



## Executive summary

# Predicting well-being in aircraft cabins

Results from the ICE project



*Infrared measurement of passenger surface temperature in an aircraft cabin (Copyright Fraunhofer IBP).*

### Problem area

Aircraft manufacturers create artificial atmospheric environments in the aircraft cabin with, in particular, air pressures equivalent to standard atmosphere at altitudes of up to 8000ft (2440m).

Widespread concerns about the impact of aircraft cabin environment on the health and well-being of passengers in commercial aircraft have received increasing attention in the past decade.

An informed judgement on the health and well-being effects of long-haul flight is contingent on well controlled experiments with substantial samples, as may be observed in aircraft cabin environment simulators.

### Description of work

To predict the effects of aircraft cabin environment on passenger health and well-being, mathematical models of these effects are needed. The development of the models is based on the data from the measurements in the experiments of the ICE project, containing the values of hundreds of variables, like blood pressures and temperatures, of about 1400 subjects. This large data set has been locked and stored, and was then further analyzed, checked and filtered into a more compact data set comprising only the key information on the experimental cabin conditions and the associated health and well-being effects. This compact data set, the

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This report is based on a presentation held at the ICE International Aviation Conference, Munich, Germany, 9-10 March, 2009.

so-called model-sheet, was then used to develop statistically based multi-variate regression type models of all the significant relations between the cabin conditions and the health and well-being effects that could be identified from the experimental data. These relations of health and well-being cover physiological quantities, such as heart rate, blood pressure and blood oxygen saturation, and psychological quantities, such as aircraft passenger comfort perception measured by questionnaires.

**Results and conclusions**

The implementation of these models allows for computational evaluation of the effects on aircraft passenger health and well-being due to variations in the aircraft cabin conditions. As such the models were used to identify aircraft cabin conditions, including combined effects of multiple conditions, for which improvements for passenger health and well-being can be expected.

**Applicability**

The implemented models described in this document will be applied for further technical recommendations for airframers and behavioural recommendations for airlines.



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## Predicting well-being in aircraft cabins

### Results from the ICE project

W.J. Vankan

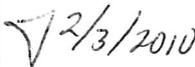
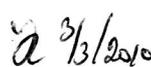
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## Summary

An informed judgement on the health and well-being effects of long-haul flight is contingent on well controlled experiments with substantial samples, as may be observed in aircraft cabin environment simulators. Two such simulators, both based on wide-bodied aircraft cabins, provided the facilities for a vast set of experiments as performed in the frame of the European research project ICE (Ideal Cabin Environment). However, the many measured variables of cabin conditions and subjects' responses in these experiments make it difficult to assess the key effects and the precise relationships that exist among the many variables. Moreover, to use these relationships for predictions of effects of aircraft cabin environment on passenger health and well-being, mathematical expressions of these relationships are needed. Therefore, in the same European research project, mathematical models were developed for the health and well-being of aircraft passengers under varying cabin environmental conditions.

The development of the models is based on the data from the experiments. From the measurements in the experiments of the ICE project a massive data set was obtained, containing the values of hundreds of variables for each of the approximately 1400 subjects. This large data set has been locked and stored, and was then further analyzed, checked and filtered into a more compact data set comprising only the key information on the experimental cabin conditions and the associated health and well-being effects. This compact data set, the so-called model-sheet, was then used to develop statistically based multi-variate regression type models of all the significant relations between the cabin conditions and the health and well-being effects that could be identified from the experimental data.

This paper presents a brief description of the models of aircraft passenger health and well-being that were developed. The data that is used in the development of these models is described in some detail, as well as the modelling procedure and the resulting models. The models allow for easy prediction of the effects of the aircraft cabin environment on each of the many different health and well-being variables, as such enabling efficient cabin design effect studies with respect to the passenger health and well-being.

## 1 Introduction

Widespread concerns about the impact of aircraft cabin environment on the health and well-being of passengers in commercial aircraft have received increasing attention in the past decade. Changing passenger demographics, the advent of ultra-long-haul services, and specific assumed air travel related health issues such as deep vein thrombosis (DVT) and severe acute respiratory syndrome (SARS) have all combined to these increased concerns [Mangili et al., 2005; Nicholson et al., 2003].

More specifically, passenger comfort was shown to be affected by humidity, pressure, temperature and noise in the aircraft cabin [Nicholson et al., 2003]. Muhm and others [Muhm et al., 2007] reported a study on healthy volunteers using a hypobaric chamber. At pressures equivalent to 8000ft altitude, SO<sub>2</sub> fell to between 93% and 91%. This was shown to contribute to a feeling of discomfort in un-acclimatised participants after between three and nine hours. An informed judgement on the health and well-being effects of long-haul flight is contingent on well controlled experiments with substantial samples, as may be observed in aircraft cabin environment simulators. Two such simulators, both based on wide-bodied aircraft cabins, provided the facilities for these experiments as performed in the frame of the European research project ICE [ICE project, 2005]. The resulting experimental data is used for detailed assessments of specific health effects, e.g. [ICE Consortium, 2009]. However, the many measured variables of cabin conditions and subjects' responses in these experiments make it difficult to assess the key effects and the precise relationships that exist among the many variables. Moreover, to use these relationships for predictions of effects of aircraft cabin environment on passenger health and well-being, mathematical expressions of these relationships are needed. Therefore, in the same European research project, mathematical models were developed for the health and well-being of aircraft passengers under varying cabin environmental conditions.

This paper presents a brief description of the models of aircraft passenger health and well-being that were developed. The data that is used in the development of these models is described in some detail, as well as the modelling procedure and the resulting models. The resulting models allow for easy prediction of the effects of the aircraft cabin environment on each of the many different health and well-being variables, as such enabling efficient cabin design effect studies, and possibly cabin optimisations, with respect to the passenger health and well-being.

## 2 The experiments

The impacts of varying levels of the aircraft cabin parameters pressure, humidity, temperature, noise and air supply rates on subjects' health and well-being were investigated using two state-of-the-art large-scale aircraft cabin environment simulation facilities. One facility, the Flight Test Facility (FTF) at the Fraunhofer Institute for Building Physics (IBP) in Holzkirchen, Germany [Mayer et al., 2007], focused on the effects of the pressure, humidity, temperature and noise in the aircraft cabin. The other facility, the Aircraft Cabin Environment (ACE) rig at the Building Research Establishment Ltd. (BRE) in Watford, UK [Grün et al., 2008], focused on the effects of ventilation and recirculation rates of the cabin air flow. In each of the FTF and ACE flight tests approximately 40 subjects participated, yielding in total more than 1400 subjects. The subjects for the FTF and ACE tests were carefully selected according to sex and age profiles.

For model validation, a series of measurements were also carried out on passengers during regular commercial flights. Measurements on passengers on board these flights, co-operating voluntarily, were taken by a questionnaire survey, complemented by a limited number of basic measurements of the cabin conditions.

Passenger responses to the changes in the aircraft cabin environment were assessed by various cardiovascular measurements, such as ECG and finger-pulse oxymetry, and by two different questionnaires, assessing passengers' state of comfort, mood, symptoms, behaviour, and personal characteristics, health status, general well-being, sensitivity, respectively. More detail about the measured variables is given in [Grün et al., 2008].

## 3 The models

Different approaches have been followed in the developments of the models. The first approach focused on generic methods, in this case based on statistical analyses, regression methods and neural networks that were applied to the data from the experiments. Another approach focused on known physical and physiological relationships between the cabin environment and its impact on the occupants, and has exploited the experimental data to further enhance these relationships on specific aspects. Both model types have been implemented in dedicated evaluation functions. This paper focuses on the first type of models that are based on the generic modelling methods.

The models provide a representation of the dependencies of a number of aspects of health and well-being of aircraft passengers on aircraft cabin conditions. These aspects of health and well-being cover a number of physiological quantities, such as heart rate, blood pressure and blood

oxygen saturation, and a number of psychological quantities, such as aircraft passenger comfort perception measured by questionnaires. The dependencies of the aspects of health and well-being on aircraft cabin conditions, such as pressure, temperature and humidity, have been assessed in detail in the ICE experiments. The results that were obtained from these experiments were used to build and validate the models.

The experimental data described above, covers an extensive set of variables that are used as inputs and outputs of the models. Therefore, these inputs and outputs are selected from this large set of variables that have been measured in the experiments and are available in the data.

### 3.1 Model inputs

First of all, the inputs of the models are primarily those physical quantities that were controlled in the experiments (both in the FTF and ACE facilities, as indicated between parentheses below), and that are representative for the investigated aircraft cabin environment:

1. pressure (FTF): cabin air pressure in hectopascal (hPa);
2. temperature (FTF): cabin air temperature in degrees Celcius ( $^{\circ}$  C)
3. relative humidity (FTF): cabin air relative humidity in %;
4. noise (FTF, ACE): cabin noise in decibel (dBA);
5. ventilation (ACE): ventilated (i.e., expelled) cabin air volume flow in cubic feet per minute (cfm);
6. recirculation rate (ACE) : re-circulated cabin air volume flow in cfm.

In addition to the 6 inputs mentioned above, also the following passenger characteristics related variables are used as inputs for the generic models in order to achieve a better representation of the data:

7. subject sex (male/female);
8. subject age (in years);
9. subject body-mass index (bmi) (in kilogram per square meter ( $\text{kg}/\text{m}^2$ ));
10. subject height (in centimeter (cm));
11. subject health status: identifies the risk group to which the subject belongs (normal, heart or lung);
12. smoke: identifies the smoking habit of subject (non-smoker, light smoker, heavy smoker);
13. lenses: identifies whether subject wears lenses (yes/no);
14. fitness: quantifies the general personal fitness of subject (variable Mean-gen-pers\_fitness, expressed on [0,1] scale)

Also the following passenger behaviour related variables are used as inputs for the models:

15. walking: quantifies the time that subjects have been standing up or walking in between two exposures (variable B-walking, expressed in minutes)

16. blanket: quantifies whether or not subjects have been using a blanket in between two exposures (variable B-blanket, expressed as yes/no)
17. clothing: quantifies the level of thermal insulation of subjects' clothes (variable B-clothing, expressed as clothing index with a range of [0,2])

Further improvement of the representation of the data by the models, can be achieved by taking some additional flight- and cabin related variables into account as inputs:

18. time: the so-called "Time On Task", which is the time elapsed since boarding, in minutes;
19. test facility : i.e., FTF or ACE;
20. seat characteristics: seat location identifier: at window, at aisle, in between 2 other seats;
21. surface temperature: cabin wall and floor temperatures in ° C;
22. vibration: vibrations in seats, as exerted during the flight tests, in dB;
23. velocities: cabin air velocities in centimeters per second (cm/s).

### 3.2 Model outputs

The output variables of the models are those quantities that represent the passenger's health and well-being. The main quantities in that respect are given by the primary output variables of which the data are stored in the experimental results and which are explained by the following table:

Table 1: Overview of all primary outputs

Variable name in model	Explanation
MEAN_C_Temp	Mean temperature comfort score [Grün et al., 2008]
MEAN_C_air	Mean air comfort score [Grün et al., 2008]
C_condition	Mean general conditions score [Grün et al., 2008]
Sym_average	Average of all reported symptoms [Grün et al., 2008]
Sym_numbers	Number of symptoms score [Grün et al., 2008]
severe_sym (>2)	Number of severe symptoms score [Grün et al., 2008]
MEAN_sym_pain	Number of pain symptoms score [Grün et al., 2008]
MEAN_sym_eyes	Number of eyes symptoms score [Grün et al., 2008]
MEAN_sym_flu	Number of flue symptoms score [Grün et al., 2008]
MEAN_sym_freeze	Number of freeze symptoms score [Grün et al., 2008]

Variable name in model	Explanation
<b>MEAN_sym_headache</b>	Number of headache symptoms score [Grün et al., 2008]
<b>MEAN_sym_pressure</b>	Number of pressure related symptoms score [Grün et al., 2008]
<b>MEAN_sym_stomach</b>	Number of stomach symptoms score [Grün et al., 2008]
<b>MEAN_sym_tired</b>	Number of tired symptoms score [Grün et al., 2008]
<b>MEAN_sym_stress</b>	Number of stress symptoms score [Grün et al., 2008]
<b>MEAN_sym_dryness</b>	Number of dryness symptoms score [Grün et al., 2008]
<b>RespFreq</b>	respiration frequency [Grün et al., 2008]
<b>Mean [BpM]</b>	Heart rate mean [Grün et al., 2008]
<b>pNN50 [%]</b>	pNN50 [%][Grün et al., 2008]
<b>log LF/HF</b>	log LF/HF [Grün et al., 2008]
<b>HF%</b>	HF% [Grün et al., 2008]
<b>SpO2_spot</b>	Oxygen saturation; Finger-pulse oxymetry spot measurement [Grün et al., 2008]

Besides this set of main quantities, the so called primary output variables, also a set of less important quantities are predicted by the model, the so called secondary output variables, which we will not explicitly present here.

## 4 Model implementation

The models allow for computational evaluation of the effects on aircraft passenger health and well-being due to variations in the aircraft cabin conditions. As such the models can be used to identify those aircraft cabin conditions for which the best results for passenger health and well-being can be expected.

To enable easy model evaluations, the models have been implemented in a software tool. The many output variables that are predicted by the models are evaluated as a function of many input variables. All these variables are clearly presented to the user in an intuitive application interface.

The model software tool has been developed in Matlab, and has been made operational as stand-alone executable code under MS-Windows-XP. The user interface of the model software tool is shown and briefly explained in the figure below.

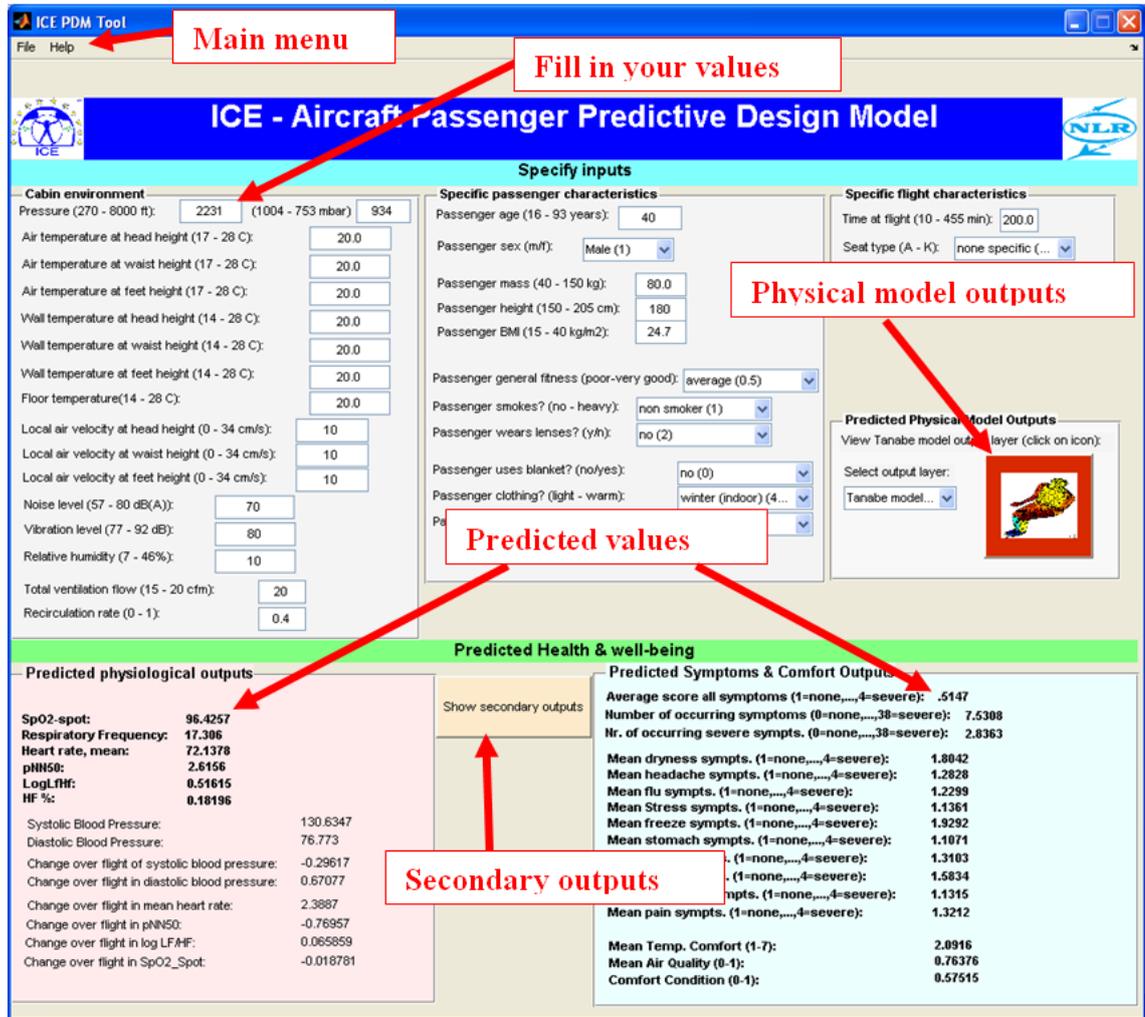


Figure 1: Main application interface window of the model software tool

Upon execution of the software tool, the main application interface window of the tool appears. A standard Windows main menu bar is available, offering the basic functions like “File/Exit”, and “Help”. The application interface window provides input boxes and pop-up menus where values for the input variables can be specified. Initially, default values for all input variables are filled in. These values can be changed by clicking in an input box and typing the desired values followed by a return. Pop-up menus can be changed by mouse clicks. As soon as one of the input variables changes its values, all output variables’ values are updated.

The output variables of the model are predicted, and presented by the software tool by their numerical values. The primary output variables' values are directly presented in the main application interface window (see figure above).

## 5 Model predictions

The generic models have been used to investigate the effects of the aircraft cabin on the passengers' health and well-being. These investigations yield information that can be used to optimise the aircraft cabin for certain aspects of the passengers' health and well-being. Because of the extensive number of input and output variables of the seat-based generic models, the scope of this investigation was limited to the effects of the main physical cabin and flight conditions on the primary output variables as predicted by the models.

In this investigation, the input variables of the model were set at appropriate fixed values ("mean conditions") that are based on the values that were measured in the FTF experiments and used in the model development; as given in the table below.

*Table 2: Mean-, minimum and maximum values of the input variables in the FTF data*

<b>Input variable</b>	<b>Mean value in FTF</b>	<b>Min value in FTF</b>	<b>Max value in FTF</b>
Seat code	[1.4, 1.6] (mean seats)	[1, 1] (A or K seats)	[2, 2] (D or G seats)
Time (after departure)	242 min	95 min	395 min
Air velocities	11 cm/s	4 cm/s	24 cm/s
pressure	834 mbar	752 mbar	954 mbar
Noise & vibration	[72 dbA; 82 db]	[64 dbA; 77 db]	[79 dbA; 92 db]
Relative humidity	24 %	8 %	45 %
Air & surface temperatures	22 °C	15 °C	27 °C
Ventilation	20 cf/m	20 cf/m	20 cf/m
Recirculation rate	40 %	40 %	40 %
Walking time	6 min	0 min	60 min
Blanket usage	0.14	0 (not at all)	1 (used)
Clothing	0.8 CLO	0.33 CLO	2.0 CLO

Input variable	Mean value in FTF	Min value in FTF	Max value in FTF
Age	44 years	16 years	85 years
BMI	24.4 kg/m <sup>2</sup>	15.3 kg/ m <sup>2</sup>	39.2 kg/ m <sup>2</sup>
Smoking	1.2	1 (non-smoker)	3 (heavy smoker)
Lenses	1.9	1 (yes)	2 (no)
Height	173 cm	150 cm	200 cm
General fitness	0.66	0 (not fit)	1 (very fit)
sex	1	1 (male)	2 (female)

Then, the following variations were applied to the input variables that represent the physical cabin and flight conditions, as given in the table below.

*Table 3: Variations in physical cabin and flight conditions, as applied in this investigation*

Input variable	Reference value (mean comfort condition)	Lower bound value	Upper bound value
Seat code	[1, 2] (C or H seats)	[1, 1] (A or K seats)	[2, 2] (D or G seats)
Time (after departure)	200 min	100 min	400 min
Air velocities	10 cm/s	5 cm/s	20 cm/s
pressure	934 mbar	750 mbar	950 mbar
Noise & vibration	[66 dbA; 80 db]	[64 dbA; 77 db]	[80 dbA; 90 db]
Relative humidity	40 %	10 %	45 %
Air & surface temperatures	23.5 °C	18.0 °C	26.0 °C

It should be noted that there are 3 air velocity input variables, 3 air temperature input variables and 4 surface temperature input variables in the models, representing the velocities and temperatures at different heights in the cabin (feet, waist and head height). Each of these 3 velocity input variables and 7 temperature input variables are set simultaneously to the values given in the table 3 above.

The effects of the variation of each of the above given single physical cabin and flight conditions input variables on each of the primary output variables was evaluated with the models. The change of the output variable relative to its value in the mean comfort condition is

calculated, and normalised with the possible range of values of that output variable as found from the evaluation with the FTF data input set described above. These relative change values for each output variable can be considered as the global sensitivities of the model for each of the single physical cabin and flight conditions input variables.

From this investigation we find several major effects, which are described below.

### **5.1 Minimum and maximum air velocity conditions**

Most large effects in the primary output variables were found in the minimum and maximum air velocity conditions. In particular the output variables MEAN\_sym\_headache, MEAN\_sym\_flu, MEAN\_sym\_stress, MEAN\_sym\_pressure, Severe\_sym, Diastolic and HF% showed large changes in these minimum and maximum air velocity conditions (figure 2).

The largest effects that were found in these conditions, was an increase in HF% of 46% and a decrease in MEAN\_sym\_flu of 46% at maximum air velocity condition, compared to the mean comfort condition.

Apparently there are strong effects of the air velocities on many of the health and well-being aspects. Consequently, further improvement for some of these aspects would be achieved in the maximum air velocity condition as compared to the mean comfort condition, e.g. decrease of several tens of percents for MEAN\_sym\_pain, MEAN\_sym\_headache, MEAN\_sym\_flu, MEAN\_sym\_stress and MEAN\_sym\_stomach. However, this condition would at the same time also cause significant increase of systolic and diastolic blood pressures and HF%.

It also appears that MEAN\_sym\_pressure increases more strongly in the minimum air velocity condition than in the minimum pressure condition. And also Sym\_average and Severe\_sym increase strongly in the minimum air velocity condition (figure 2).

### **5.2 Minimum pressure condition**

The main effects in the minimum pressure condition are decrease of SpO<sub>2</sub>, and increase of MEAN\_C\_Temp and MEAN\_sym\_pain (figure 2).

### **5.3 Maximum noise condition**

The main effects in the maximum noise condition are decrease of MEAN\_sym\_stress, MEAN\_sym\_eyes, Sym\_average, and logLF/HF. However, also RespFreq and PNN50% increase in this condition (figure 2).

### **5.4 Minimum RelHum condition**

The main effect in the minimum relative humidity condition is an increase of MEAN\_sym\_dryness (figure 2).

### **5.5 Minimum temperature condition**

The main effects in the minimum temperature condition are a decrease of MEAN\_C\_Temp, and significant increase of MEAN\_sym\_headache and MEAN\_sym\_freeze (figure 2).

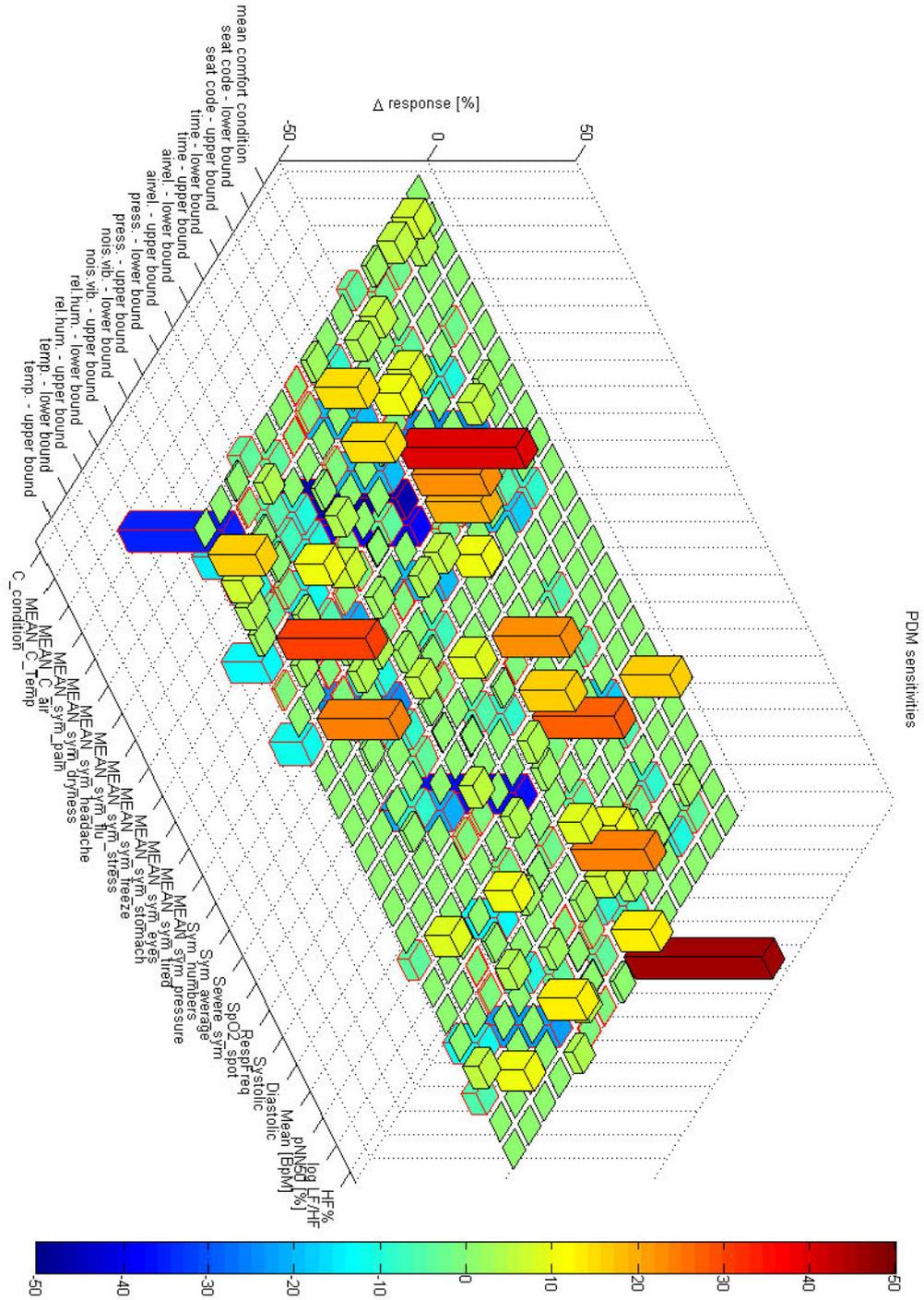


Figure 2: Model sensitivities: relative responses (in %) of all primary output variables evaluated with the model and resulting from the above given variations of the input variables. Note, for example, the clear dependence of temperature comfort (Mean\_C\_Temp) on cabin temperature (temp. – lower/upper bound). Typically, the drop of oxygen saturation (SpO2\_spot) at low cabin pressure (press. - lower bound) can be clearly observed, as expected. In addition, the mean temperature comfort score (MEAN\_C\_Temp) also clearly drops when cabin air temperature (temp. - lower bound) is at the lower limit level.

## 6 Combined effects

The combination of more than one non-comfort conditions can have different effects on an output variable. These effects may compensate or amplify each other. From the analysis above, a few cases have been selected for more detailed analysis. The main results of these considered cases are given in the figure 3 below.

### 6.1 Combined effects: Minimum pressure and maximum air velocity condition

From the results of the sensitivity analysis it can be observed that some of the main effects in the minimum pressure condition (decrease of SpO<sub>2</sub>, and increase of MEAN\_C\_Temp and MEAN\_sym\_pain) may be compensated by the maximum air velocity condition. Therefore the combination of these 2 conditions has been evaluated.

It is found that MEAN\_sym\_pain in the minimum pressure condition indeed can be compensated by the maximum air velocity condition. In the combined condition MEAN\_sym\_pain is about 5% lower than in the general mean comfort condition, whereas in the minimum pressure condition MEAN\_sym\_pain is about 15% higher than in the general mean comfort condition.

MEAN\_C\_Temp however appears to get worse in the combined minimum pressure and maximum air velocity condition. In the combined condition MEAN\_C\_Temp is about 19% higher than in the general mean comfort condition, whereas in the minimum pressure condition MEAN\_sym\_pain is about 15% higher than in the general mean comfort condition.

There is no additional effect on SpO<sub>2</sub> due to maximum air velocity, when combined with the minimum pressure condition, as could be expected.

### 6.2 Combined effects: Minimum pressure and minimum temperature condition

In the combined minimum pressure and minimum temperature condition, MEAN\_C\_Temp appears to switch to a decrease of 21% (lower than in the general mean comfort condition), instead of an increase for the minimum pressure condition of 15% (higher than in the general mean comfort condition).

MEAN\_sym\_pain in the minimum pressure condition can also be compensated by the minimum temperature condition. In the combined condition MEAN\_sym\_pain is only about 5% higher than in the general mean comfort condition, whereas in the minimum pressure condition MEAN\_sym\_pain is about 15% higher than in the general mean comfort condition.

SpO<sub>2</sub> in the minimum pressure condition can also be slightly compensated by the minimum temperature condition. In the combined condition SpO<sub>2</sub> is about 27% lower than in the general mean comfort condition, whereas in the minimum pressure condition SpO<sub>2</sub> is about 36% lower than in the general mean comfort condition.

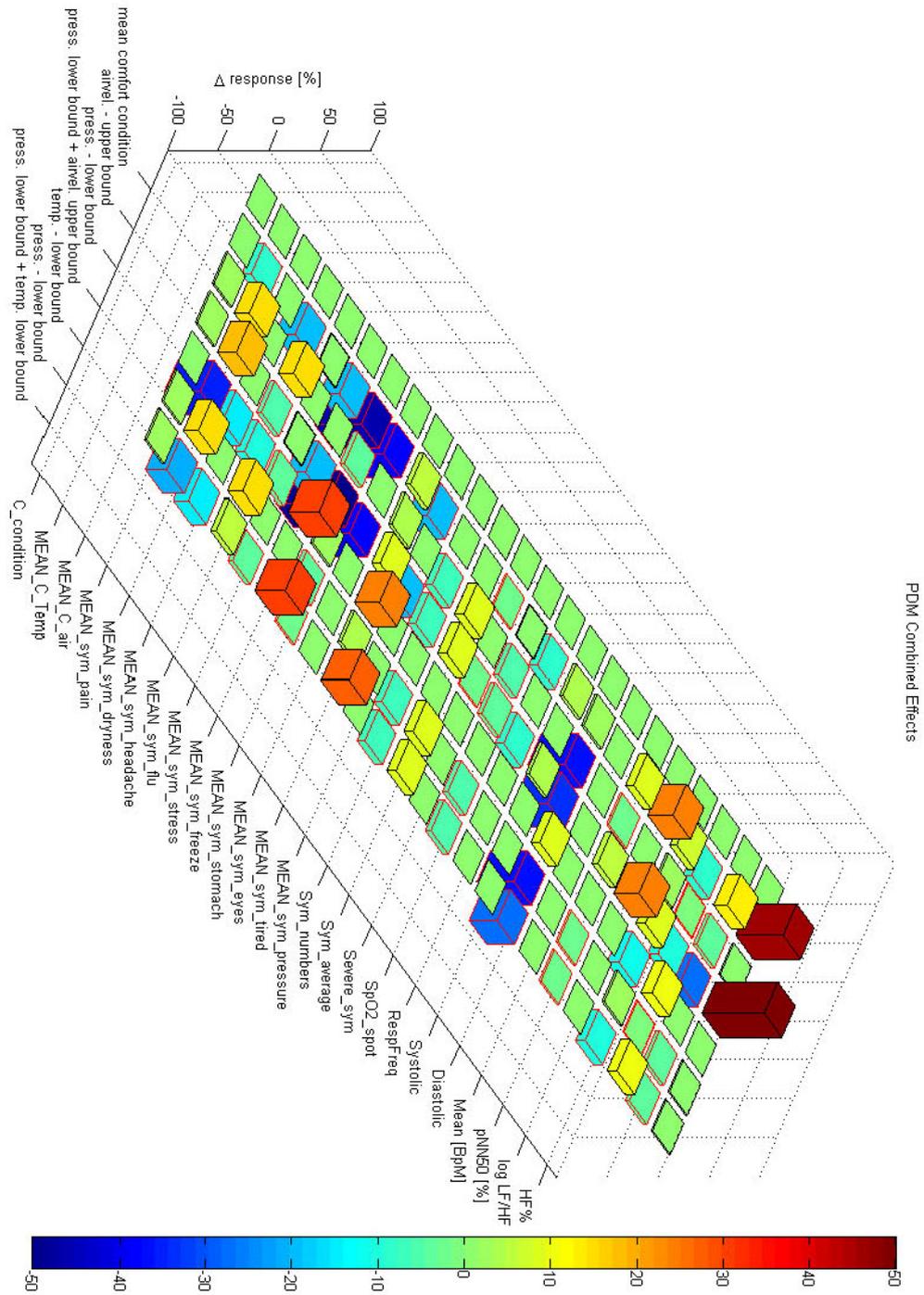


Figure 3: Combined effects: relative responses (in %) of all primary output variables evaluated with the model and resulting from some combinations of the above given variations of the input variables

### **6.3 Combined effects: Conclusions**

From the considered cases of combined effects it can be concluded that some effects in the minimum pressure condition can be slightly improved by changes in other conditions. In particular mean SpO<sub>2</sub> increases from 91.8% in the minimum pressure condition to 92.7% in the combined minimum pressure and minimum temperature condition.

The value for MEAN\_sym\_pain also slightly improves, from 1.6 in the minimum pressure condition to 1.4 in the combined minimum pressure and minimum temperature condition.

However, besides these slight improvements there are also some other output variables that get worse in the combined minimum pressure and minimum temperature condition. In particular MEAN\_sym\_headache and MEAN\_sym\_freeze increase from 1.1 to 1.3, and from 1.5 to 2.0, respectively.

## **7 Conclusions**

The impact of the cabin environment on passengers' health and well-being has got increasing attention in the past decade. There is a growing need to improve the passengers comfort onboard aircraft further. The ICE experiments have resulted in an extensive data set on health and well-being of passengers. To evaluate the impact of technical and/or behavioural changes of the cabin environment and its passengers on the passengers' health and well-being, prediction of the key indicators of passengers' health and well-being as a function of key cabin environmental variables is needed.

The models developed within the ICE project provide a representation of the dependencies of various physiological and psychological aspects of aircraft passengers on aircraft cabin conditions, flight characteristics and passenger characteristics, including behaviour. The software implementation of the models allows for quick computational evaluation of this representation.

The model has been applied in several cases that assess the effects of the cabin conditions on the health and well-being of aircraft passengers in order to prepare for the technical and behavioural recommendations for the various stakeholders.

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