IMPROVED LIFETIME STACKS FOR HEAVY DUTY TRUCKS THROUGH ULTRA-DURABLE COMPONENTS

Grant agreement no.: 101006641
Start date: 01.01.2021 – **Duration**: 36 months
Project Coordinator: D. J. Jones, CNRS

DELIVERABLE REPORT

D6.1: INITIAL DATA FROM FUEL CELL HD TRUCKS PROVIDING LOAD FREQUENCY DISTRIBUTION	
Due Date	December 2021
Author (s)	Leonidas Tsikonis
Workpackage	WP 6, HD powertrain validation and system recommendations
Workpackage Leader	FPT Industrial
Lead Beneficiary	FPT Industrial
Date released by WP leader	3rd January 2022
Date released by Coordinator	3rd January 2022

DISSEMINATION LEVEL		
PU	*Public*	**X**
PP	*Restricted to other programme participants (including the Commission Services)*	
RE	*Restricted to a group specified by the consortium (including the Commission Services)*	
CO	*Confidential, only for members of the consortium (including the Commission Services)*	

NATURE OF THE DELIVERABLE		
R	*Report*	**X**
P	*Prototype*	
D	*Demonstrator*	
O	*Other*	

SUMMARY	
Keywords	*Heavy-duty load profile test*
Abstract	*The development of high durability and performance MEAs for heavy-duty trucks requires the design of load profile testing adapted to the specific application. Several real-life truck missions were selected and used for the simulation of commercial heavy-duty trucks of various gross vehicle weights, electrified powertrain configurations, ambient conditions, and fuel cells. The simulation of such missions provided a significant number of load profiles for the fuel cell stack. Based on appropriate selection criteria a small number of load profiles were selected which, in turn, will be used to produce the desired load profile testing procedures.*
Public abstract for confidential deliverables	–

REVISIONS			
Version	**Date**	**Changed by**	**Comments**
0.1	16.12.2021	Leonidas Tsikonis	First draft.
0.2	21.12.2021	Thomas Mittermeier	Comments
0.3	03.01.2022	Leonidas Tsikonis	Finalisation

D6.1 INITIAL DATA FROM FUEL CELL HD TRUCKS PROVIDING LOAD FREQUENCY DISTRIBUTION

CONTENTS

1 CONTEXT

The IMMORTAL project aims at developing *"exceptionally durable and high power density MEAs well beyond the current state of the art up to TRL4 by building on understanding of fuel cell degradation pathways specific to heavy-duty truck operation and developing lifetime prediction models from extensive real-life stack operation, accelerated stress test and load profile cycles on short stacks."* [1]

Within this context, a successful development of MEAs requires performance and durability testing that corresponds to real-life applications, that is, testing that reflects the real application conditions that a fuel cell stack will need to correspond to during heavy-duty truck operation. This is where Task 6.1 of WP6 provides the necessary information.

In the framework of this task, several real heavy-duty commercial vehicle missions available at FPT industrial were selected. Based on those missions, FPT executed simulations of heavy-duty trucks. The trucks were of various gross vehicle weights (GVW), equipped with different electrified powertrain configurations and fuel cell systems, and they were operated at various ambient conditions. Figure 1 depicts this sequence of actions.

The result was the production of a significant number of different missions, that is load profiles, to which the stack is subjected under heavy duty applications. Among the total crowd of produced load profiles, a small number, if not one, would be necessary to be processed for the creation of relevant stack testing. For this reason, appropriate selection criteria were defined by the partners in WP6 and used as a tool to distinguish the most appropriate cycles.

The following sections elaborate more on the activities and the results of this task's actions.

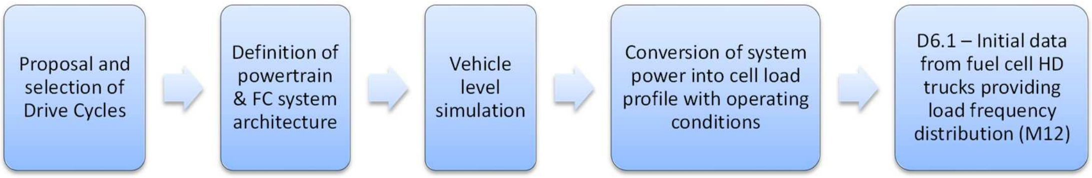

Figure 1. Steps taken to produce stack load profiles based on real-life heavy-duty truck drive cycles.

2 IMPLEMENTATION OF MODELLING

2.1 Modelling structure

Figure 2 depicts the overall structure of FPTs modelling approach. For the various missions' simulations different models needed to be developed on the following levels:

- Fuel stack,
- Fuel cell system, that is, stack and balance-of-plant,
- Electrified powertrain, including the vehicle's battery characteristics and hybridisation strategies,
- Vehicle, including not only the general dynamic behaviour on the road but also the vehicle's cooling system that interacts with the fuel cell.

The overall vehicle model was used to simulate the behaviour of heavy-duty fuel cell electric trucks on different drive cycles. Finally, the results of the simulations allow us to predict potential loads that the fuel cell stack will need to respond to, including currents, voltages, cooling and stack temperatures, reactant pressures etc.

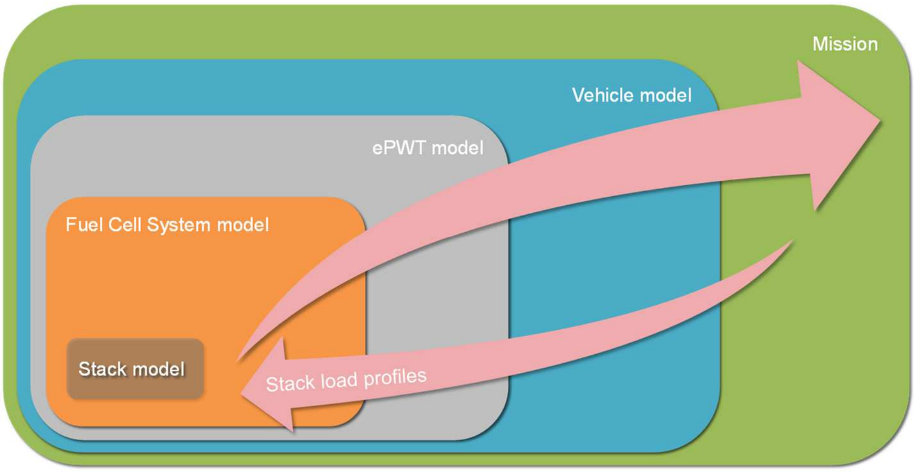

Figure 2. Cascade of models for the production of stack load profiles.

2.2 Models, drive cycles, and selection of running cases

The drive cycles as well as the models used from the stack up to the vehicle are proprietary and confidential. General information is provided in this paragraph.

2.2.1 Fuel cell system

Since the current research is not based on a specific product, an effort was made to develop simulation models of a broad set of fuel cell stacks and systems. The decisions taken are based on the current state of the art in the fuel cell industry. Among the various possible choices and configurations five different fuel cell system designs were implemented on model level within the following ranges:

- Nominal current density from 1.1 A/cm^2 up to 1.78 A/cm^2, the latter being the IMMORTAL project's target, i.e. 1.2 W/cm^2 at 0.675 V.
- Operating temperatures between about 65°C and 75°C.
- Three different nominal absolute operating pressures at the stack inlet: 1.5 bar, 2.2 bar and 2.5 bar. Equal pressure between anode and cathode was considered.

2.2.2 Road missions, vehicles, and e-powertrain architectures

While it would be possible to combine all different selected drive cycles with all types of vehicles and options in powertrain, it was decided to group them into typical combinations that are operative sensible. For example for long haul missions, only vehicles that typically perform such missions were considered and not vehicles that are destined to urban or regional drive cycles. Based on this approach, six such combinations were done as follows:

- Road missions were ranging from urban up to regional and long haul.
- The vehicles' gross vehicle weight ranging from 25t up to 44t.
- The battery capacity and type were adapted to the corresponding mission and vehicle.

2.2.3 Powertrain control strategies

In the power hybridisation industry, it is well known that the power controls strategy has a determinant effect on the load profile, not only of a fuel cell but of an internal combustion engine or other power source used in a hybrid scheme. For this application, three such approaches were selected to be implemented.

2.2.4 Ambient conditions

The ambient conditions have an impact on the operation of the fuel cell systems, especially as far as their cooling is concerned but also the inlet pressure of the compressor. In order to diversify this aspect of operation, FPT industrial based the assumed ambient conditions on the SAE J2615 definition of external conditions:

- -20°C (freezing day)
- 5°C (cold day)
- 15°C (reference conditions)
- 40°C (hot day)

To these four levels that were considered at sea level, a fifth was added corresponding to hot conditions at high altitude:

- 31°C at 1400 m

The latter corresponds to a hot day at sea level.

2.2.5 Total number or ran cases

Given the above assumptions a total of 5 x 6 x 3 x 5 = 450 different simulations were executed which provided the same number of different load profiles for the stacks.

2.3 Results: Examples of differentiation of load profiles

While it would not be practical to show all results in this report, it does make sense to show how two important factors differentiate the simulation results, namely the drive cycles and the powertrain control strategies.

The top row of Figure 3 shows the current density profiles for four different vehicle missions. The other factors, fuel cell, ambient conditions and e-powertrain controls remain the same. The lower row shows the occurrence probability histograms for 10 bins of current density levels.

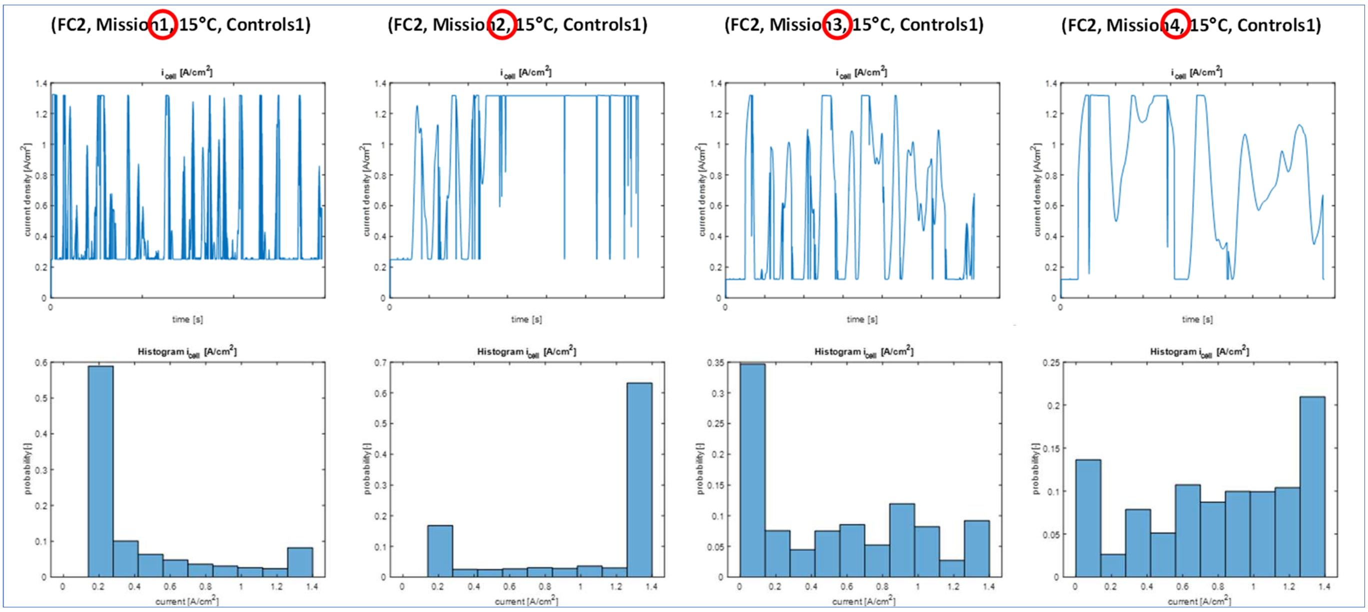

Figure 3. Current density profile for four different missions. The fuel cell system here is FC2, ambient temperature 15°C and the powertrain control strategy #1 was used.

The profiles range from highly dynamic, such as Mission 1, up to smoother transients like the ones seen on Mission 4. Also, the distributions are quite different, with some more homogeneous within the span of possible values and others operating mainly on the maximum (Mission 2) or the minimum values (Missions 1 and 3) of the current density.

Similarly, Figure 4 depicts the impact on the powertrain control choices on the load of the stack, here the current density. The result may vary from relatively smooth to highly dynamic.

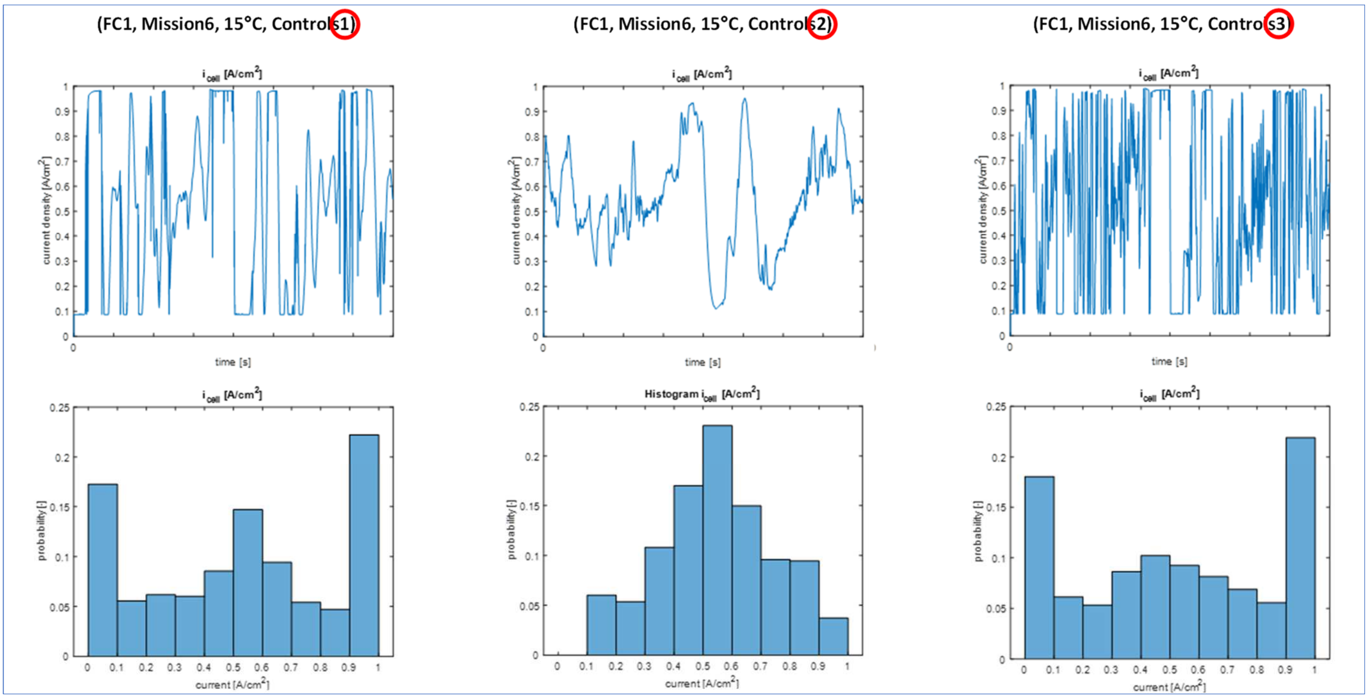

Figure 4. Current density profile for three different powertrain control strategies. The fuel cell system here is FC1, mission number is 6 and the ambient temperature is 15°C.

3 SELECTION OF MISSIONS FOR LOAD PROFILE TESTING

3.1 Criteria for selection of appropriate missions for the development of LPTs

Among the 450 simulation-produced load profiles for the stack one or maybe more needed to be selected. The selected one(s) will be used as a basis for the creation of load profile testing (LPT) for short stack, so that the IMMORTAL MEA and stack is tailored for heavy-duty truck applications.

For the selection two sets, or two dimensions, of criteria were defined. The first dimension is the stressors of interest and these are:

- the current density i [A/cm],
- the cell voltage U [V],
- the temperature T [°C] and
- the relative humidity RH [%].

The second dimension comprises the metrics to measure the afore-mentioned stressors bases on which a selection can be made. For metrics several statistics were considered such as minimum, maximum, arithmetic mean, median and mode of each stressor, as well as the standard deviation as a measure of the dynamic behaviour.

An alternative measure of the dynamic behaviour was additionally introduced by the author in this work. Named *"dynamic throughput"* and in its normalised form *"normalised dynamic throughput"*, this metric takes into consideration both the slope of the changes of dynamic signals as well as their amplitudes at the same time. The definition and relevant discussion are given in the Appendix in section 0. The metric was accepted by the WP6 partners as additional criterion.

Table 1 shows the two dimensions of selection criteria, i.e. the stressors and the metrics of interest.

Table 1. The two dimensions of selection criteria.

	i	U_{cell}	T_{stack}	RH_{in}
min				
max				
mean				
median				
mode				
std. deviation				
throughput				

3.2 Remarks regarding the selection of the appropriate missions

Before the implementation of the selection process and after a first examination of the simulation results, the following observations were made that had an impact on the subsequent choice of load profiles.

- Examination of the data showed that, with few exceptions, missions with high values of current did not correlate with high values of temperature and vice versa.

- Generally, missions with high values on the stressors would have low dynamic behaviour and vice-versa.
- Temperature is an important stressor for fuel cell degradation; however, it is highly dependent on the stack manufacturer. In the specific application for this project, FPT designed the simulated fuel cell system's temperature regime based on the current state of the art. This means that for the LPTs that are going to be used in the IMMORTAL project, the temperatures may very well be different.
- The relative humidity calculated in the FPT simulations, refer to the inlet of the stack. For the outlet it was assumed close to saturation, but it was not calculated. Therefore, it would not be appropriate for LPTs for short stacks.
- The pressure behaviour is correlated with that of the current, therefore it is not used as a separate selection criterion.

The afore-mentioned points are supported by the charts of Figure 5 on page 9.

A factor of importance was also the understanding that choosing a cycle where all metrics are at their extreme values, would not represent a realistic application and it would lead to a design of an MEA of unnecessarily high costs.

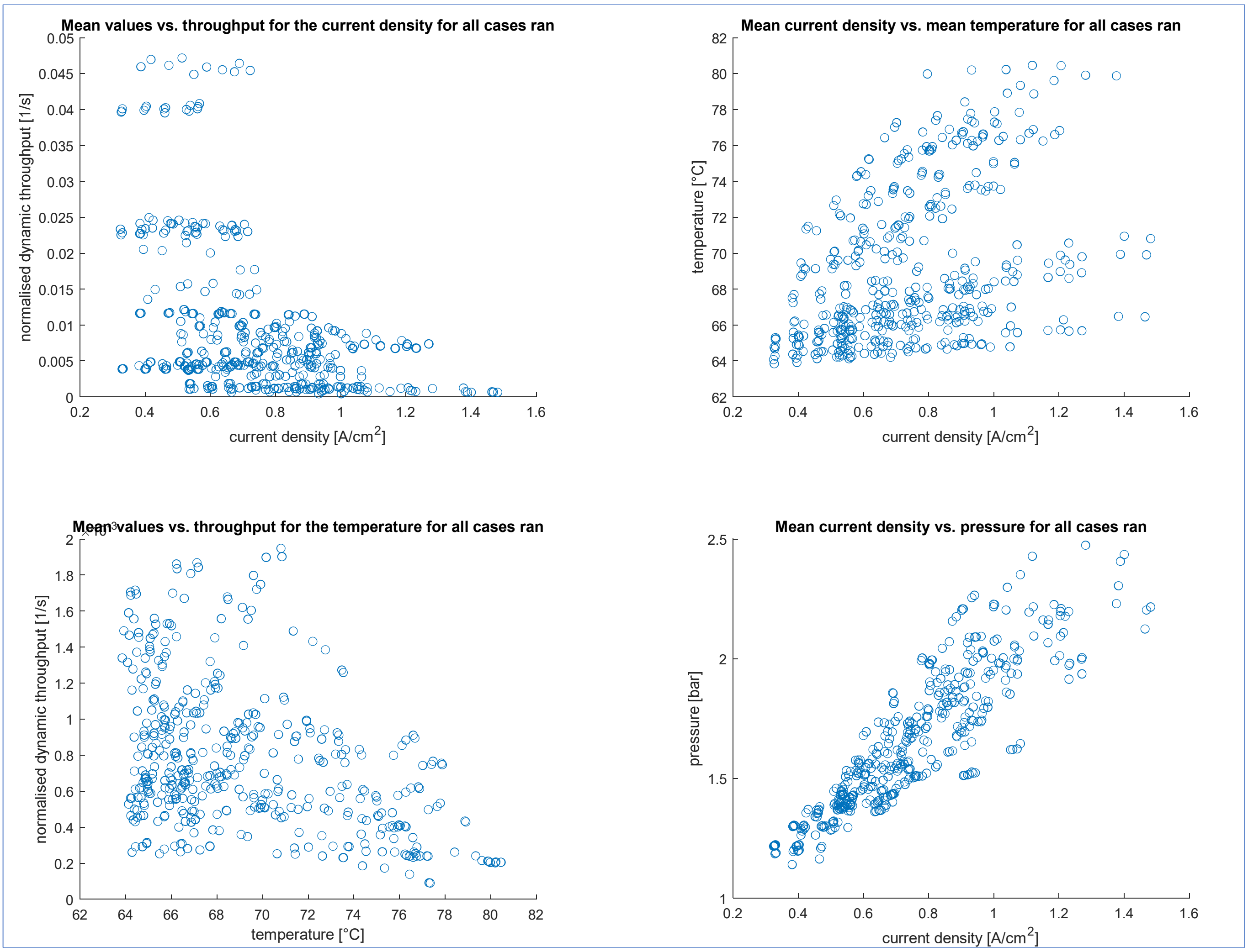

Figure 5. Correlations between selected magnitudes.

How the selection criteria vary for the chosen stressors can be overviewed in the Appendix B: Values of selection criteria for various stressors (page 17). Runs of particular interest are distinguished with red rectangles.

Having taken the above into consideration the following runs – stack missions – where distinguished:

- Case #383 which had the highest mean current density.
- Case #282 that had the maximum cell voltage and current density normalised dynamic throughput.
- Cases #197 and #241 with maximum current density mode.
- Cases #3 and #33 presenting maximum mean cell voltage.

However, from these missions, #383 has zero mode for the current density, that is, the most frequent value during the mission, while the rest of the time the fuel cell output was kept at high values. Choosing that would not make practical sense for the creation of an LPT. Moreover, between #3 and #33, #3 has a stronger dynamic behaviour for voltage and temperature and it was preferred over #33.

3.3 Final missions delivered

Given the above, simulations #3, #197, #241 and #282 were selected as potential sources for the creation of LPT procedures in the IMMORTAL project. The missions have been delivered to the WP6 partners for further processing and the final extraction of the LPTs that are going to be implemented.

The following Figure 6 up to Figure 9 present the selected cases by depicting the current density that the stack delivers as well as the temperature and the absolute pressure levels that it is subject to. As in the cases of Figure 3 and Figure 4, histograms showing the respective probability distributions are also given.

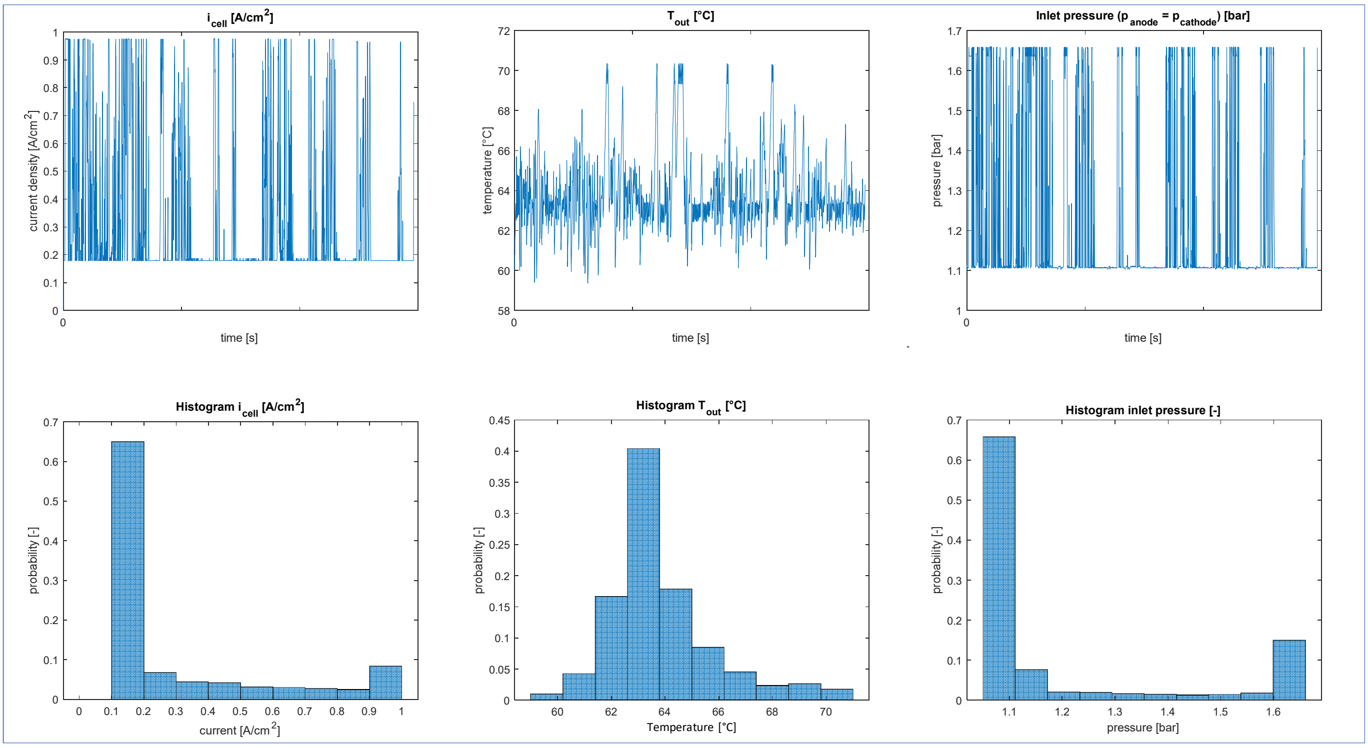

Figure 6. Current density, temperature and pressure for simulation run #3.

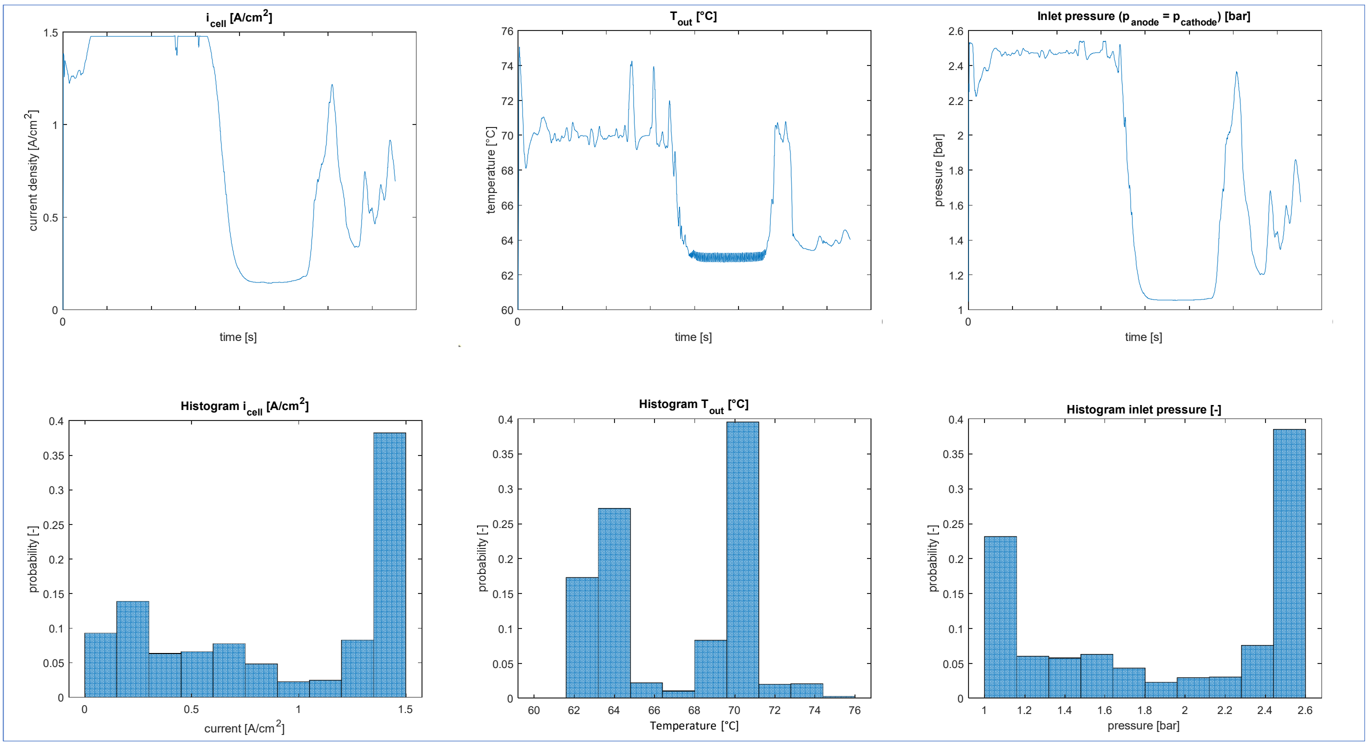

Figure 7. Current density, temperature and pressure for simulation run #197.

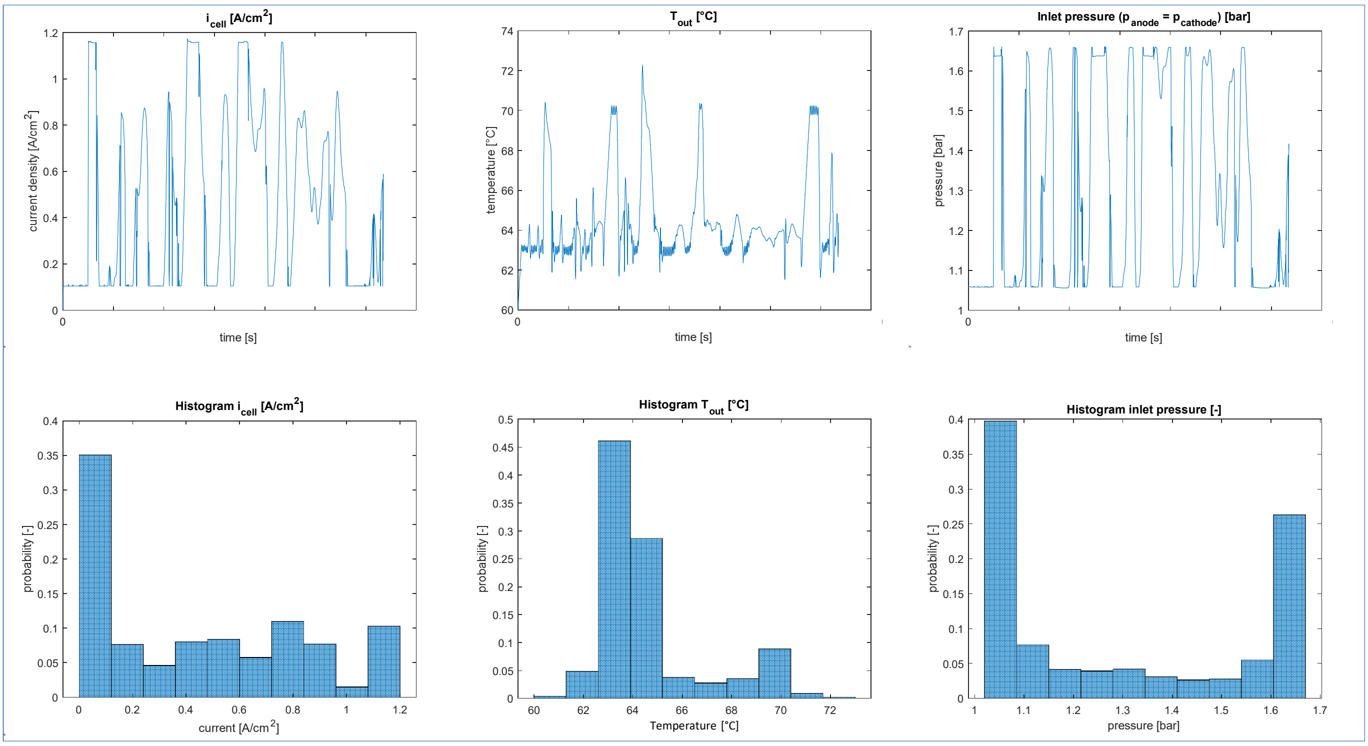

Figure 8.Current density, temperature and pressure for simulation run #241.

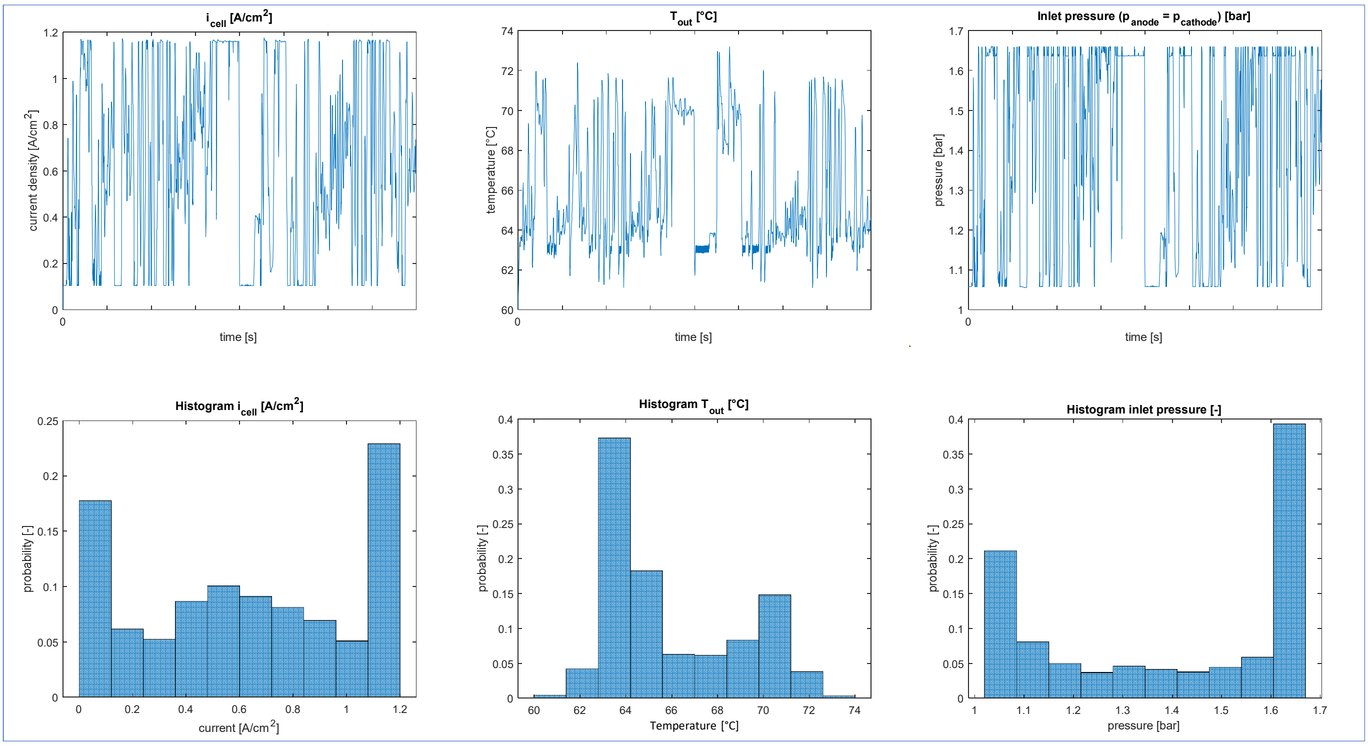

Figure 9.Current density, temperature and pressure for simulation run #282.

4 CONCLUSIONS AND FUTURE WORK

The development of MEAs for heavy-duty truck applications, requires tailored testing procedures that correspond to the specific conditions. Within the context of Task 6.1 in the first year of project IMMORTAL, a series of simulations based on real-life drive cycles and realistic ambient conditions were executed by FPT industrial. Using selected metrics of specific stressors, a small number of stack load profiles were distinguished. Those load profiles will be used to produce appropriate load profile tests (LPTs) for the IMMORTAL stack.

Future work foreseen in the context of Task 6.1 is the introduction of additional drive cycles, such as the one that will be produced in the H2Haul project. The stressors metrics will be evaluated, and it will be judged whether an update of the LPTs will be necessary.

One other point that the author considers worth investigating is further statistical processing of the 450 missions in order to extract ways to standardise LPTs for heavy-duty truck applications. The production of Markov chain-type transition matrices is one option.

5 REFERENCES

[1] Abstract of the IMMORTAL project proposal, Nr. SEP-210656636
[2] SAE J2615, Testing Performance of Fuel Cell Systems for Automotive Applications, SAE International, October 2011.

6 APPENDIX A: AN ALTERNATIVE DEFINITION OF THROUGHPUT

Throughput is a common metric used for batteries used to express the amount of charge that is transferred, either by discharging or charging. It is defined as the integral of the absolute value of magnitude of interest in time, divided by the total amount of time. Simpler put, it is the mean absolute value of the magnitude during a certain period of time. For example, the current throughput of a battery is defined as follows:

$$battery\ current\ throughput = \frac{1}{T_{tot}} \int_0^{T_{tot}} |current| \cdot dt$$

This is also practically depicted in Figure 10.

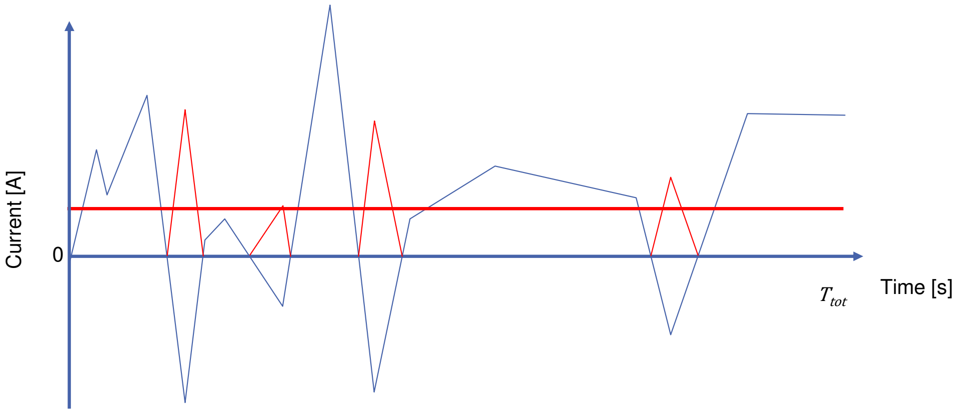

Figure 10. Calculation of battery current throughput. Blue is the real signal. The negative parts are considered at their absolute values (thin red lines) and the average is calculated (thick red horizontal line).

However, for fuel cells – but also for batteries – this definition is not taking into consideration the real dynamics of the measured magnitude, which is of importance in the estimation of degradation. In other words, one may calculate the same throughput for two different dynamic behaviours as shown in Figure 11.

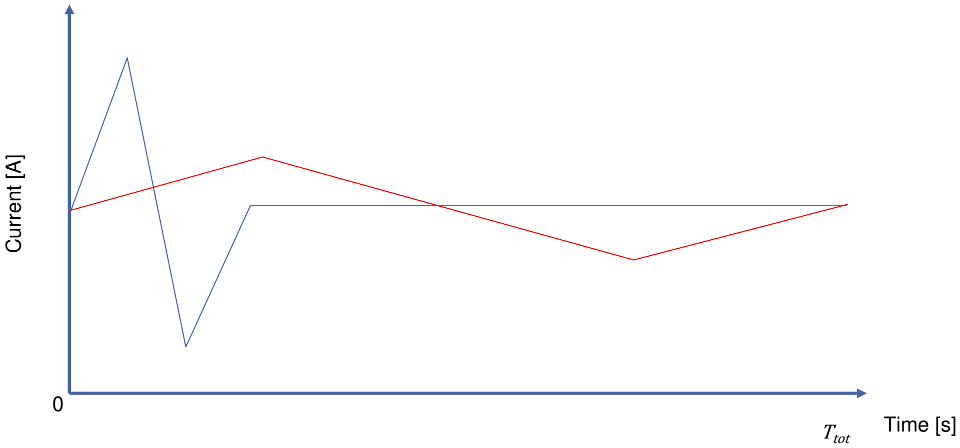

Figure 11. Current profiles of similar throughput but very different dynamic effect.

For this reason, a different approach was introduced for the calculation of throughput, which takes into consideration the number of oscillations per time unit (i.e. the time derivative) as well as the amplitude of those oscillations. This magnitude is called *"dynamic throughput"* and it is measured in *"units per time unit"*, e.g. A/s, bar/s, K/s etc. The dynamic throughput's definition is:

$$dynamic\ throughput = \frac{1}{T_{tot}} \int_0^{T_{tot}} \left| \frac{d}{dt} magnitude \right| \cdot dt$$

i.e. it is the average absolute time derivative of the measured magnitude.

Figure 12 and Figure 13 shows schematically how this is implemented on three different signals (Figure 12), two of which have the same dynamic behaviour but at different timing. All three have equal throughput according to the above definition. Figure 13 shows how the slope in the oscillations as well their magnitudes are better represented when measured with the dynamic throughput.

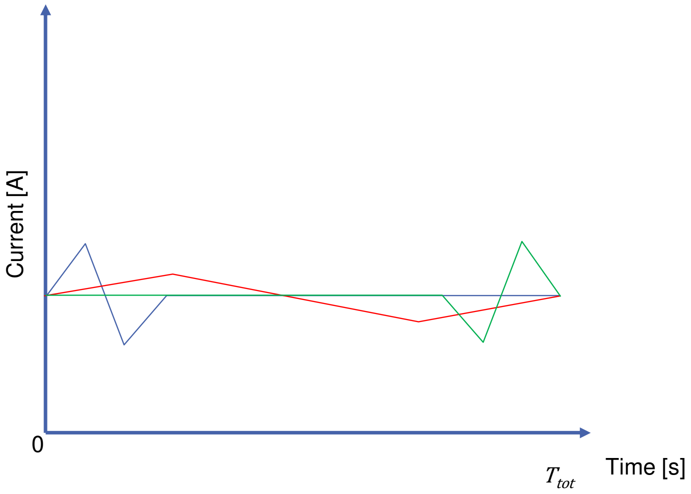

Figure 12. Three different signals with equal throughput. The green signal (oscillations on the right) is symmetrical to the blue (oscillations on the left).

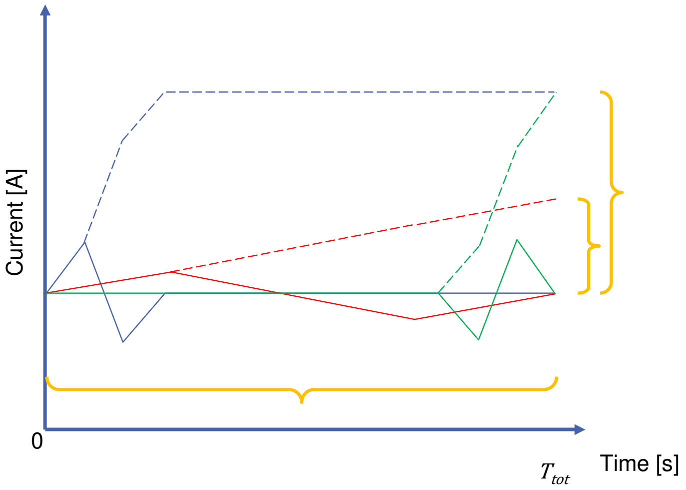

Figure 13. Calculation of dynamic throughput for the three signals. Negative slopes are replaced by their absolute values. Averaging is done on the dashed lines. The green and blue signals have equal dynamic throughput.

In general, it can be understood that if two similar signals with the same amplitude are considered but the second has double frequency, the latter will have double dynamic throughput. Such an example can be seen in Figure 14.

Similarly, between two similar signals of equal frequency but with the second of double amplitude, the latter will have double dynamic throughput as well.

The two signals in Figure 14 have equal standard deviation. When comparing their dynamic behaviour, the dynamic throughput is a better representation.

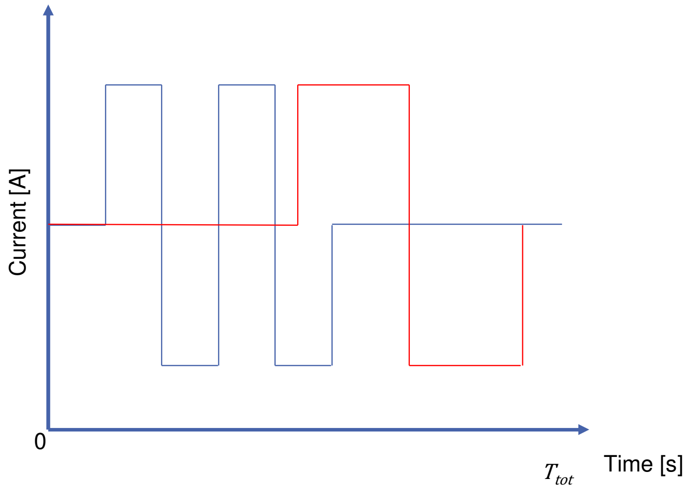

Figure 14. Two signals of equal standard deviation but different dynamic throughput.

One aspect the dynamic throughput is not taking into consideration is the dynamic effect, mainly the amplitude, compared to the mean value of the signal. For example the same dyn. throughput of current will have different impact if the average current is high or if it is low. For this reason, a normalised version is also introduced and used in this work by dividing by the average value of the considered magnitude. The *"normalised dynamic throughput"* is defined therefore as:

$$normalised\ dynamic\ throughput = \frac{\frac{1}{T_{tot}}\int_0^{T_{tot}} \left|\frac{d}{dt} magnitude\right| \cdot dt}{\frac{1}{T_{tot}}\int_0^{T_{tot}} magnitude \cdot dt}$$

7 APPENDIX B: VALUES OF SELECTION CRITERIA FOR VARIOUS STRESSORS

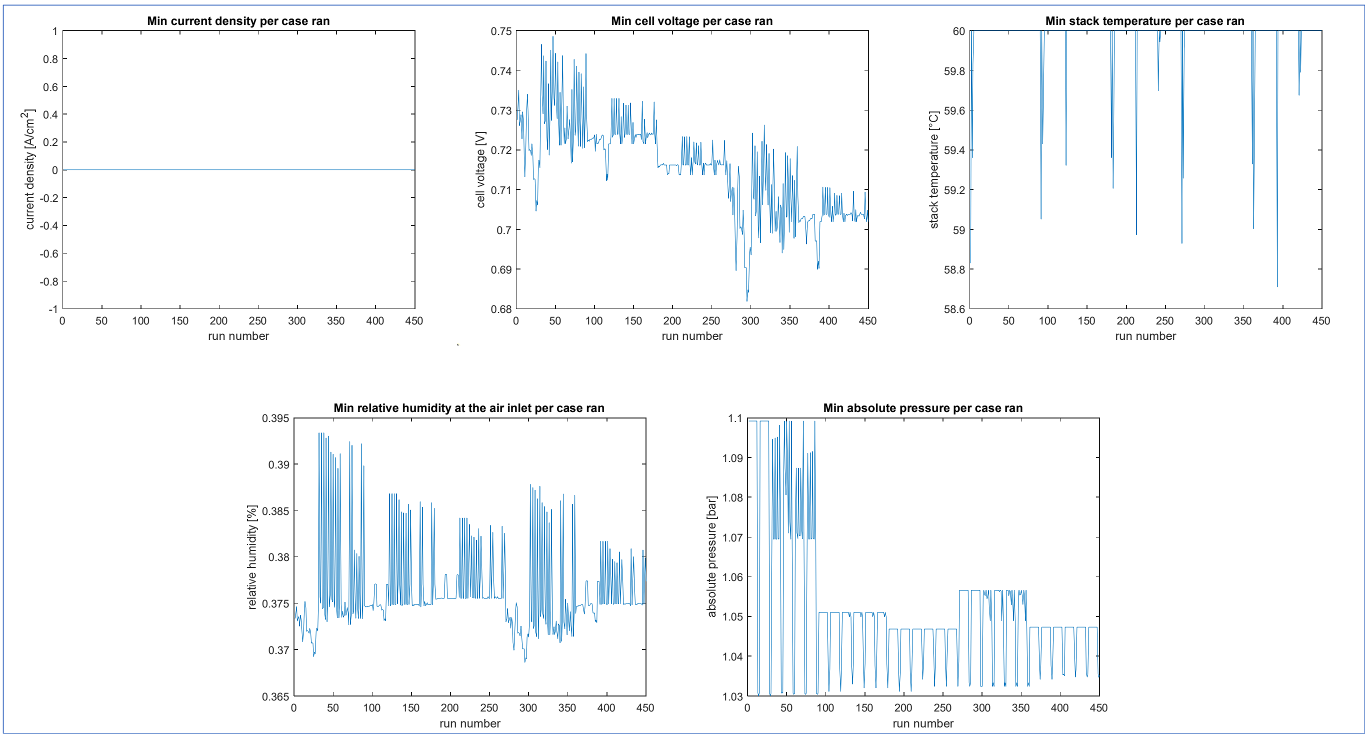

Figure 15. Minimum values per stressor and case ran.

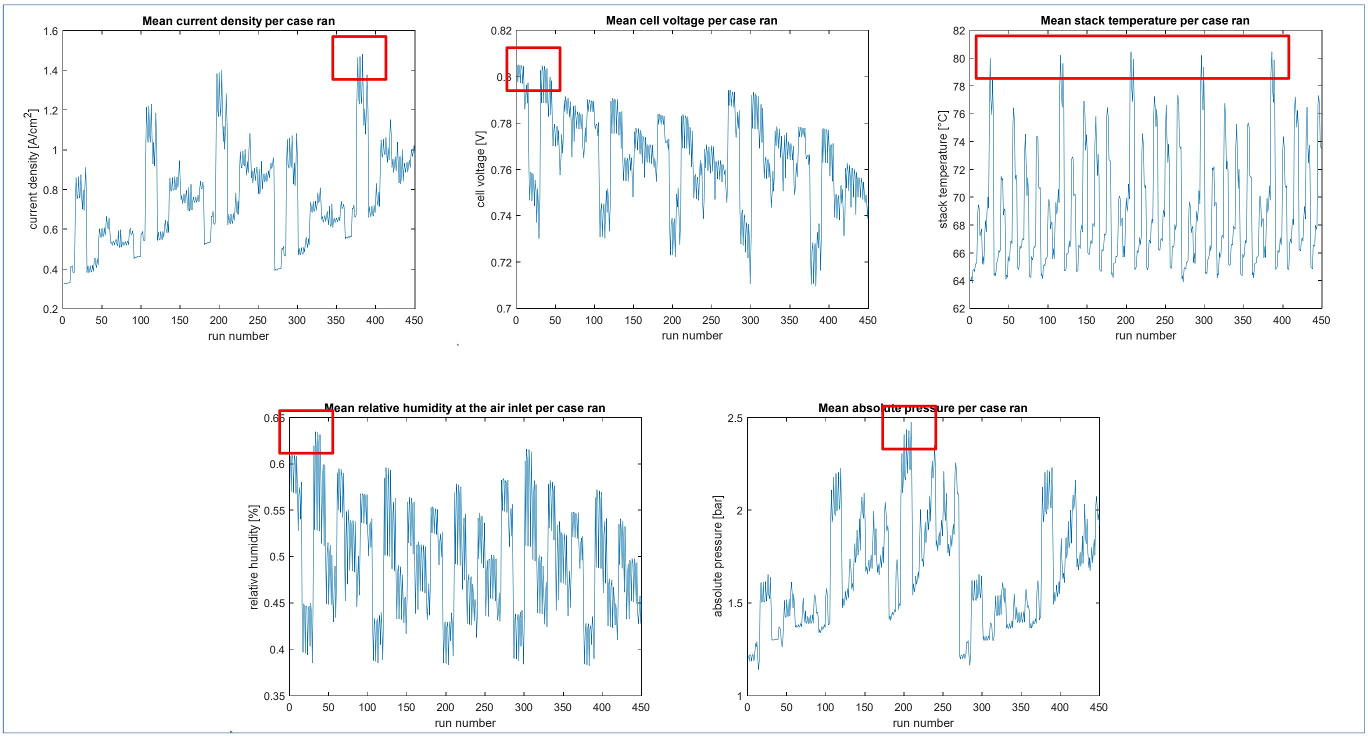

Figure 16. Mean values per stressor and case ran. Red rectangles show runs of particular interest.

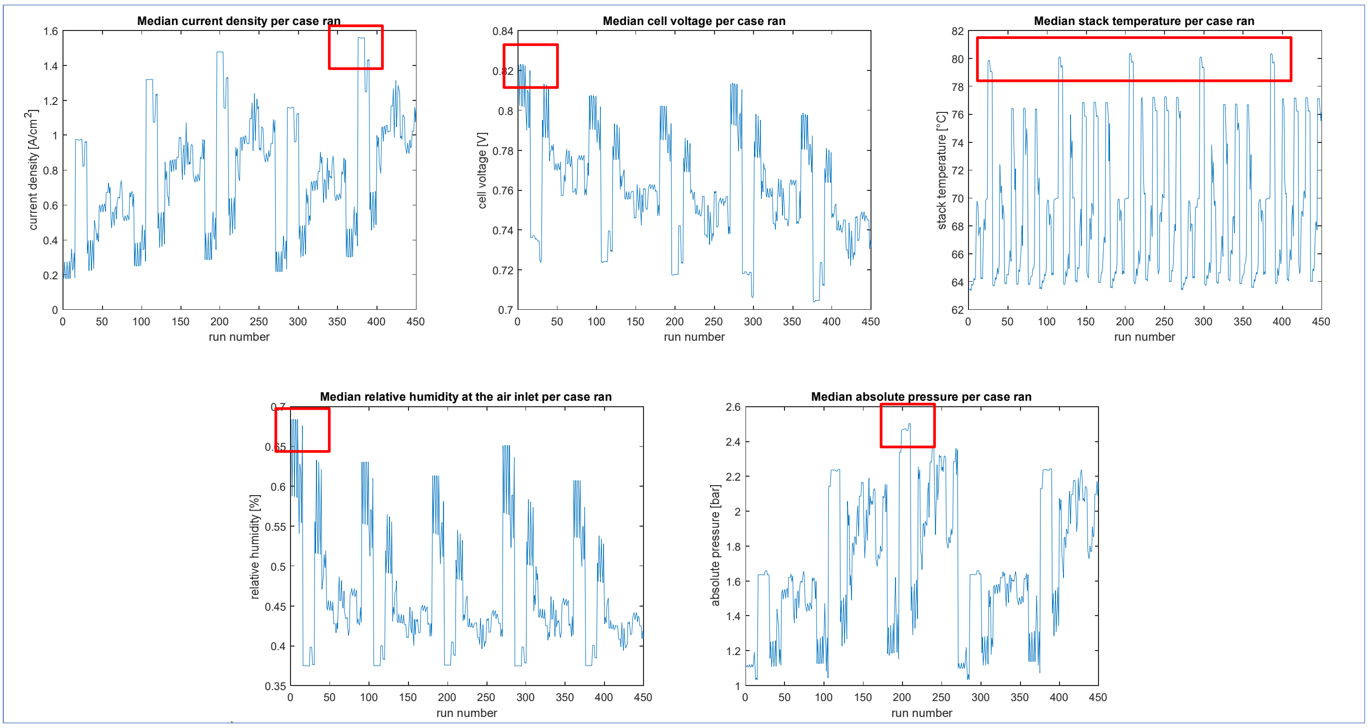

Figure 17. Median values per stressor and case ran. Red rectangles show runs of particular interest.

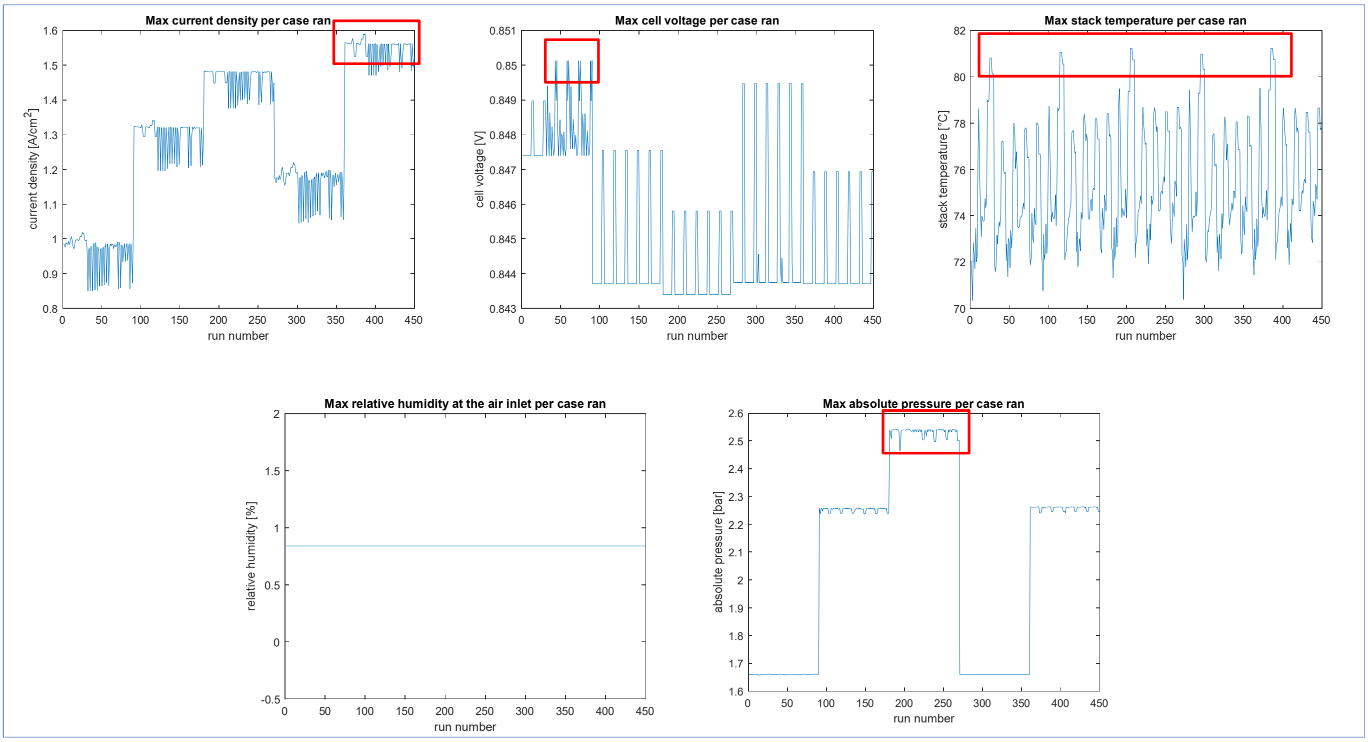

Figure 18. Maximum values per stressor and case ran. Red rectangles show runs of particular interest.

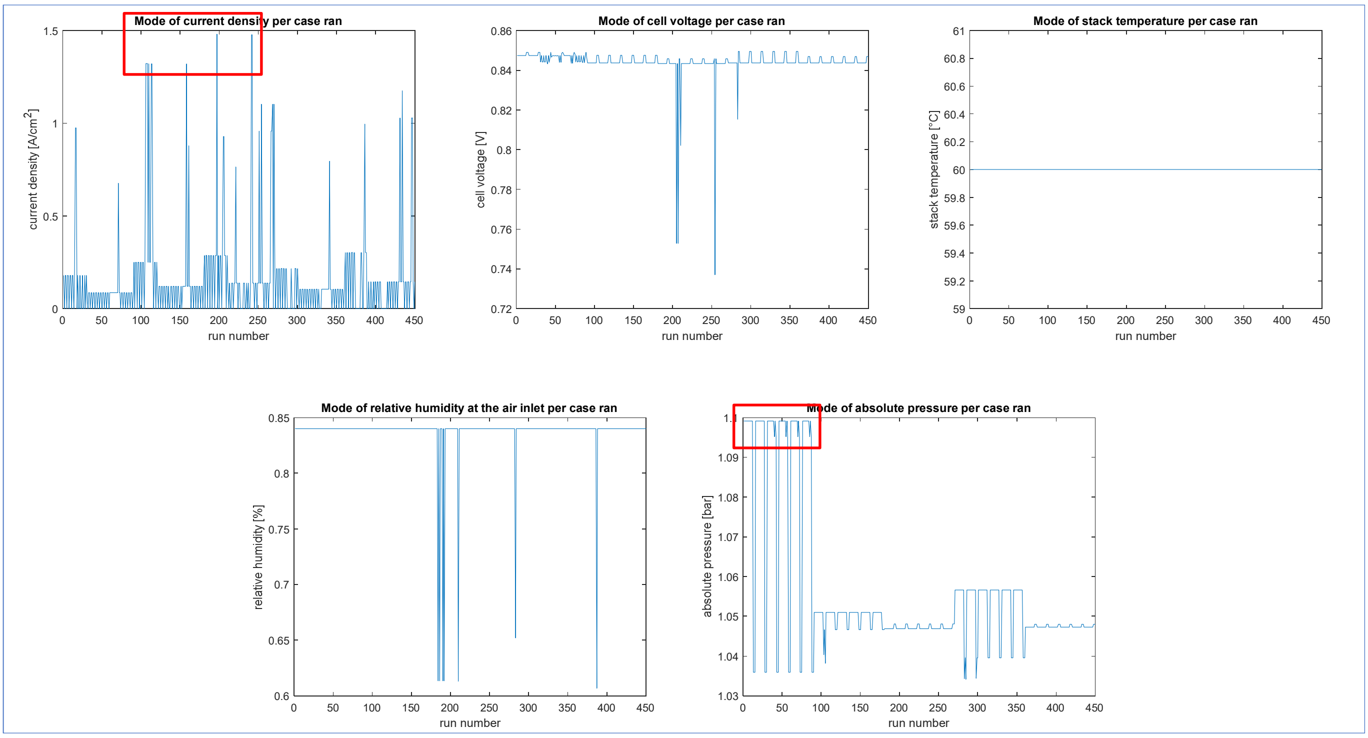

Figure 19. Modes per stressor and case ran. Red rectangles show runs of particular interest.

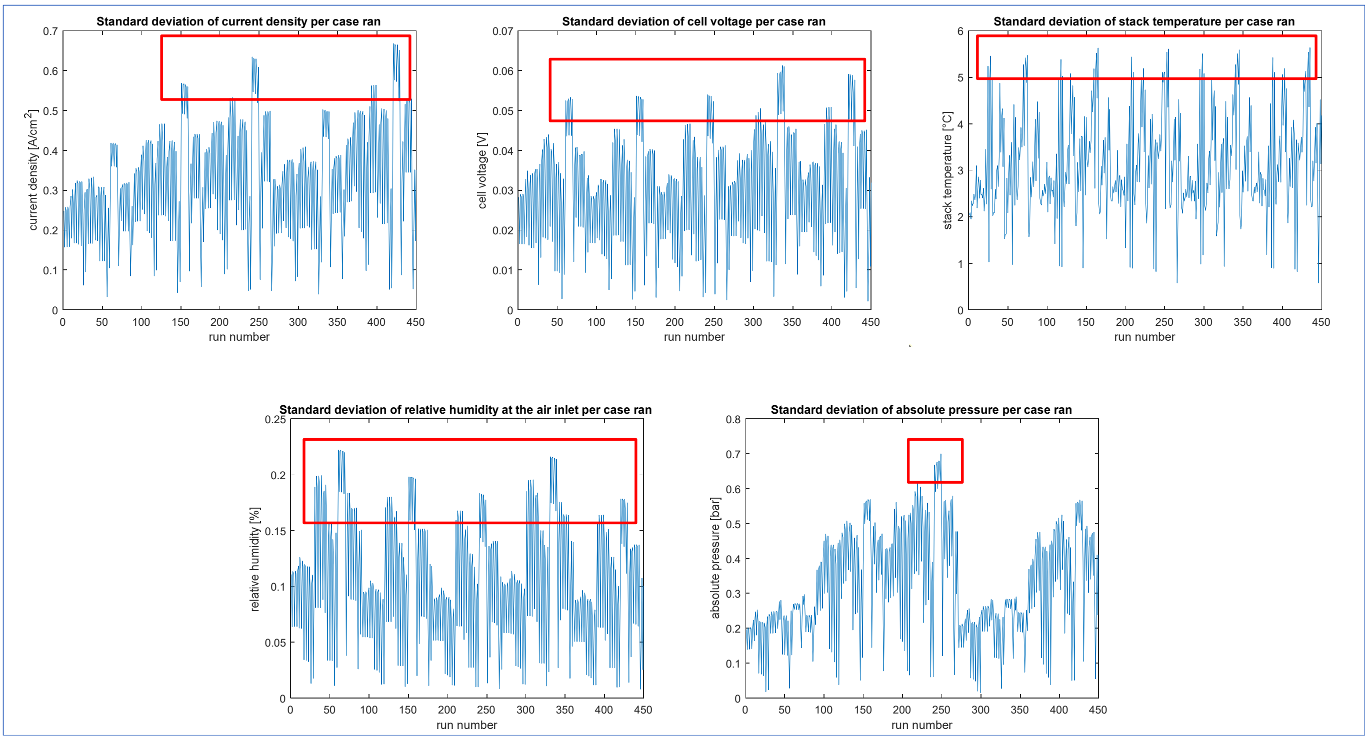

Figure 20. Standard deviation per stressor and case ran. Red rectangles show runs of particular interest.

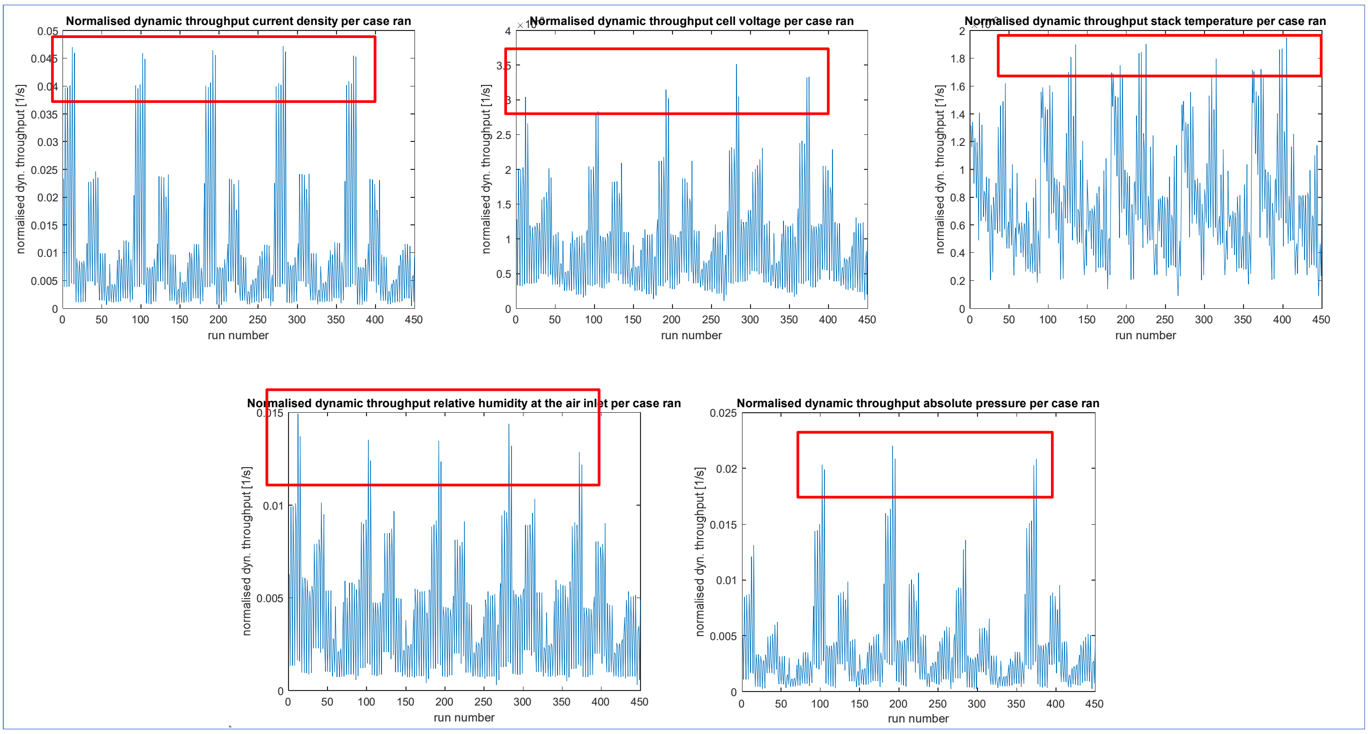

Figure 21. Normalised dynamic throughput per stressor and case ran. Red rectangles show runs of particular interest.

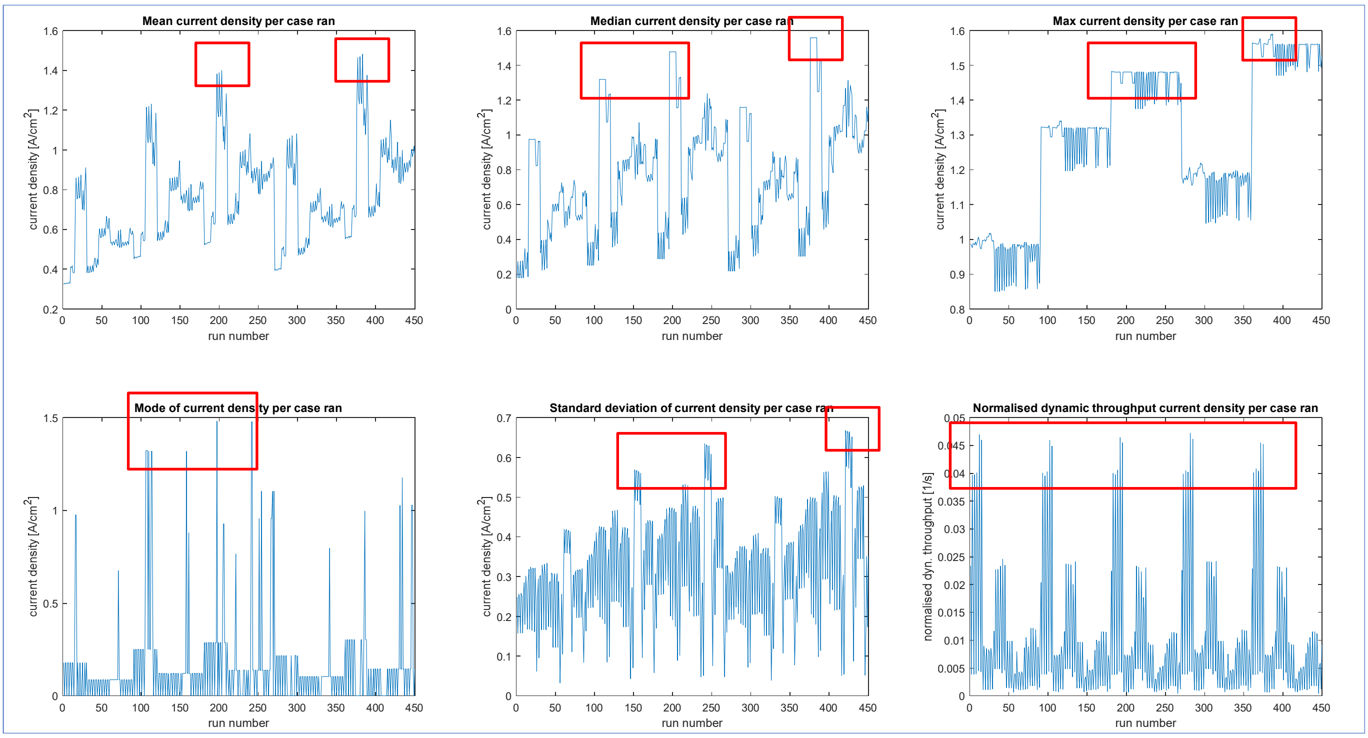

Figure 22. Selection metrics for the current density per case ran. Red rectangles show runs of particular interest.

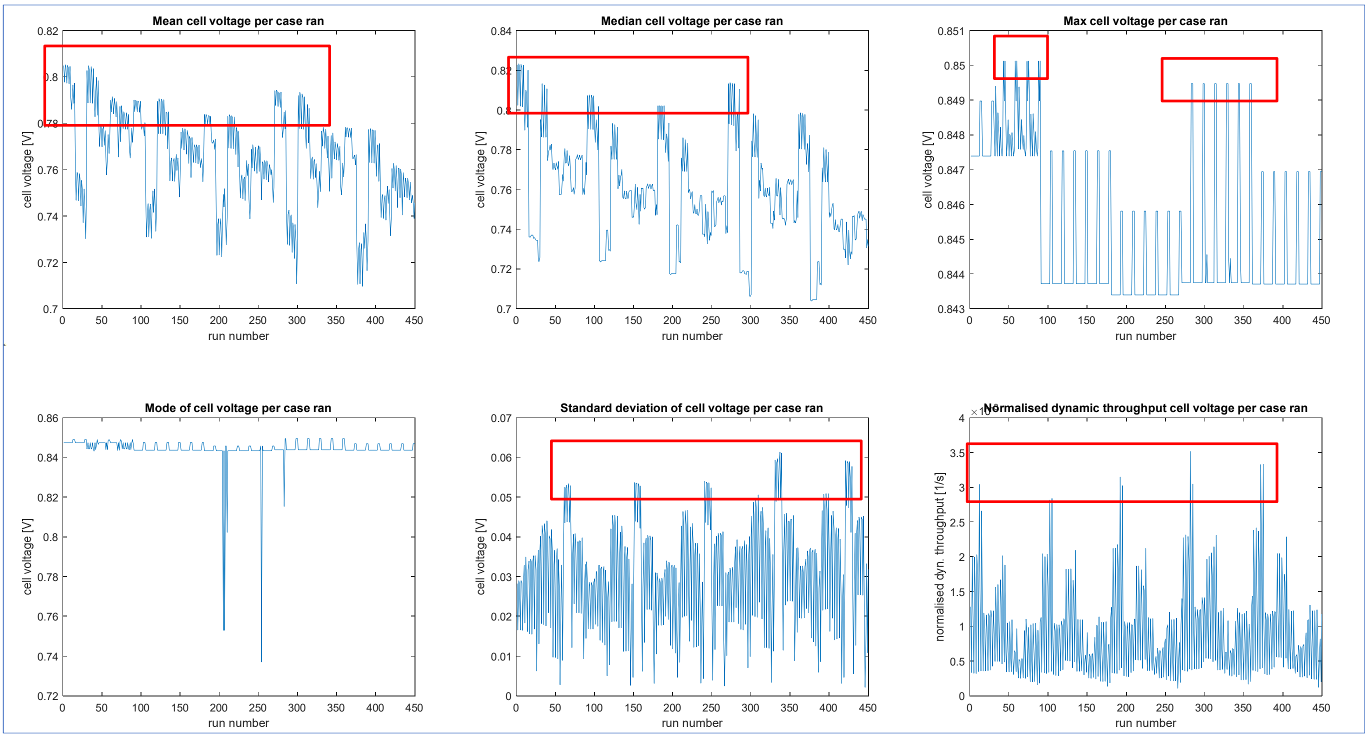

Figure 23. Selection metrics for the cell voltage per case ran.

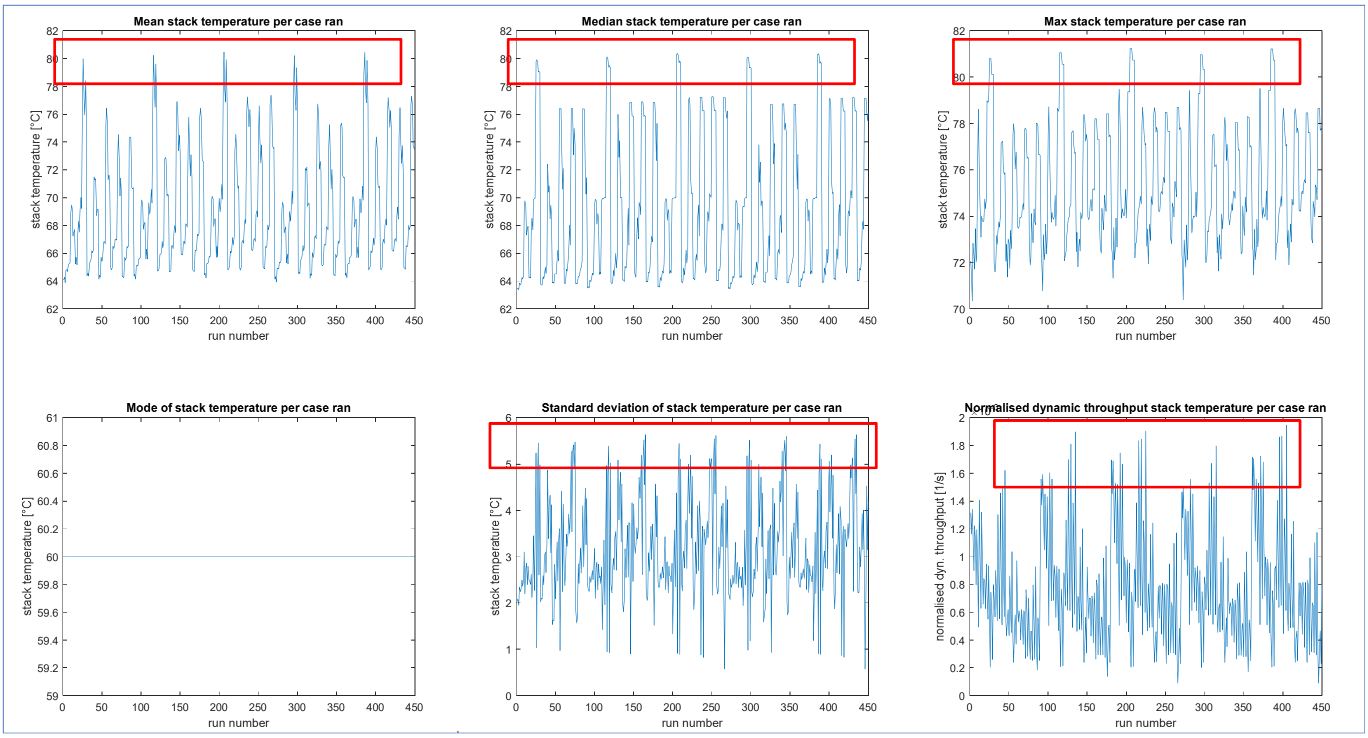

Figure 24. Selection metrics for the temperature per case ran.