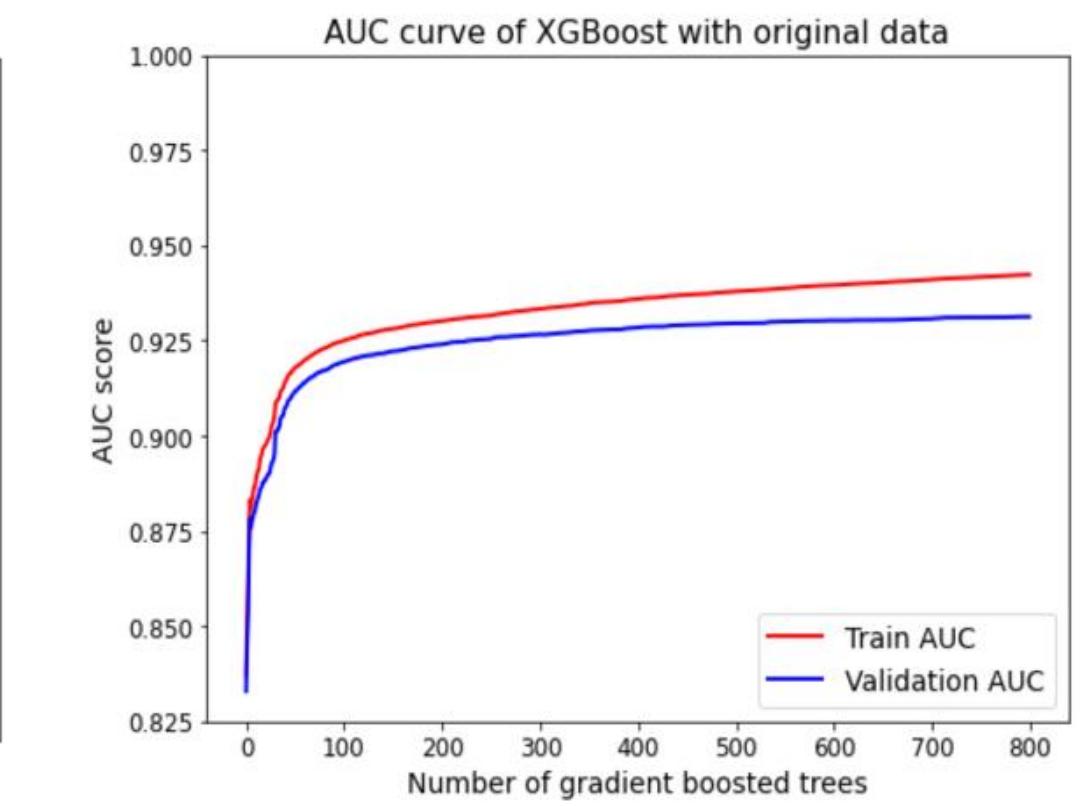
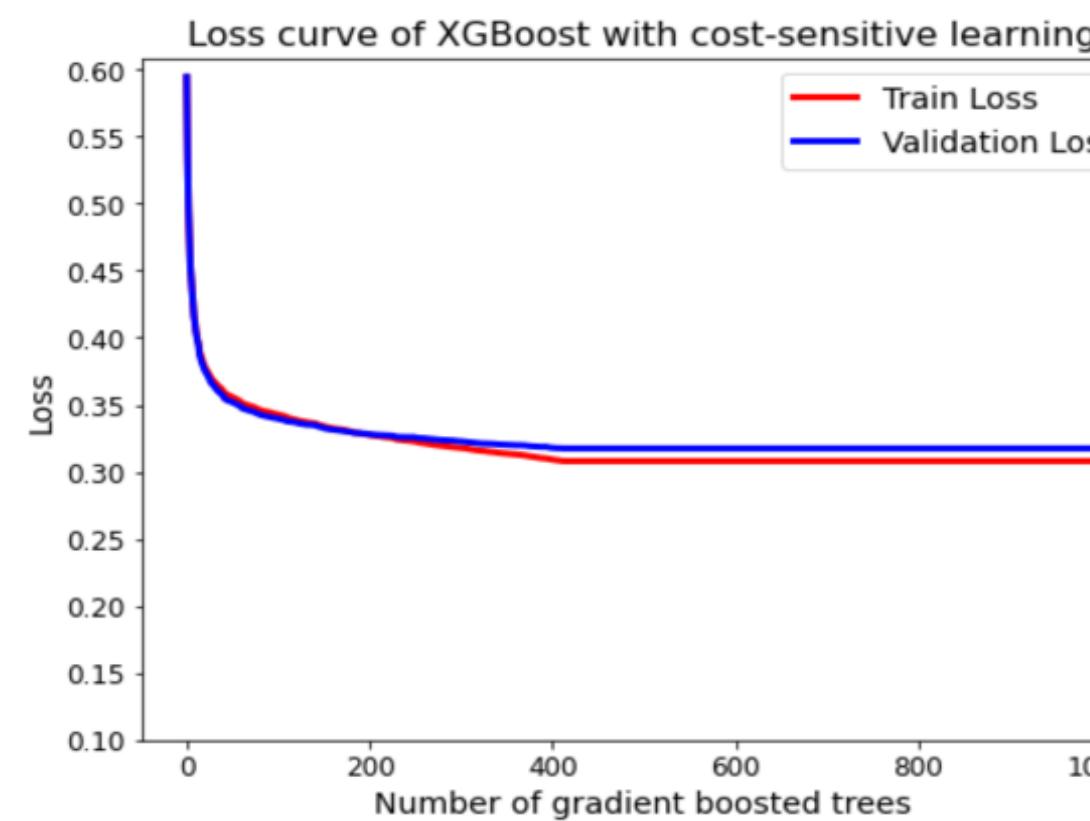
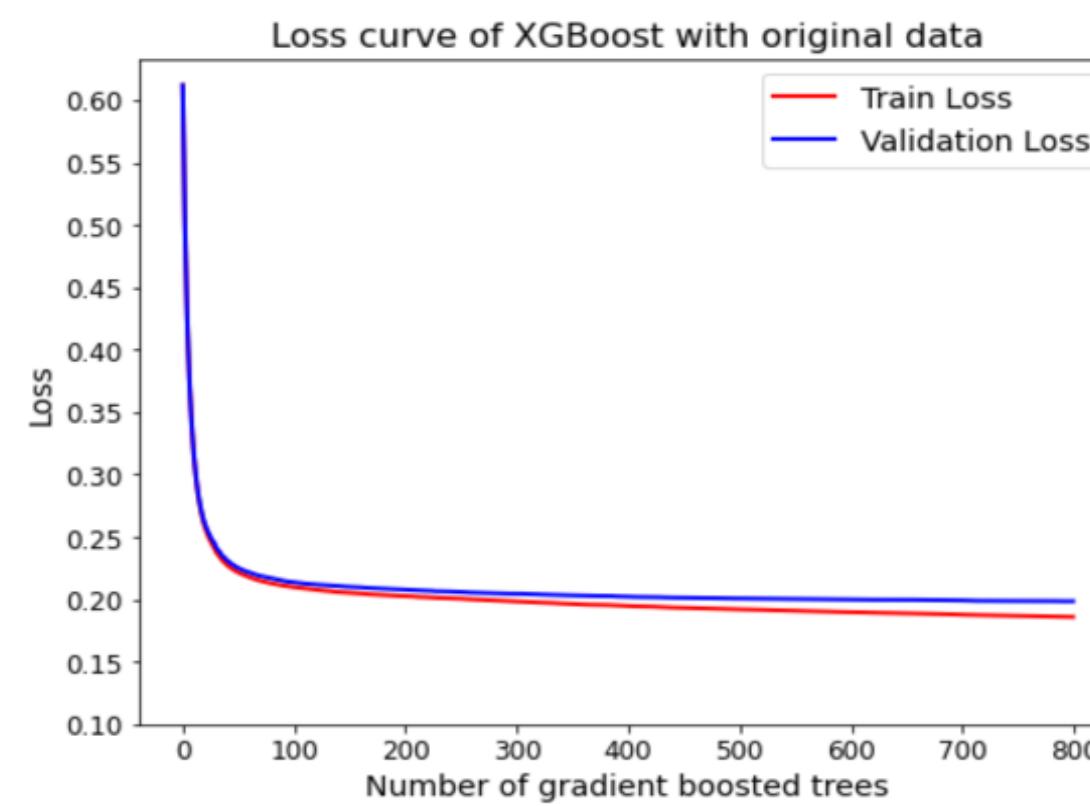
Training and Validation AUC Score Progression of Logistic Regressions



Predictive Model Findings



Training and Validation Loss and AUC Score Progression of XGBoost



Predictive Model Findings



Training and Validation Loss and AUC Score Progression of ANN

