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Process Description

1. In the manufacture of aerospace structures, a common method is to use a process called co-curing to create honeycomb sandwich structures. This involves **bonding partially cured thermoset prepreg sheets** (a material made up of fibers impregnated with a resin) **with an adhesive layer to either side of a honeycomb core structure**. This is done under a specific pressure and temperature cycle. However, there are often defects in the final product due to the complex nature of this process.
2. One of the key stages in this process is called consolidation. This involves **applying pressure and heat to the fiber preforms and uncured liquid resin to eliminate any voids or spaces before the resin solidifies**. This process involves first filling the voids and compressing the reinforcement, aided by heat which reduces the viscosity of the resin. Then, the resin cures and solidifies.
3. However, during co-curing, **defects can form in the adhesive bond-line** (the area where the adhesive meets the honeycomb core). These include things like porosity (presence of tiny holes or voids) and poorly formed adhesive fillets (the curved junction where the adhesive meets the honeycomb core). There is a strong relationship between these defects and the materials used, the geometry of the part, and the process parameters.
4. To better understand and reduce these defects, researchers have created analysis tools and comprehensive models to simulate the process and track the formation of defects. These tools take into account factors like material properties, the pressure and temperature cycle, and the evolution of core pressure. The outputs can help in understanding and improving the manufacturing process.
5. With the help of these models, researchers are able to better understand the bond-line porosity. By understanding how the fillet shape affects the escape of bubbles from the bond-line and the gelation time of the adhesive and resin, they can predict and reduce the final porosity.
6. Other research utilizes an in situ visualization method that allows for direct observation of the co-cure process in real-time and under realistic conditions. This method can provide insights into the complex physics of the co-cure process and help troubleshoot issues, reducing the amount of trial-and-error typically involved in the process.

Problem Statement:

(i) *find the <u>governing process parameters</u> in each phenomenon.*
(ii) *<u>understand the interactions</u> of different phenomena in the co-cure process.*
(iii) *build a tool, based on the provided data, to <u>design new cure cycles</u> and to <u>predict the facesheet consolidation level and bond-line porosity</u> of the co-cured sandwich structure.*
(iv) *implement an optimization model in the tool to find the best cure cycle for your assumed objective function. The objective function must include <u>at least two</u> of the following parameters: (a) Facesheet consolidation level (b) Bond-line porosity (c) Total time of the cure cycle (Including more parameters in the objective function is a plus). In other words, you must introduce a cure cycle that contain the highest possible consolidation level and lowest bond-line porosity in the shortest cure cycle.*

Basic Exploratory Data Analysis

Input Parameters:	Output
Cycle Number	AD. Porosity (%)
Heat Rate 1 [C/min]	PR. Porosity (%)
Ramp 1 Duration [min]	Eff. Porosity (%)
Temperature Dwell 1 [min]	Max (Fiber Volume Fraction) (%)
Heat Rate 2 [C/min]	Cure Cycle Total Time [min]
Ramp 2 Duration [min]	AD. Volume [m^3]
Temperature Dwell 2 [min]	PR. Volume [m^3]
Vacuum Pressure (*Patm) [Pa]	
Vacuum Start Time [min]	
Vacuum Duration [min]	
Autoclave Pressure (*Patm) [Pa]	
Autoclave Start Time [min]	
Autoclave Duration [min]	

Description:

1. **Cycle Number**: The number of cycles through which the co-curing process has been performed. In this context, a cycle would refer to the complete sequence of heating, pressurizing, and cooling the prepreg material.
2. **AD. Porosity (%)**: The percentage of porosity in the adhesive bond-line, likely determined through some form of testing or modeling.
3. **Heat Rate 1 [C/min]**: The rate at which the temperature is increased during the first heating stage (ramp 1) of the cycle, measured in degrees Celsius per minute.
4. **PR. Porosity (%)**: The percentage of porosity in the prepreg (PR) material, likely determined through testing or modeling.
5. **Ramp 1 Duration [min]**: The time duration for which the first heating stage (ramp 1) is applied.
6. **Eff. Porosity (%)**: Effective porosity is the proportion of void space that contributes to fluid flow.
7. **Temperature Dwell 1 [min]**: The amount of time the system is held at a specific temperature after the first heating stage.
8. **Max (Fiber Volume Fraction) (%)**: The maximum percentage of the volume of the composite that is made up of fiber material.
9. **Heat Rate 2 [C/min]**: The rate at which the temperature is increased during the second heating stage (ramp 2) of the cycle, measured in degrees Celsius per minute.
10. **Cure Cycle Total Time [min]**: The total duration of the curing cycle, including all stages of heating, pressurizing, and cooling.
11. **Ramp 2 Duration [min]**: The time duration for which the second heating stage (ramp 2) is applied.
12. **AD. Volume [m^3]**: The total volume of adhesive used in the process.
13. **Temperature Dwell 2 [min]**: The amount of time the system is held at a specific temperature after the second heating stage.
14. **PR. Volume [m^3]**: The total volume of the prepreg material used in the process.

15. **Vacuum Pressure (*Patm) [Pa]**: The pressure applied to the system when a vacuum is created, measured in Pascals. The vacuum helps to compress the materials and remove voids or spaces.
16. **Vacuum Start Time [min]**: The time at which the vacuum pressure is applied.
17. **Vacuum Duration [min]**: The duration for which the vacuum pressure is applied.
18. **Autoclave Pressure (*Patm) [Pa]**: The pressure applied inside the autoclave, which is typically greater than atmospheric pressure, measured in Pascals.
19. **Autoclave Start Time [min]**: The time at which the autoclave pressure is applied.
20. **Autoclave Duration [min]**: The duration for which the autoclave pressure is applied.

Descriptive Statistics

	count	min	mean	median	max
cycle_number	1,770.0	1.0	899.9	897.5	1,800.0
heat_rate_1_c_min	1,770.0	1.0	2.3	2.0	4.0
ramp_1_duration_min	1,770.0	22.5	59.4	80.0	90.0
temperature_dwell_1_min	1,770.0	60.0	75.0	60.0	120.0
ramp_2_duration_min	1,770.0	-	29.3	16.8	67.0
vacuum_pressure_patm_pa	1,770.0	0.0	0.3	0.1	1.0
vacuum_start_time_min	1,770.0	1.0	40.3	40.0	80.0
vacuum_duration_min	1,770.0	120.0	213.5	199.3	336.0
autoclave_pressure_patm_pa	1,770.0	2.0	3.0	3.0	4.0
autoclave_start_time_min	1,770.0	1.0	40.1	40.0	80.0
autoclave_duration_min	1,770.0	120.0	213.6	199.3	336.0
ad_porosity_percent	1,770.0	-	44.2	65.0	88.6
pr_porosity_percent	1,770.0	-	59.5	85.9	98.1
eff_porosity_percent	1,770.0	-	47.1	65.0	89.8
max_fiber_volume_fraction_percent	1,770.0	55.9	57.4	57.6	58.6
cure_cycle_total_time_min	1,770.0	200.0	253.7	219.3	337.0
ad_volume	1,770.0	0.0	0.0	0.0	0.0
pr_volume	1,770.0	0.0	0.0	0.0	0.0

- Each variable is closely knit, there does not seem to be any specific skewness in any variable
- The mean porosity values for both adhesive and prepreg materials (AD. Porosity (%) and PR. Porosity (%)) are high, around 44.2% and 59.5% respectively. This indicates that porosity is a significant issue.
- The maximum fiber volume fraction (Max Fiber Volume Fraction % remains consistent, with a mean value around 57.4% indicating that the fiber composition is stable across different cycles.

Correlation Plots

Correlation between independent variables

			Pearson's correlation	Spearman's Coefficient	Description
1	ramp_2_duration_min	autoclave_duration_min	0.876487	0.80774	Positive relation
2	vacuum_duration_min	autoclave_duration_min	0.778976		Positive relation
3	cycle_number	ramp_1_duration_min	-0.869573		Negative Relation
4	heat_rate_1_c_min	ramp_1_duration_min	-0.885846		Negative Relation
5	temperature_dwell_1_min	ramp_2_duration_min		-0.774891	Negative Relation
6	cycle_number	temperature_dwell_1_min	-0.749606		Negative Relation
7	ramp_2_duration_min	vacuum_duration_min	0.87604		Positive relation

- As number of cycles increase, ramp 1 duration decreases dwell time after 1st ramp decreases
- Higher the heat rate, lower the ramp duration (for 1st ramp)
- Higher the duration of dwell time after first ramp, shorter the duration of second ramp

Correlation with dependent variables

			Pearson's correlation	Spearman's Coefficient	Description
1	ramp_2_duration_min	cure_cycle_total_time_min	0.992743		Positive relation
2	autoclave_duration_min	cure_cycle_total_time_min	0.882746		Positive relation
3	vacuum_duration_min	cure_cycle_total_time_min	0.882375		Positive relation
4	temperature_dwell_1_min	cure_cycle_total_time_min		-0.774891	Negative Relation
5	ad_porosity_percent	eff_porosity_percent	0.990689		Positive relation
6	pr_porosity_percent	eff_porosity_percent		0.70787	Positive relation
7	autoclave_pressure_patm_pa	max_fiber_volume_fraction_percent	0.919051		Positive relation

- Adhesive, Prepreg and effective porosity are highly correlated to each other
- Largest the autoclave pressure, higher the maximum fiber volume fraction

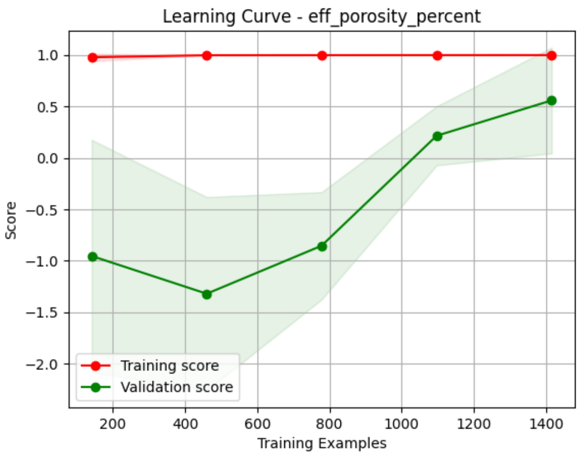
Modelling

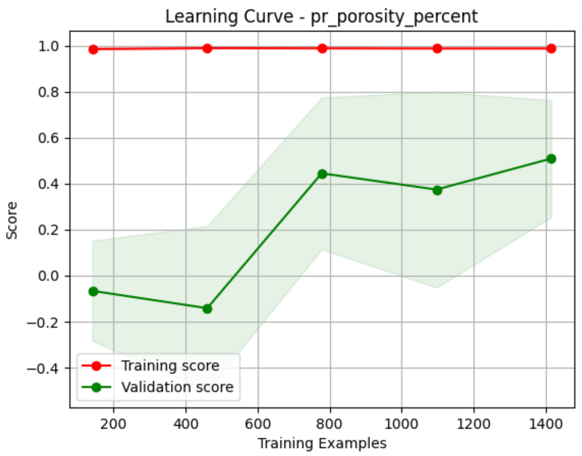
Model Selection:

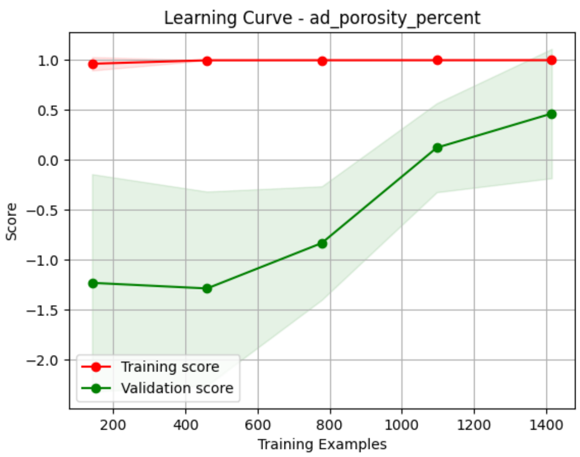
Model Name	Score	Comments
Linear Regression	0.744560973	Average
Polynomial Regression	0.825193668	Good
Ridge Regression	0.742110803	Average
Lasso Regression	0.376339799	Bad
SVR	0.447117742	Bad
Random Forest	0.979043532	Excellent
XGBoost	0.975781875	Excellent

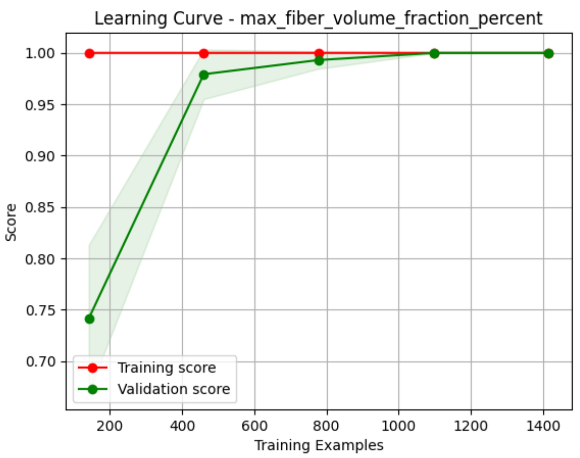
We choose the Random Forest model

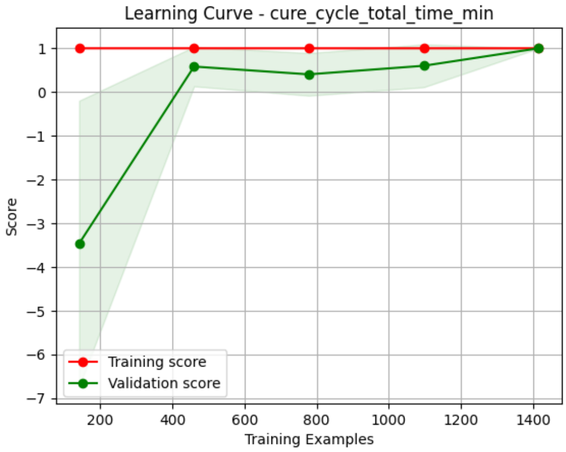
Model Training:







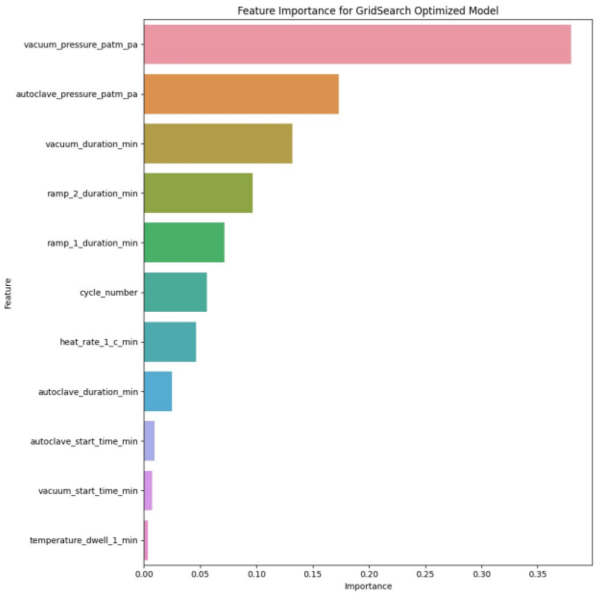


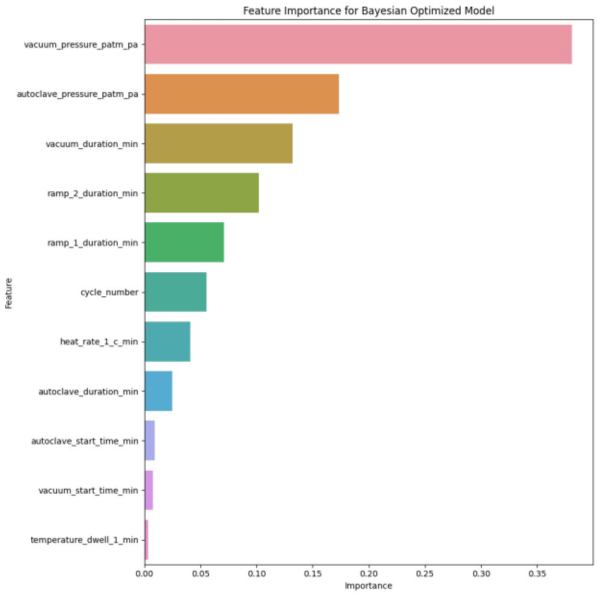


We note that the validation curves have not got time to saturate. This arises in two cases, when the data does not have enough predictive power and when there is not sufficient data for the model to identify patterns. I strongly suspect it is the latter because we are seeing improvement in validation scores as the number of training examples increases

Feature importance:

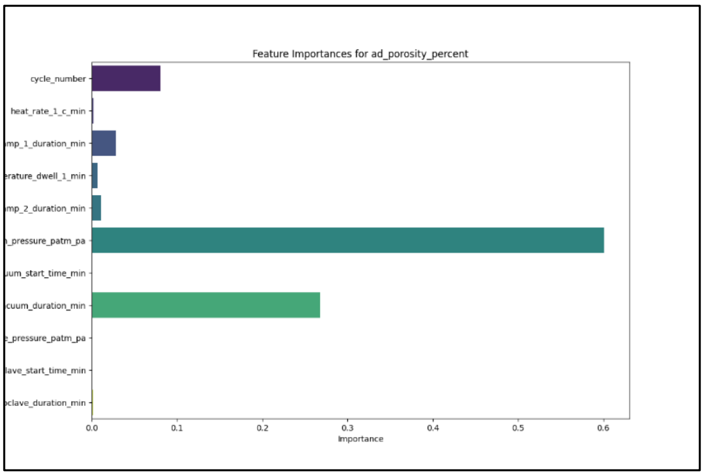
The contribution of each feature to the prediction of the output

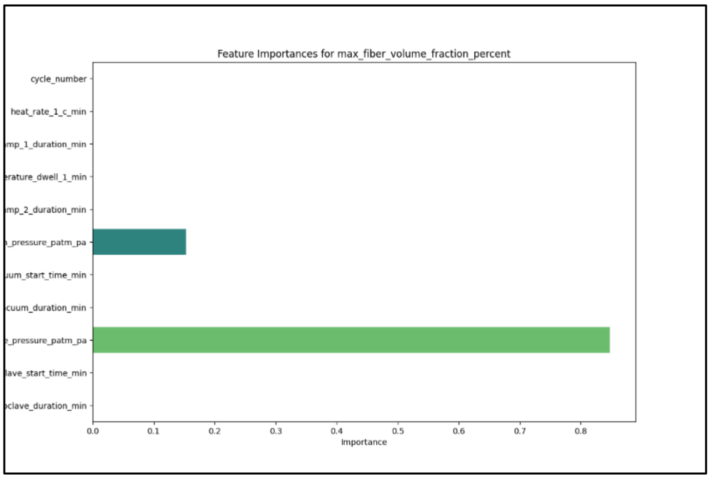


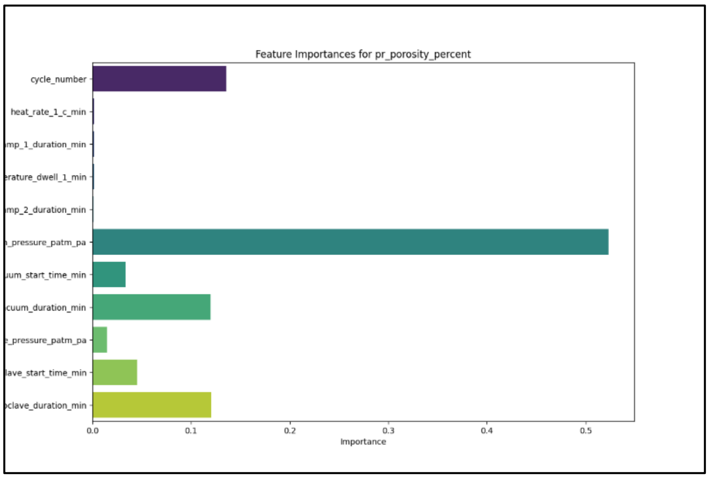


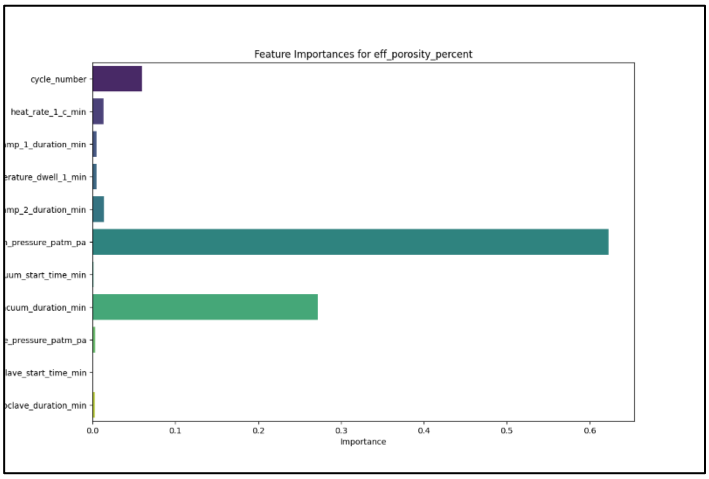
Feature importance show that pressure is the most dominating factor while predicting the values of the facesheet consolidation level and bond-line porosity.

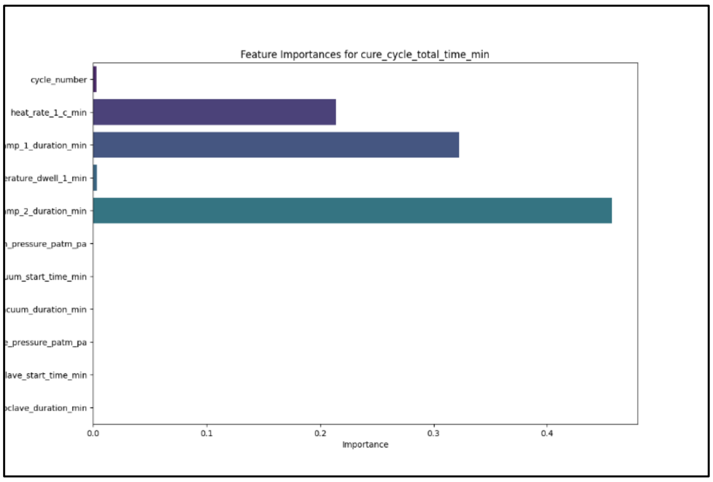
To understand in more detail, Following are the plots for each output





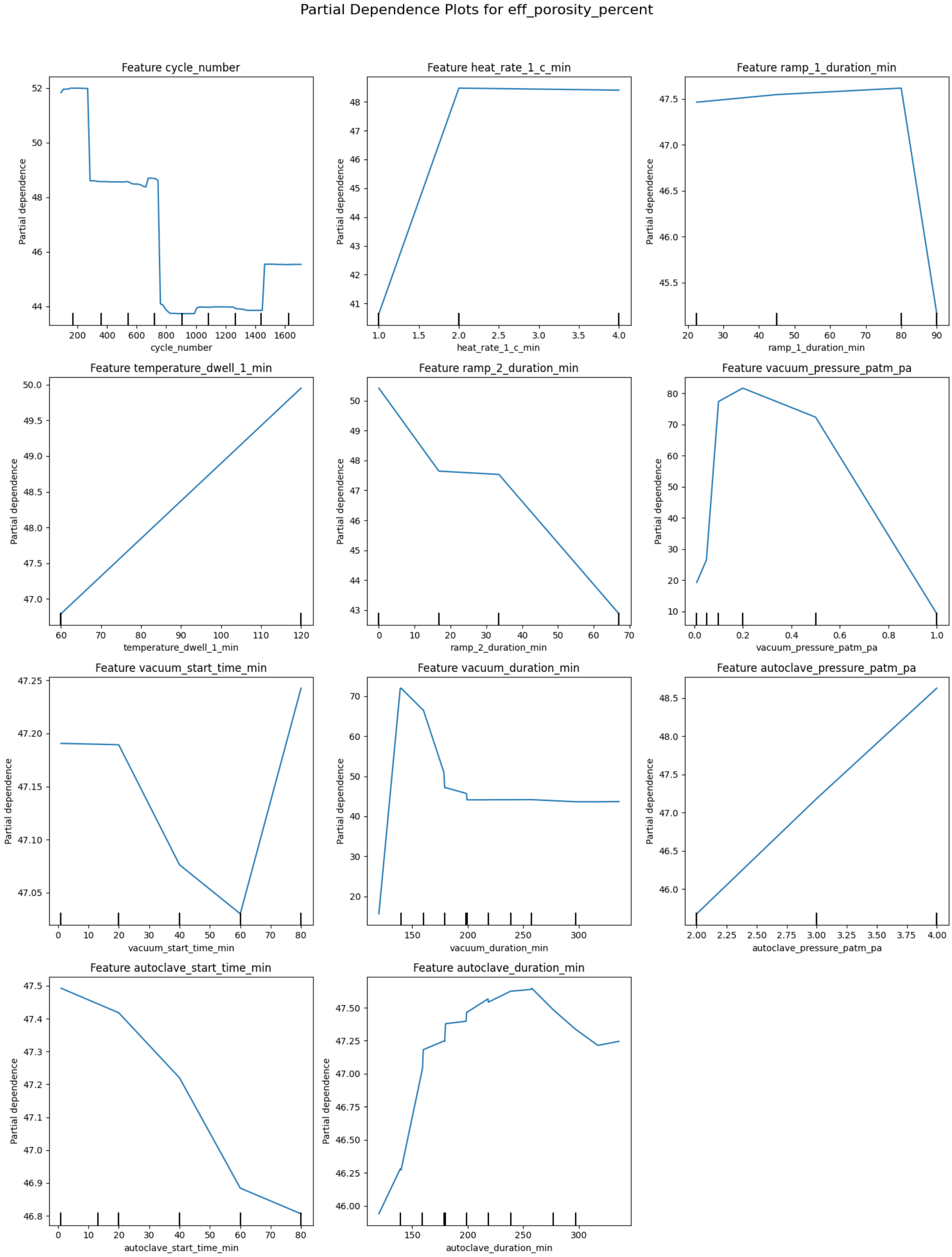


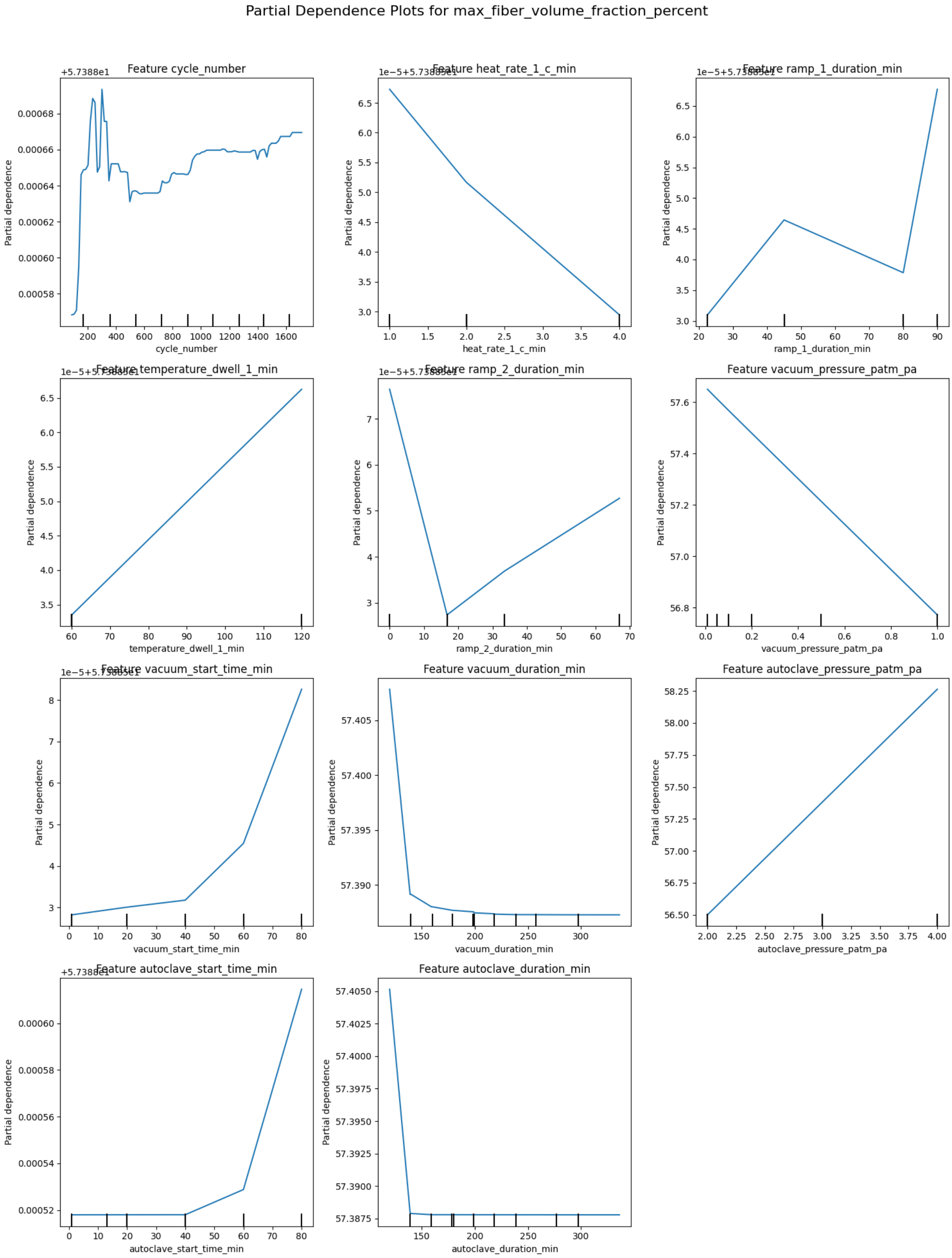




Output	**Most Important Features**
Adhesive Porosity	1) Vacuum pressure 2) Vacuum duration 3) Cycle Number
Prepreg Porosity	1) Vacuum Pressure 2) Vacuum Duration 3) Autoclave Duration
Effective Porosity	1) Vacuum pressure 2) Vacuum duration 3) Cycle Number
Max fiber volume	1) Autoclave Pressure 2) Vacuum Pressure
Cure cycle total time	1) Ramp 2 duration 2) Ramp 1 duration 3) Heat rate 1

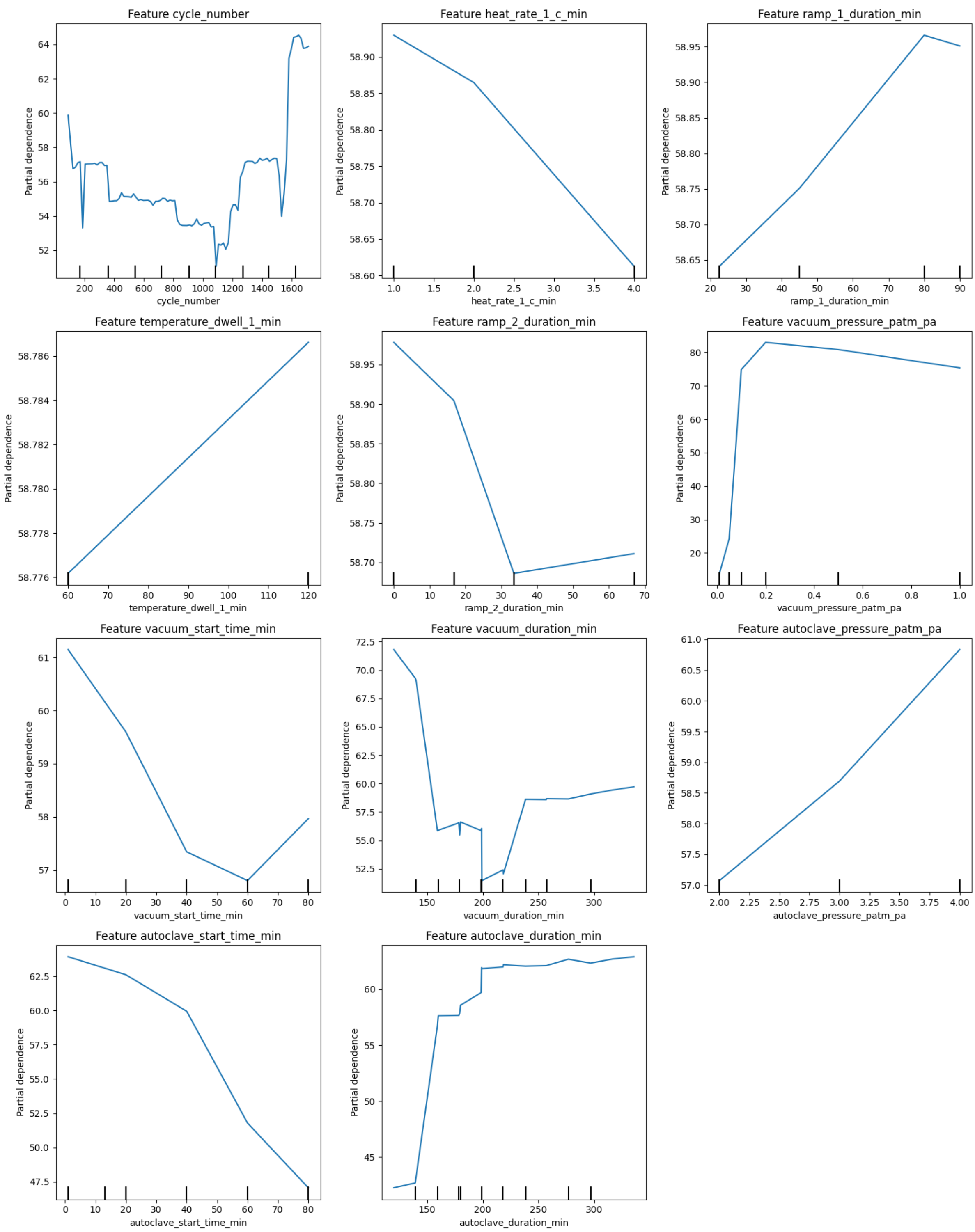
Following are the partial dependence plots for each of output variable:
Partial dependence plots in Python are visualizations that help understand how changing one variable affects the outcome of a model, while keeping all other variables fixed.

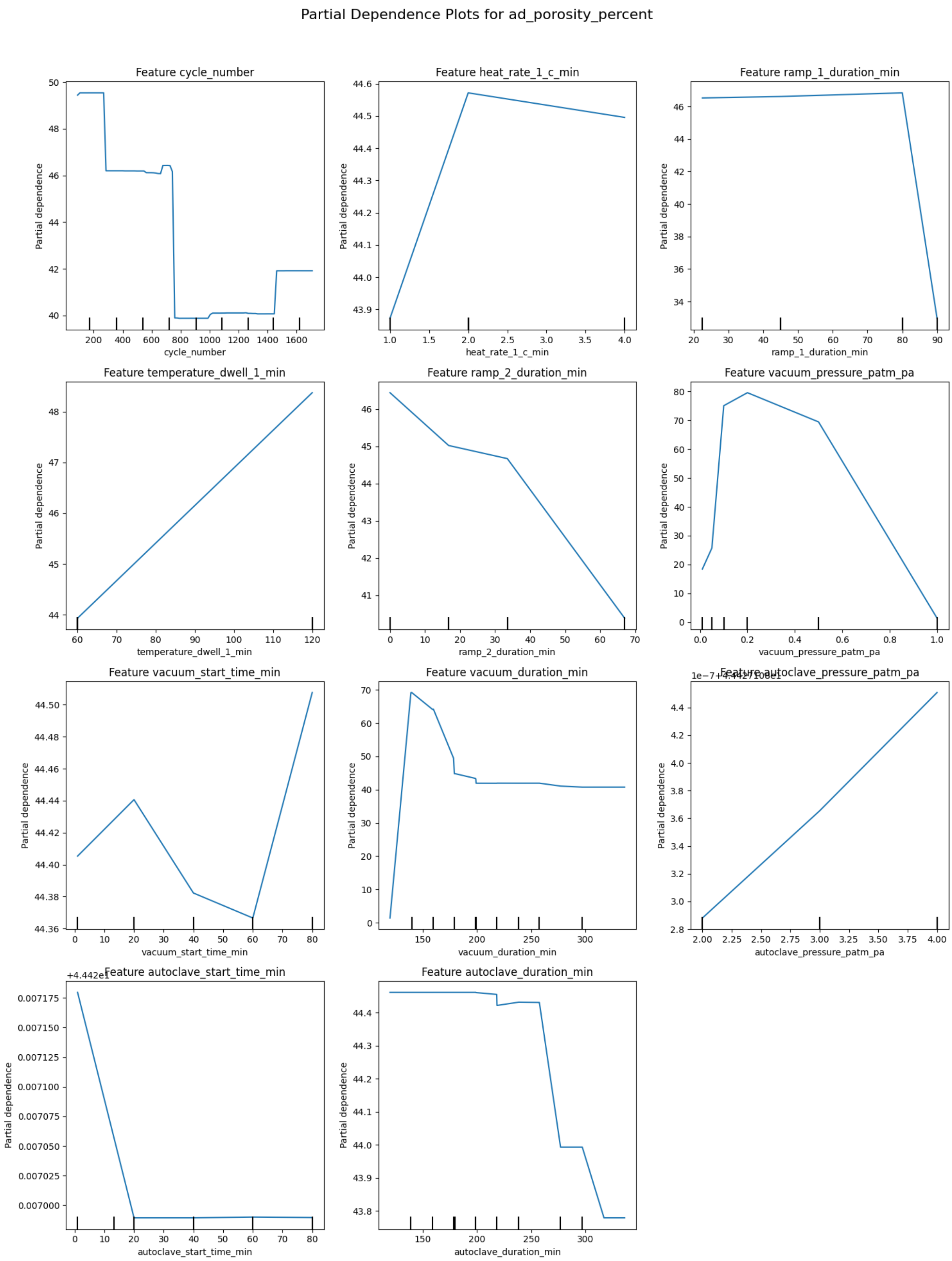




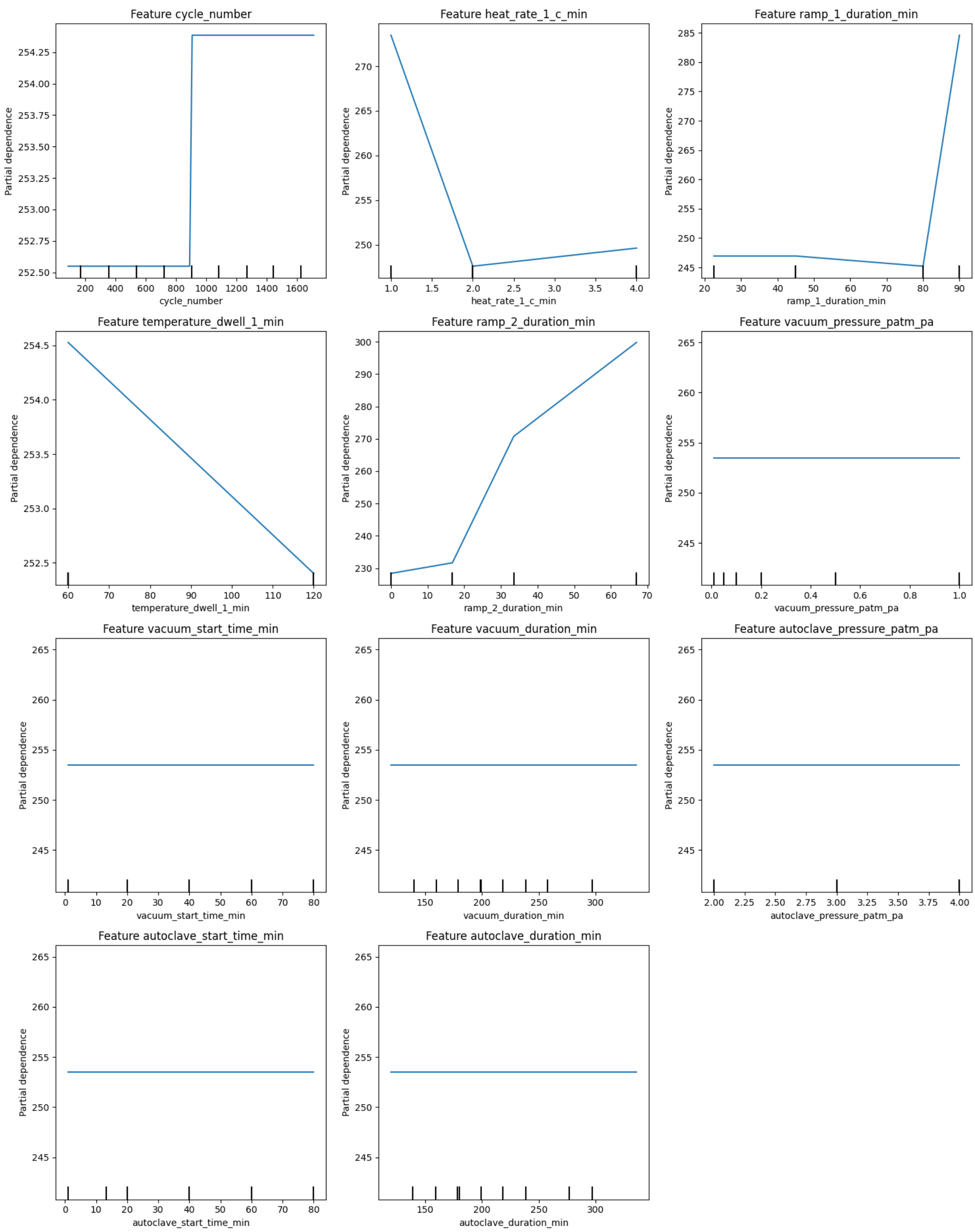
Partial Dependence Plots for max_fiber_volume_fraction_percent
Feature cycle_number
Feature heat_rate_1_c_min
Feature ramp_1_duration_min
Feature temperature_dwell_1_min
Feature ramp_2_duration_min
Feature vacuum_pressure_patm_pa
Feature vacuum_start_time_min
Feature vacuum_duration_min
Feature autoclave_pressure_patm_pa
Feature autoclave_start_time_min
Feature autoclave_duration_min
Partial dependence
cycle_number
heat_rate_1_c_min
ramp_1_duration_min
temperature_dwell_1_min
ramp_2_duration_min
vacuum_pressure_patm_pa
vacuum_start_time_min
vacuum_duration_min
autoclave_pressure_patm_pa
autoclave_start_time_min
autoclave_duration_min

Partial Dependence Plots for pr_porosity_percent




Partial Dependence Plots for ad_porosity_percent
Feature cycle_number
Feature heat_rate_1_c_min
Feature ramp_1_duration_min
Feature temperature_dwell_1_min
Feature ramp_2_duration_min
Feature vacuum_pressure_patm_pa
Feature vacuum_start_time_min
Feature vacuum_duration_min
Feature autoclave_pressure_patm_pa
Feature autoclave_start_time_min
Feature autoclave_duration_min
Partial dependence
cycle_number
heat_rate_1_c_min
ramp_1_duration_min
temperature_dwell_1_min
ramp_2_duration_min
vacuum_pressure_patm_pa
vacuum_start_time_min
vacuum_duration_min
autoclave_pressure_patm_pa
autoclave_start_time_min
autoclave_duration_min
+4.442e1

Partial Dependence Plots for cure_cycle_total_time_min



Evaluation:

Evaluation Metric	GridSearch Model	Bayesian Optimized Model
MSE	37.94	37.87
R2 Score	0.98	0.98
MSE for ad_porosity_percent	0.08	0.06
MSE for pr_porosity_percent	188.54	188.24
MSE for eff_porosity_percent	1.10	1.05
MSE for max_fiber_volume_fraction_percent	0.00	0.00
MSE for cure_cycle_total_time_min	0.00	0.00
R2 for ad_porosity_percent	1.00	1.00
R2 for pr_porosity_percent	0.89	0.89
R2 for eff_porosity_percent	1.00	1.00
R2 for max_fiber_volume_fraction_percent	1.00	1.00
R2 for cure_cycle_total_time_min	1.00	1.00

Objective Function

Goal 1:
1. Minimum prepreg porosity
2. Minimum adhesive porosity
3. Minimum Effective or bondline porosity
4. Maximum fibre volume fraction
5. Lower cure cycle total time

Objective Function = λ1 * (Adhesive Porosity) + λ2 * (Prepreg Porosity) + λ3 * (Effective Porosity) + λ4 * (Fiber Volume Fraction) + λ5 * (Cure Cycle Total Time)

Weights= [-2,-2,-2,+2,-1]
Penalty= $(\text{Prediction} - 30)^2$

Algorithm: Genetic optimization

Result:
Objective Function = -2.0 * (35.03) + -2.0 * (23.82) + -2.0 * (26.31) + 2.0 * (57.60) + -1.0 * (258.5)

Cure Cycle Parameters:

	Feature	Value
1	cycle_number	1010.91
2	heat_rate_1_c_min	3.86
3	ramp_1_duration_min	80.45
4	temperature_dwell_1_min	101.63
5	ramp_2_duration_min	40.46
6	vacuum_pressure_patm_pa	0.04
7	vacuum_start_time_min	28.78
8	vacuum_duration_min	193.33
9	autoclave_pressure_patm_pa	3.22
10	autoclave_start_time_min	60.33
11	autoclave_duration_min	335.59