



University of Southern Denmark

Bachelor Thesis

Optimal control of ventilation systems

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*In memory of my mom. You left fingerprints of grace on our lives. You
shan't be forgotten.*

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Abstract

Nowadays, most ventilation systems in use are being calibrated manually. Considering this and the need to ensure sufficient ventilation in all rooms, the systems normally ran at a much higher capacity than is really needed. Due to this, there are good opportunities to achieve large energy savings by introducing optimal control strategies with the aim of ensuring sufficient air ventilation at minimum energy consumption. In order to facilitate this, ventilation systems with valves situated at each exit grill will be considered as this opens up for local control of the ventilated air.

Optimal control strategies give the requirements that are needed, with the least energy consumption in each situation. In order to do the optimal control in ventilation systems, the first step is to know the fundamental equations and how these systems work. To implement the optimal control in these systems, the main parameters has to be known. Some parameters such as the parameters of the exit valves and fan features will be known but other parameters like ducts will not be known (usually, the system is already built and it is not known how the ducts are). These parameters have to be estimated. Now the current challenge is to design how to estimate these parameters of ventilation systems. If the parameters are known, the system can work with a minimum energy consumption for each situation. Consequently, you will reach the best efficiency.

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List of variables

- Q_i = quantity of air in each point i, l/s
 K_i = loss constant in each point i, $Pa/(l/s)^2$
 K_{vj} = loss constant of each valves j
 K_{gj} = loss constant of each exit gill j, $Pa/(l/s)^2$
 a_j = loss constant of valves, $Pa/(l/s)^{kvj}$
 Q_{vj} = quantity of air in each valve, l/s
 Q_{gj} = quantity of air in each exit grill, l/s
 P_{drop} = drop pressure, Pa
A = static pressure of the fan, shut off point, Pa
B = characteristic shape of the fan, $Pa/(l/s)^2$
Q = quantity of air, l/s
 P_k = pressure in point K, balance points, Pa
 Q_{input} = quantity of air that comes into a balance point, l/s
 Q_{output} = quantity of air that goes out from a balance point, l/s
 x_n = different points in Newton method algorithm
 ϵ = distance between two consecutive points in Newton method algorithm iteration
- F = vector of all equations
 $F_1(x)$ = one equation from the system
 min_x = minimum value depends of x
 n_1 = velocity of the fan in point 1
 n_2 = velocity of the fan in point 2
 Fan_{power} = theoretical power of the fan, W
 Q_{wp} = quantity of air in working point, m^3/s
 P_{wp} = static pressure in the working point, Pa

Chapter 1

Introduction

This project is related to ventilation systems in the workplaces. The main goal is to put enough air in offices with the minimum energy consumption.

In order to achieve this goal, the search was about the optimal control of ventilation systems. It was about searching for these VAV (Variable Air Volume) systems. Most of the information collected, was regarding optimal control in HVAC (Heating, Ventilating and Air Conditioning) systems. However in this project, the main aim is only to control the ventilation. It was attempted to apply this research in the ventilation control, but since this project was considered as a steady state in the ventilation systems, it was impossible to apply these strategies.

This study was considered as a steady state system because, when the air flow is changing (transient state in a real office), it takes some minutes, but some minutes, if it only takes care of air flow, it is a good assumption to be considered. In this way the calculations about these systems are simplified. In other way, if it has to beware about the temperature control (HVAC), then it have to take care more about the time ([1] to [7]) and it would not be possible to work in a steady state, in order to get a good optimal control.

Therefore, the project changed to estimate the parameters but with the same aim of ensuring sufficient air ventilation at minimum energy consumption.

In order to estimate the parameter of one ventilation system, the first step was to make reference to some system like it is done in the figure 1.

Once this was known, the following steps in the project were to find out the main equations of this particular system, losses in ducts, fan equations, losses in exit valves (for example in each room). After this research process, a model to work with was designed, and this can be seen in model development chapter.

With this model built, in order to estimate the parameters, some other

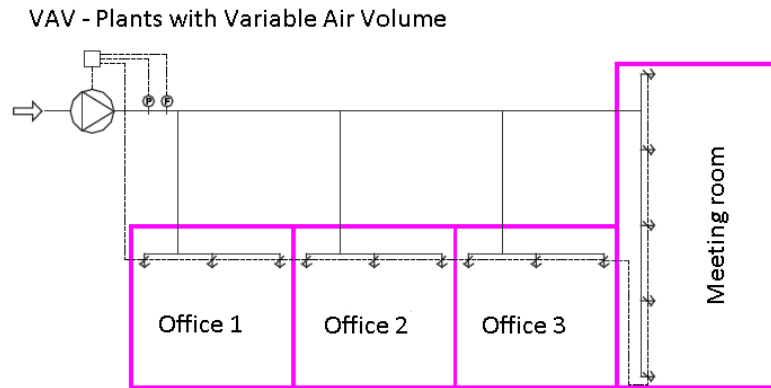


Figure 1.1: Ventilation system

values like the inputs and output of the system have to be known (input are the variables that can be changed and output is variables that can be measured). It will be explained in more detail and how it was solved in the chapter parameter estimation.

After estimate the parameters, some noise was considered in the measurements. In this way, the deviation of estimated parameters was seen when the measurements have some noise (due to bad measurements and other factors).

Last step in this project was to set up different positions of valves in order to get a minimum energy consumption. Therefore, showing the energy saved with this new system.

Chapter 2

Model development

In order to make this study, it was necessary to create a mathematical model to work with. For this project there was not any available office to make the tests that were necessary to do, therefore, all the tests that should have been done in an office will be done in the model. This model has to represent a general ventilation system. Because of that, the next model was chosen:

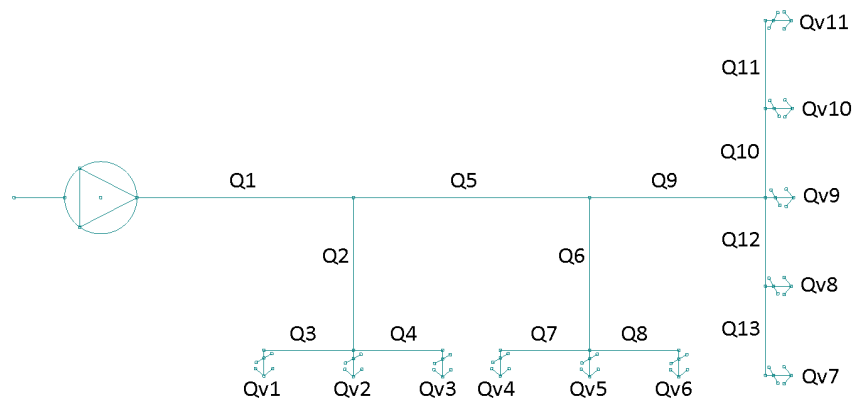


Figure 2.1: Model with variables of amount of air

In the figure 2.1, Q_i refers to the amount of air in each duct and Q_{vj} makes reference to the amount of air in each valve. The i makes reference to the number of each tube following the numbers from the figures 2.1 and j makes reference to the number of each valve, following the numbers in figure 2.1.

Figure 2.2 represents the losses of air in each ducts (K_i) and the losses in each exit valves (K_{vj}). The symbols of controlled valves and fan are in figure 2.3.

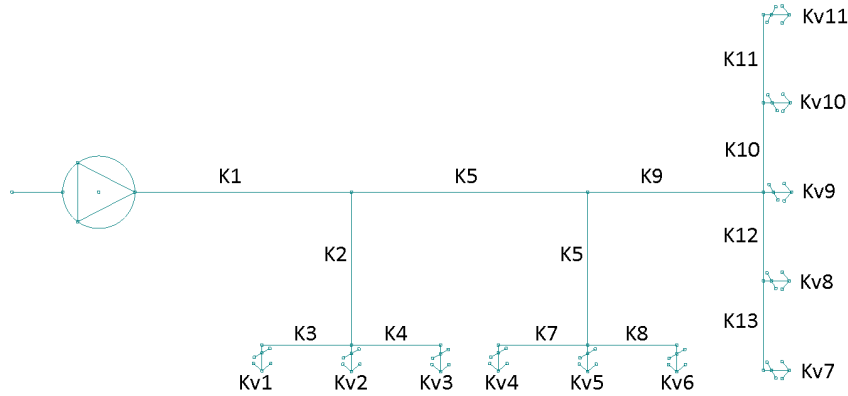


Figure 2.2: Model with variables of losses



Figure 2.3: Controlled valves symbol(left) and fan symbol (right)

K_i losses are dependent on Q_i^2 [8], there is also some supplier that give them in table to make the losses calculations easier [9]. The pressure will be calculated in pascals, the amount of air in (l/s), so due to this, the K_i should be in the corresponding units. It was used (l/s) because the manuals of the different suppliers are in this units. By use of this units, it turns to be easier to make the calculations when some losses need to be added.

The losses in exit valves (K_{vj}) were chosen from one supplier [9] because these losses depend on the construction and shape and it could not be possible to test them in a real office. As it was proved in the tables of the supplier, the losses in these valves had two coefficients that follow the next law:

$$P_{drop} = a_j Q_{vj}^{K_{vj}}; \quad (2.1)$$

where Q_{vj} is the quantity of air in each valve j and P_{drop} is the pressure drop in each valve j .

In order to make the calculations simpler and since the supplier did not give the real equation of pressure loss in the valves (P_{drop}), only K_{vj} was used in the calculations and the value of a_j was assumed to be equal to $1[Pa/(l/s)^{k_{vj}}]$. Due to this assumption, in the comparison part of this project the available working range of the valves should be checked (it is explained in the comparison chapter). Also, if it is wanted to work with this a_j as a variable, the method employed can also be used by adding this variable.

In this way, there will be less variables, and it will be easier to follow the calculations. The variables a_j and K_{vj} depend on the position of the valve, so both depend on the same variable.

The losses as K_{vj} and K_i are produced due to friction in the tubes and valves.

In this project, it was not taken into account minor losses. These losses can also be found in some tables from different suppliers [9]. There are a lot of different types of these losses (and there are also some references about these losses in some books like [8]). The minor losses are just a constant that can be added in the (K_i) of the corresponding tube, therefore they were not added in the system to avoid a large amount of coefficients, variables, and constants (it is a small change, if it is wanted to go deep in a real system). The minor losses in these systems depend on the geometrical construction of the tubes and the impact of the construction has on the air flow due to changes in velocity and cross flow fluid accelerations.

The fan is represented by the equation 2.2.

$$A = BQ^2 \tag{2.2}$$

This is a simplified equation in order to make the calculation more understandable (in reality this equation has a constant B in the second order and another constant C in the first order) and it is a good approximation to be considered as a parabolic shape, in order to do the analytical calculus. The constant A refers to the maximum static pressure that one fan can reach (shut off point in the figure 2.4). B is the constant that makes the characteristic shape (parabolic shape) of the fan. Also with constant B , the maximum air that the fan can produce can be calculated (maximum free delivery point in the figure 2.4).

In the next few lines, the characteristics equations with the different meanings will be shown. The model that was exposed before, requires a lot of equations and steps to show how was solved, so a simplified version of the model will be shown instead. These equations are a introduction to the

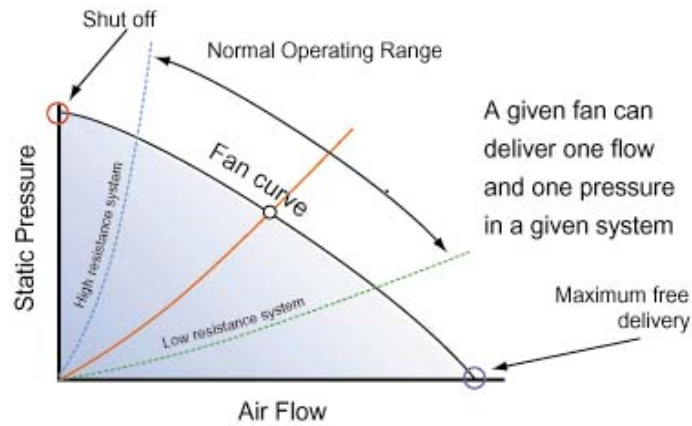


Figure 2.4: Fan characteristic curve

model (all equations from the model will be show in the appendix A).
The figure 2.5 is the simplified model.

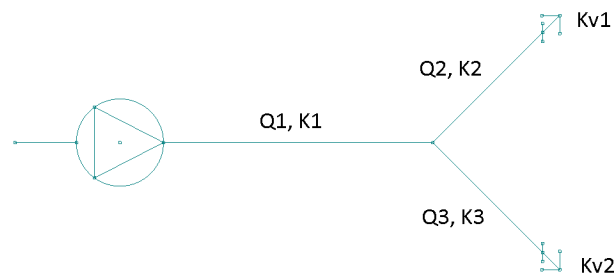


Figure 2.5: Simplified model

The steps to solve this are:

1. Select a point to make the energy and mass balance (P_k). It has to be done in all P_k that the system have. These P_k are all points where there is a division of air flow. The simplified version (figure 2.6) have one.
2. Make the balance of mass in each (P_k):

$$Q_{input} = Q_{output} \quad (2.3)$$

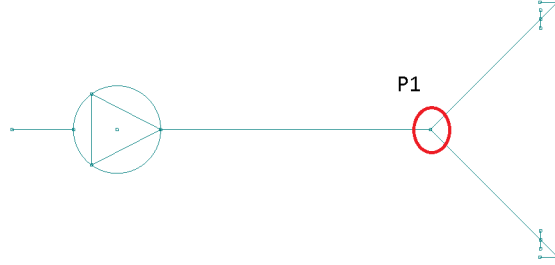


Figure 2.6: Simplified model with balance point

Then, it is:

$$Q_1 = Q_2 + Q_3 \quad (2.4)$$

3. Make the balance of energy in each (P_k):

- The first equation, it is the union between the system (first point of balance) and the fan:

$$P_k = A - BQ_i^2 - K_iQ_i^2 \quad (2.5)$$

- This equation will be applied between each P_k and each exit (valve):

$$P_k = K_iQ_i^2 + a_jQ_{vj}^{K_{vj}} \quad (2.6)$$

- This equation will be used in the case when there is more than one point of balance (in this simplified model it will not be used due to that there is only one point):

$$P_k = K_iQ_i^2 + P_{k+1} \quad (2.7)$$

Then it is:

$$P_1 = A - BQ_1^2 - K_1Q_1^2 \quad (2.8)$$

$$P_1 = K_2Q_2^2 + a_1Q_{v1}^{K_{v1}} \quad (2.9)$$

$$P_1 = K_3Q_3^2 + a_2Q_{v2}^{K_{v2}} \quad (2.10)$$

Putting all equations together and reordering them, the final equations are shown and will be used in the next chapter, parameter estimation.

$$A - B(Q_2 + Q_3)^2 - K_1(Q_2 + Q_3)^2 - K_2Q_2^2 - a_1Q_{v1}^{K_{v1}} = 0 \quad (2.11)$$

$$A - B(Q_2 + Q_3)^2 - K_1(Q_2 + Q_3)^2 - K_3Q_3^2 - a_2Q_{v2}^{K_{v2}} = 0 \quad (2.12)$$

These equations are the characteristic equations from the simplified system. All the characteristic equations from the model can be found in the appendix A. It can be seen from these equations the dependence on several variables. Usually, A,B (features of the fan), K_{vi} (features of exit valves) are known. The other parameter can be known or not. These equations are non-linear. In the next chapter, it will be explained how to solve these equations and different types of system that can be found.

Chapter 3

Parameter estimation

In this chapter it will be shown how to solve the equations (2.10, 2.11) in order to get the parameter that it is needed. In this system, if it is known the parameter of the ventilation system (K_i), all quantities of air can be calculated in each exit valve because, usually (stated previously) the fan features and exit valves features are known, therefore the problem would be solved. But if the parameters are unknown, we cannot calculate it. To be able to solve this system, the parameters need to be estimated. It will be show in this chapter how to estimate the parameters of one system, where the structure is known (the structure is the graphic of pipes).

The terms of work will be defined in the next chapter. The inputs in the system are the parameters that can be controlled, like the position of exit valves (K_{vj}) and the fan velocity. With these inputs, the system can be changed, that is to say, the quantity of air in exit valves can be changed. The outputs in the system are the quantity of air in each exit valve. There are 11 valves in the model (due to this the number of measuring sensor that should be in the real office are 11). The number of equations are the same as the number of valves in the system, this can be seen in the development chapter (2 equation, 2 valves in simplified model).

In order to estimate the parameters, some measurements in the system have to be taken. At least one test should be done in an office to get the quantities of air in each exit valve with a determined position of the exit valves. With these inputs and outputs values, the parameters can be estimated. However, as it was written above, there was not any available office to work with. Due to that, the output values that should be taken with sensors in the office were calculated with Matlab using the equations from the model.

The input values used in Matlab were different values of the K_{vj} that correspond with different positions of exit valves, the values of the pipe pa-

rameters were taken from one supplier [9] and the features of the fan were taken from a standard fan (FANTECH). With these values, the outputs of the system were calculated. To solve this problem as it can be seen in the equations 2.11 and 2.12, a non-linear system should be solved using the same equations and unknowns. In this project, Newton Method was used in order to solve this non-linear equations. This method was chosen because it has a quadratic convergence, a fast solution will be find. However, this method has an inconvenience, if in the way to find the solution there is a minimum, it will get stuck there. This behavior can be seen in equation 3.3, where the derivative of a minimum is 0, therefore at this point it will stop. This was taken into account in this project.

Newton method [12] is a rootfinding algorithm that uses the first term of Taylor series of a function $f(x)$ in the vicinity of a suspected root. In this method it has to give a starting point x_0 . This is very important because if a bad starting point is given, the algorithm might diverge. The equation 3.1 is the general equation.

$$f(x_0 + \epsilon) \approx f(x_0) + f'(x_0)\epsilon \quad (3.1)$$

In this case, the values of the variables $x = Q_{vj}$ that makes the the equations equal to zero need to be found (the other variables are known). And then these variables are the solution of the quantity of air in each valve.

$$f(x_0 + \epsilon) = 0 \quad (3.2)$$

Solving the general equation and letting $x_1 = x_0 + \epsilon_0$, calculating a new ϵ_1 and repeating the process until it converges to a fixed point ($\epsilon_1 = 0$). This point is the root that it was searched. In the equation 3.3, it can be seen the algorithm that it was used.

$$x_{n+1} = x_n + \frac{f(x_n)}{f'(x_n)} \quad (3.3)$$

Usually, these systems have more parameters(that are unknown) than equations, as it can be seen in simplified model (equations 2.11 and 2.12) has 3 parameters to estimate (K_1, K_2, K_3) and 2 equations. Therefore, to be able to solve it, it is needed to increase the number of equations. One way is to put different inputs and with each input, it is taken one block of equations (characteristic equations from the system), so, with all different inputs it will have different blocks of equations dependent on the same unknown (parameters). In this way, more equations than unknowns are in the system and the system can be solved (in real life, this part of increasing the number of equations corresponds on making some test in the office with

different position of exit valves). The number of tests that should be done depend on the system. These should be done as much as possible, in order to get a good accuracy in the results but at some point, more test will not be needed. In this point, it will increase the number of equations (increase the computer time, and testing time) without any improvement. There is a balance between accuracy in the parameter estimation and number of test that should be done. In this chapter the number of tests to get good results in this model and some references about the model will be detailed. Consequently, several calculus with Matlab were done in order to get different outputs (associated with inputs) to be able to estimate the parameters.

Newton method can be used to solve this parameters since it is working in theoretical case, due to the inputs and outputs values did not have any noise (this values come from Matlab, therefore they do not have any error or it can be neglected). In real life, when the measurements are taken, there could be some noise (bad measurements like bad set up of sensors, bad approximation between the real value of K_{vi} and the estimated value due to position), below it will be discussed about this. In this way, Newton method could not converge (in this equations for example could happen that there is not 0), or could give a wrong approximation. In order to get the best approximation although there is some noise, nonlinear least-squares method was used (some constrains can be added).

Non-linear least squares method [11] is used in system with non-linear equations when there are more observations than unknowns. With this method an improvement of the solution can be found (respect to Newton method) because, if the solution have a minimum where the equation do not reach 0, Newton method will not converge. With non-linear least squares method, some lower and upper bounds can be added. This allow to guide the method into a region where it is wanted to search. In order to use this method, the equations have to be defined as:

$$(F(x, z) - Y) \tag{3.4}$$

where x is the coefficient that solve the problem, Y is the observed data, z is the input data and $F(x, z)$ is the vector or matrix valued function.

In the equation 3.1 the general equation can be seen. The non-linear least squares method will calculate the minimum of these functions over the change of x . In this method (as Newton method) a initial point(x) is needed to start the calculation (as close as possible).

$$\min_x \|F(x, z) - Y\|_2^2 = \min_x \sum_i (F_1(x, z_i) - Y_i)^2 \tag{3.5}$$

where i is the number of equation.

Lower bounds were used in order to get consistent results (due to a negative K_i is physically impossible). In the system Y is the measurement of the quantity of air in each valve. The $F(x, z)$ in the system with exit valves can not be put as in the equation 3.4. This is the reason why it has been put inside of the least square method a Newton method to make the $F(x, z)$. The Newton method will solve the amount of air in each valve (as it was done before to get the quantity of air in each valve) with the parameters ($x = K_i$) and the inputs ($z = K_{vj}$). In this way, non-linear least squares method can compare the measurements of air(Y), with the quantities of air from the model $F(x, z)$ (solved with Newton method) and minimize over the change of the parameters (see appendix B).

In the next part of this chapter, it will be explained how it was solved with the simplified model and some references about the model that was used in this project will be made. The resolution follow the next steps:

1. This part consist on the test in the office. In this case, some different inputs (K_{vj}) were written in Matlab and equations 2.11,2.12 were solved to get the outputs (Q_{vj} , like sensor in real life):

The inputs that were used are K_{v1}, K_{v2} . The parameters of the office are $K_1 = 0,004$, $K_2 = 0,004$, $K_3 = 0,004$, $A = 100$ and $B = 0,004$. Using the Newton method with Matlab (calculus in appendix F), the obtained are in Table 3.1.

Test	1	2
Input kv1	2	1,5
Input kv2	2	2
Output Qv1[l/s]	9,8247	20,2633
Output Qv2[l/s]	9,8247	9,6170

Table 3.1: Test in simplified model

2. From this table the value of Y (measured data) can be taken as well as the input data (K_{vj}). With the input data and the estimate parameters (initial guess of K_1 , K_2 and K_3), Newton method can calculate the amount of air in each valve and give back to non-linear least square method. Non-linear least square method will calculate the value and it will give another parameters in order to minimize this value until reaching a minimum (the best case it would be 0, no error). In this project there was no office available, first, some outputs were generated with K_1 , K_2 and K_3 . Then, in the estimation part, with the generated

outputs and inputs, the values of K_1 , K_2 and K_3 should be found. Due to this, in this project it was checked, if the estimated parameters fit perfectly with K_1 , K_2 and K_3 or there was some error. In the next equation it will be explained briefly how it works.

$$F = (f(x, z_1) - 9,8247)^2 + (f(x, z_2) - 9,8247)^2 + (f(x, z_3) - 20,2633)^2 + (f(x, z_4) - 9,6170)^2 \quad (3.6)$$

where estimated parameter $x(K_1, K_2$ and $K_3)$ is changing each iteration of non-linear least squares method. Then $z_1(K_{v1}, K_{v2})$, $z_2(K_{v1}, K_{v2})$ depends on test 1 and $z_3(K_{v1}, K_{v2})$, $z_4(K_{v1}, K_{v2})$ depends on test 2. Newton method calculate for each $f(x, z_i)$ with the x and z_i one quantity of air. Non-linear least squares method is minimizing this function F over the change of x .

In this case, with two test was enough to get $K_1 = 0,004$, $K_2 = 0,004$, $K_3 = 0,004$, therefore it was found the correct values (calculus in appendix F).

In the model the same steps than before were applied. The characteristics of the system are $A = 1000$, $B = 0,004$ and all $K_i = 0,004$. First, the test on the model was made (see equations in appendix A with exit valves), previously done in the simplified model. With this test the output values were gotten (amount of air in each exit valve). In this step, the number of equations and unknowns are the same (as in the simplified model). The results of the tests that were done, can be found in appendix D (Test in model) and the algorithm to solve the equations can be seen in appendix B.

As it was done in the simplified model, with all measured data (Q_{vj}) and input data (K_{vj}), the non-linear least square method was used and newton method inside to obtain the amount of air in order to compare and minimize as before. In this case, it will be working with 13 unknowns (parameters) and 11 equations.

The calculations were done using Matlab (see appendix B) and the results of the parameter estimation was $K_i = 0,004$. Again perfect values were reached. In order to get enough accuracy in the results, some tests had to be done. In this project, 24 tests were done and perfect results were gotten in the estimation. In order to see if is possible with less test to get the same result, the number of tests taken into account in the parameter estimation were changed. It was checked that 5 test were enough for this model (this is a field to study because when it is working in this test, it is not known how many tests it are needed necessary to do).

In this example, if 24 tests are used instead of 5, the computer time increased 194,83% (24 equations = 8579,448seconds, around 2 hours 23minutes and 5 equations = 2909,925 seconds, around 48,5 minutes, this test was done in a computer with Intel Core i3 M330 2,13GHz, with windows 7). Another point to take in account is the time that you have to spend doing this test, as less as possible test in order to get the maximum efficiency.

All the previous calculations were just theoretical. In real life, there are a lot of factors that can modify the theoretical calculations. One factor could be, a bad approximation of losses in valves with the position. This factor in this project it was not taken into account. Another factor could be the measuring error with sensors (outputs), during the testing. The measurements could be taken wrong due to bad set up of sensors and errors in sensors. The last factor was taken into account. In order to see how much influence have this factor in the parameter estimation, a Gaussian noise was added in the outputs values (measures of quantities of air in each valve, from appendix D). The Gaussian noise was written as a Normal distribution, a mean and standard deviation were needed to be able to work with this distribution [13] with mean the output values, and the standard deviation was written as one percentage of the mean. Four different percentages were put (0,1%, 1%, 5% and 10%) in order to know the influence. In this way, the calculus were closer to real life conditions. These calculus were only done in the model and the equations are in appendix C.

Because working with statistics, 10 estimates was made for each percentage of noise and for each number of equations (5,12,24) to get a consistent sample (the time to make all this estimates was large, so it were not done more test). Appendix C will show, how the different outputs with noise (amount of air in each valve) were generated for each estimation as well as all the estimations (with the calculus). In the next figures the mean and standard deviation from these estimations will be analyzed.

First, the results with 5 tests will be explained (minimum value that it was reached the correct value of the parameters without noise).

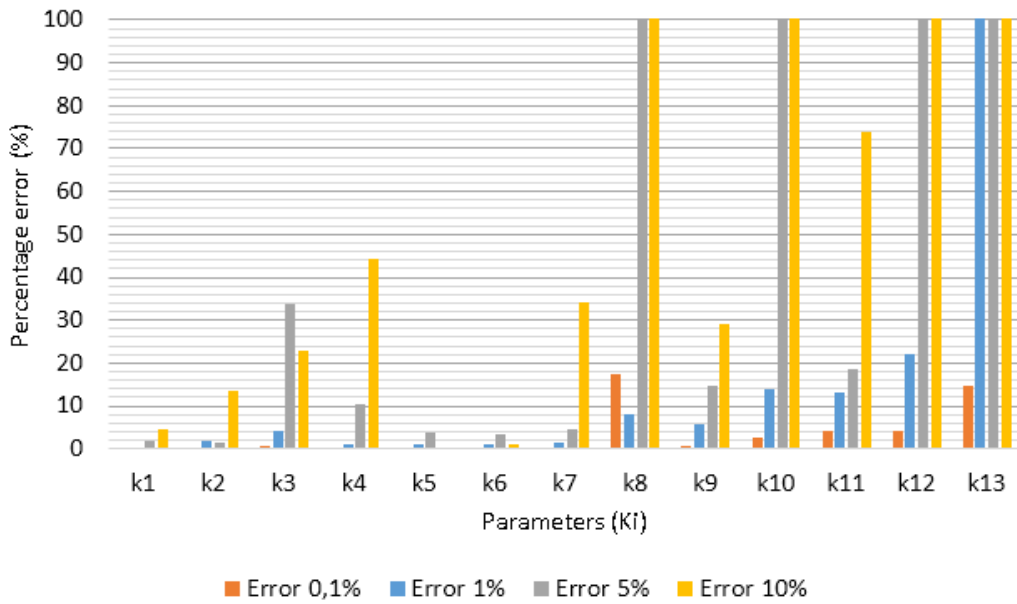


Figure 3.1: Mean of estimate parameters with 5 test

In the figure 3.1 the estimation of each parameter can be seen. Here, it is shown the mean [13] of the 10 simulations (since the noise is a random signal). This figure shows the influence of noise, in the estimation. It can be seen that with 10% of noise, the estimation of the parameters have a big error (unacceptable higher than 100%). The estimation with less noise reach better approximation, but with 0,1% of noise in some points the error is bigger than 10%, therefore the approximation of 5 test under low noise conditions is not good enough.

Another trend can be seen. The parameters which are further from the fan reach worse results. Some errors are higher than 100% but these results are far away from the goal, therefore showing them in the study is meaningless. The error was put in percentage, in this way it is easy to compare with the others figures.

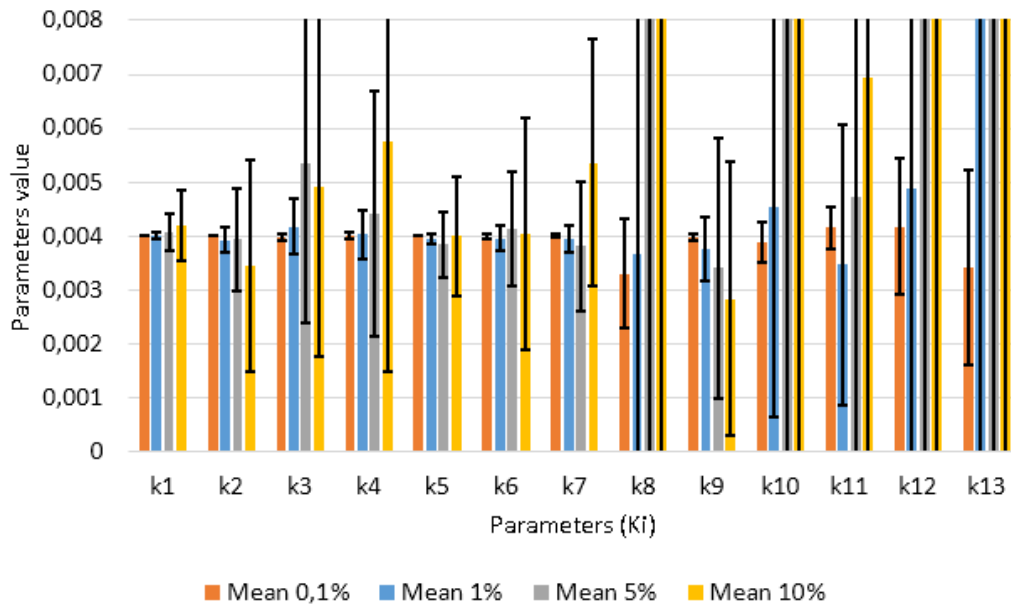


Figure 3.2: Standard deviation of estimate parameters with 5 test

In the figure 3.2 the standard deviation of the estimate parameters can be seen. The bars show the mean and the black line of each bar shows the standard deviation. This figure shows the high deviation when the measurements have some noise. Only with the lower signal noise (0,1%), the deviation is lower than 50% of the mean value in all parameters. It can be seen that 5 test are not enough to give a good parameter estimation (under noise conditions), since when there is a signal with low noise conditions, a high deviation in the estimation takes place.

Another trend can be seen, the parameters which are further from the fan reaches higher deviations. Some deviations are higher than the scale of the figure but this value was chosen in order to compare with the other estimates with more tests as well as to see parameter values below 100% of error.

Now, the results with 12 tests will be analyzed in detail.

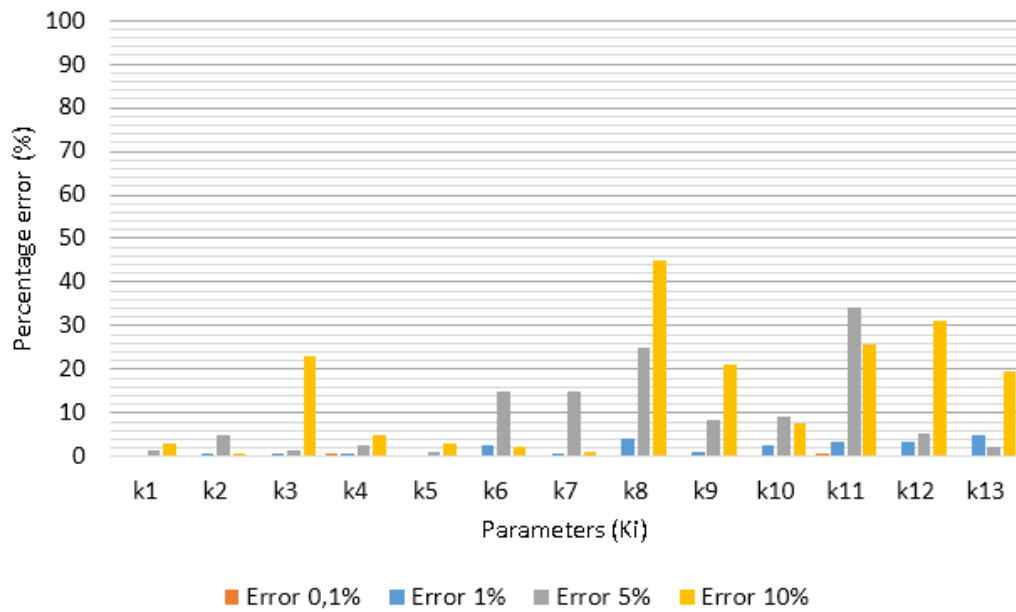


Figure 3.3: Mean of estimate parameters with 12 test

The figure 3.3 show the mean of parameter estimation with 12 tests. It can be seen that there is a big difference between 5 tests and 12 test. With more test, the results are closer to the real values but with 10% and 5% of noise, there are some values with large error. The test with 1% of noise reach values below 5% of error in each parameter and the parameter estimation with 0,1% of noise reach almost perfect values, below 1% of error in each parameter.

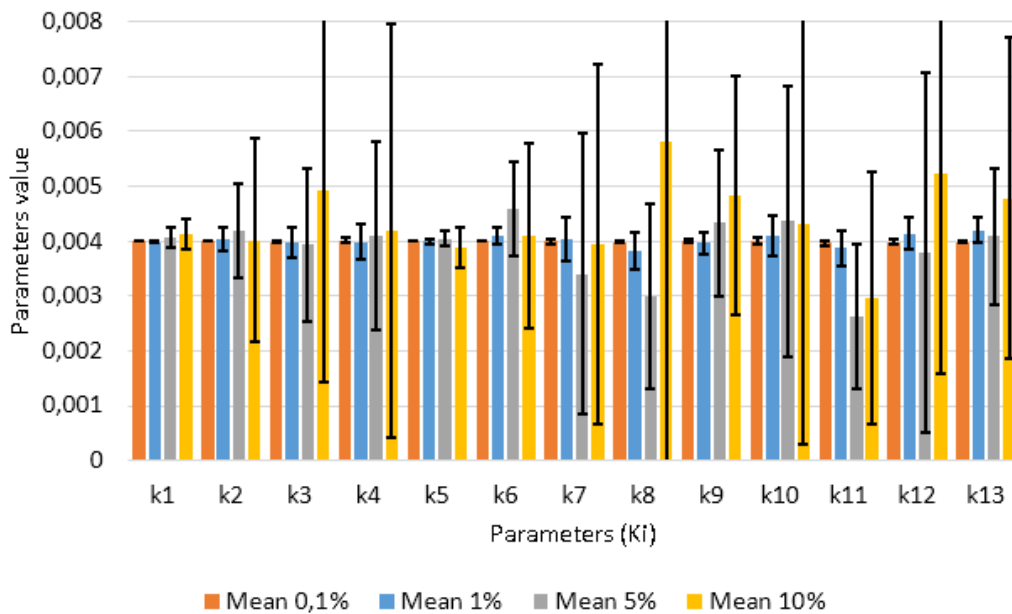


Figure 3.4: Standard deviation of estimate parameters with 12 test

In the figure 3.4 the standard deviation of the parameter estimation can be seen. The deviation with 10% and 5% of noise is large. With lower values of noise (0,1% and 1%) the deviation is low. Certainly, if it is working with low noise (0,1%), the deviation is lower 0,14% (appendix C). It can be seen that 12 test are enough to give a good parameter estimation, under low noise conditions.

Another trend can be seen, the parameters which are further from the fan reached higher deviations. In this point after the use of more test, if it is wanted to reach better parameter estimation with noise, more sensors should be added. These sensors located further from the fan will give more characteristics about the system. With these new characteristics, it should give better parameter estimation under noisy conditions. This is another field of study, where the sensors should be put to get better approximation.

After studying the system with 12 tests, the trend does not change with more test (it can be seen in appendix F with 24 tests).

Chapter 4

Comparison between different strategies of control

In this chapter the energy consumption in same system will be compared by using different strategies. On the one hand, a system with exit grilles is used. On the other hand, a system with manually valves is used and finally a system with controlled valves is used. The graph of the model will be used but using real losses from the supplier [9], in order to get consistent results. In the figure 4.1, the system is shown.

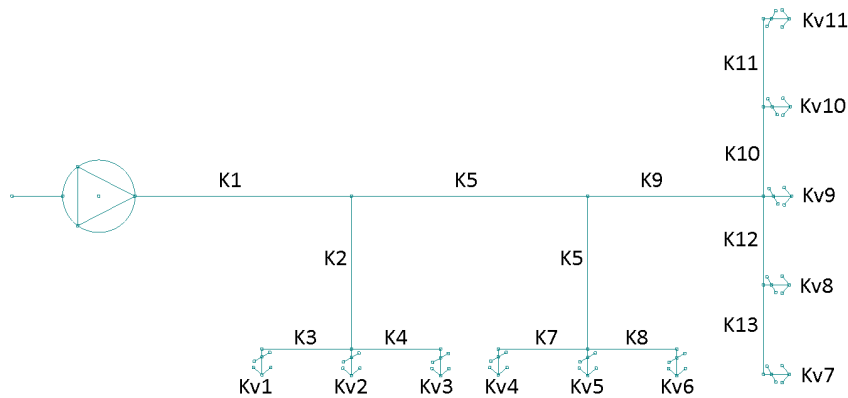


Figure 4.1: Model with variables of losses

The characteristics of the system are: $K_1 = K_5 = K_9 = 0.00006$ (diameter tube 200mm, 3m), $K_2 = K_6 = 0.0025$ (diameter tube 100mm, 3m), $K_3 = K_4 = K_7 = K_8 = K_{10} = K_{11} = K_{12} = K_{13} = 0.00125$ (diameter tube

100mm, 1.5m). The fan that was chosen to work with was MTP 306 (from FANTECH, put max A = 50 and B = 0.00025).

The whole system will be working under the norm EN 13779 [13] and with the quality of air IDA 1. This requires a default air of 20[l/s] per person. In this project, two different rooms were considered. On the one hand, small rooms where two people are assumed to be in. On the other hand, a big room (meeting room) where five people are assumed to be in. In the small rooms, there are three valves in each one (K_{v1}, K_{v2}, K_{v3} and K_{v4}, K_{v5}, K_{v6}) and in the meeting room there are 5 valves ($K_{v7}, K_{v8}, K_{v9}, K_{v10}, K_{v11}$). All the calculus for this comparisons are in appendix F.

1. System with grilles.

It was chosen in each exit point an output grill of 125mm of diameter. The characteristic of this grill is perfectly parabolic and follow the equation 4.1.

$$P_{drop} = K_{gj}Q_{gj}^2 \quad (4.1)$$

where K_{gj} is the loss in each exit grill and Q_{gj} is the quantity of air in each exit grill.

Due to this, the equations used in this project with the valves were changed (the equation from the valves to the exit grilles was changed, see in appendix A.2). With these parameters, the minimum velocity of the fan was calculated to reach the default air (minimum energy consumption). The minimum velocity of the fan to reach 20[l/s] per person is related with the characteristic curve, so if the velocity of the fan is changed, the maximum static pressure will change (shut off point from figure 2.4). This change can be seen in figure 4.2. The relation between maximum static pressure and velocity of the fan follow the equation [14].

$$P_a = P_b \left(\frac{n_1}{n_2} \right)^2 \quad (4.2)$$

where P_a and P_b are different static pressures of the fan at different velocities.

In figure 4.2, the red lines are the characteristic curve of the fan and the black lines are the characteristic curve of the system. n_1, n_2 variables are different fan velocities ($n_1 > n_2$). The blue circle mark the working point and show where the fan is working. This point depends on the characteristic curve of the system, for l=1 is different than for l=2 (l

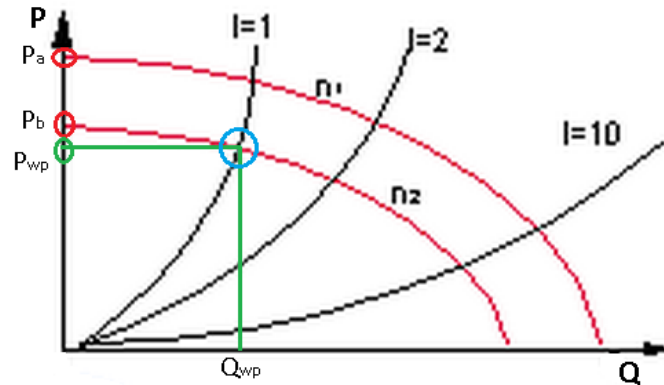


Figure 4.2: Fan curves and working point

show different system characteristics). From the working point, if it is followed the horizontal line until the P axis, this value represent the pressure in the working point. On the other hand, if the vertical line is followed until the Q axis, this value is the quantity of air that the fan is putting in the system. In the equations, the static pressure was changed (A parameter was present in the equations along this project). The quantities of air in each valve are shown in table 4.1. This quantities are given with a shut off point of 32 pascals. With lower shut off points the air quantity was below 20[l/s] per person in each office.

Exit grilles	Values[l/s]
Q1	17.5756
Q2	17.8662
Q3	17.5756
Q4	16.9241
Q5	17.2039
Q6	16.9241
Q7	19.6970
Q8	20.0226
Q9	21.2954
Q10	20.0226
Q11	19.6970

Table 4.1: Quantity of air in each exit grill

When the quantity of air and maximum static pressure are known from

the fan (shut off point), the theoretical power can be calculated (in this theoretical power the efficiency of the fan is not taken into account). The theoretical power can be calculated with the equation 4.3 [13].

$$Fan_{power} = Q_{wp}[m^3/s]P_{wp}[Pa] \quad (4.3)$$

where Fan_{power} is the theoretical power of the fan, P_{wp} is the pressure of the fan in the working point and Q_{wp} is the quantity of air in the working point. The pressure in the working point can be calculated with the next equation:

$$P_{wp} = A - BQ_{wp}^2 \quad (4.4)$$

The Q_{wp} is also the sum of all quantities from the valves, so, the quantity of air that the fan gives to the system (both points can be taken from the working point, if it is available a graph). Therefore, the theoretical fan power can be calculated.

$$P_{wp} = A - BQ_{wp}^2 = 32 - 0.00025 \times (204.8041)^2 = 21.5138[Pa] \quad (4.5)$$

Where $Q_{wp} = 204.8041[l/s] = 0.2048[m^3/s]$

$$Fan_{power} = Q_{wp}[m^3/s]P_{wp}[Pa] = 0.2048 \times (21.5138) = 4.4060[W] \quad (4.6)$$

The theoretical power is 4.4060[W] for this system under the constrains.

2. System with manual valves.

Valves of 125mm of diameter were chosen in each exit point (to follow the same structure than before and make the minimum change in the office). In this system the calculations were done differently. First, in the equations the quantities of air in each valve were written (predefined following IDA 1). The parameters (K_i) are known. The values of A and K_{vj} are missing, therefore some iterations were done by changing the parameter A in order to get the solution of K_{vj} .

By using K_{vj} , the pressure drop can be calculated and this correspond with the losses in valves.

$$P_{drop} = a_j Q_{vj}^K \quad (4.7)$$

The pressure drop and the quantity of air in each valve are known, therefore it can be checked in the supplier table[3], if this point is available in the range of work of this valve. These calculations were done like that, due to use the assumption $a_j = 1[Pa/(l/s)^{kvj}]$. Some iterations were done and since the table only showed pressure drop over 10 pascals, this value was used as minimum drop pressure for each valve.

When the parameter A was found (shut off point, 26 pascals) to give at least 10 pascals of drop pressure in each valve, this parameter A was used in the comparison. In table 4.2, the pressure drop in each valve its shown as well as the quantity of air and the correspondent position of the valves. Figure 4.3 shows the supplier table.

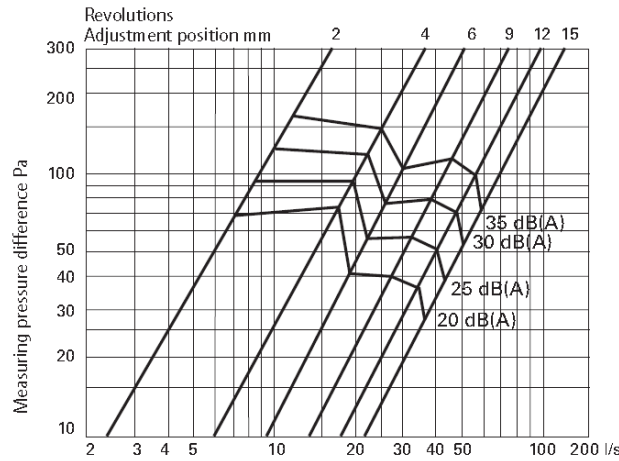


Figure 4.3: Manually valves

Valve	$P_{drop}[Pa]$	Air[l/s]	Position[mm]
1	11.73	13.34	6-9
2	11.95	13.34	6-9
3	11.73	13.34	6-9
4	10.56	13.34	6-9
5	10.77	13.34	6-9
6	10.56	13.34	6-9
7	11.67	20	12-15
8	12.17	20	12-15
9	14.18	20	9-12
10	12.17	20	12-15
11	11.67	20	12-15

Table 4.2: Correspondent position of manually valves

At this point, the static pressure in the working point can be calculated since the quantity of air in the system is known. The theoretical fan power can be calculated.

$$P_{wp} = A - BQ_{wp}^2 = 26 - 0.00025 \times (180.04)^2 = 17.8964[Pa] \quad (4.8)$$

Where $Q_{wp} = 180.04[l/s] = 0.1800[m^3/s]$

$$Fan_{power} = Q_{wp}[m^3/s]P_{wp}[Pa] = 0.1800 \times (17.8964) = 3.2214[W] \quad (4.9)$$

The theoretical power is 3.2214[W] for this system under the constrains.

3. System with controlled valves.

Valves of 125mm of diameter were chosen in each exit point (to follow the same structure than before and make the minimum change in the office). The calculus are the same than in manually valves. However, the difference is that these valves have more drop pressure in the same dimension than manually valves (it can be seen in the table from the supplier, probably because these valves have more elements). The shut off pressure was found to be 36 pascals.

The pressure drop in each valve is shown in table 4.3 as well as the quantity of air and the correspondent position of the valves (following the supplier tables, figure 4.4).

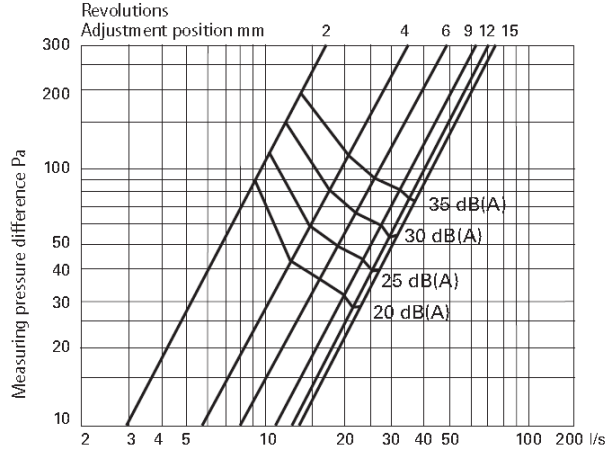


Figure 4.4: Controlled valves

Valve	$P_{drop}[Pa]$	Air[l/s]	Position[mm]
1	21.72	13.34	≈ 6
2	21.95	13.34	≈ 6
3	21.72	13.34	≈ 6
4	20.55	13.34	≈ 6
5	20.77	13.34	≈ 6
6	20.55	13.34	≈ 6
7	21.68	20	≈ 15
8	22.18	20	≈ 15
9	24.18	20	≈ 12
10	22.18	20	≈ 15
11	21.68	20	≈ 15

Table 4.3: Correspondent position of controlled valves

At this point, the static pressure in the working point can be calculated since the quantity of air in the system is known. Therefore the theoretical fan power can be calculated.

$$P_{wp} = A - BQ_{wp}^2 = 36 - 0.00025 \times (180.04)^2 = 27.8964[Pa] \quad (4.10)$$

Where $Q_{wp} = 180.04[l/s] = 0.1800[m^3/s]$

$$Fan_{power} = Q_{wp}[m^3/s]P_{wp}[Pa] = 0.1800 \times (27.8964) = 5.0214[W] \quad (4.11)$$

The theoretical power is 5.0214[W] for this system under the constrains.

The controlled valves have one advantage, they can be closed depending on the needs. Here, two examples are going to be shown. The first one shows the situation when the meeting room is not used. The second example is based on the use of just one office. In both cases, less air is needed, therefore the velocity of the fan decreases (as it was commented earlier in this chapter the shut off point decrease). In these cases the static pressure (P_{wp}) and amount of air (Q_{wp}) in the working point are lower. Accordingly, the power consumption is lower. In these case, the same constraints in valves are considered (at least 10 pascals, pressure drop).

First case.

Air is introduced in two offices. The shut off point (A) was 17 pascals. In table 4.4, the pressure drop in each valve, the quantity of air and the correspondent position of the valves are shown (following the supplier tables, figure 4.4).

Valve	$P_{drop}[Pa]$	Air[l/s]	Position[mm]
1	10.79	13.34	9-12
2	11.01	13.34	9-12
3	10.79	13.34	9-12
4	10.69	13.34	9-12
5	20.77	13.34	9-12
6	10.91	13.34	9-12

Table 4.4: Correspondent position of controlled valves

In this point, the static pressure in the working point can be calculated since the quantity of air in the system is know. Therefore the theoretical fan power can be calculated.

$$P_{wp} = A - BQ_{wp}^2 = 17 - 0.00025 \times (80.04)^2 = 15.3984[Pa] \quad (4.12)$$

Where $Q_{wp} = 80.04[l/s] = 0.0800[m^3/s]$

$$Fan_{power} = Q_{wp}[m^3/s]P_{wp}[Pa] = 0.0800 \times (15.3984) = 1.2319[W] \quad (4.13)$$

The theoretical power is 1.2319[W] for this system under the constrains.

Second case.

Air is introduced in one office. The shut off point (A) was 15 pascals. In table 4.5, the pressure drop in each valve, the quantity of air and the correspondent position of the valves are shown (following the supplier tables,figure 4.4).

Valve	$P_{drop}[Pa]$	Air[l/s]	Position[mm]
1	10.28	13.34	9-12
2	10.50	13.34	9-12
3	10.28	13.34	9-12

Table 4.5: Correspondent position of controlled valves

In this point the static pressure in the working point can be calculated and the quantity of air in the system is known. Therefore the theoretical fan power can be calculated.

$$P_{wp} = A - BQ_{wp}^2 = 15 - 0.00025 \times (40.02)^2 = 14.5996[Pa] \quad (4.14)$$

Where $Q_{wp} = 40.02[l/s] = 0.0400[m^3/s]$

$$Fan_{power} = Q_{wp}[m^3/s]P_{wp}[Pa] = 0.0400 \times (14.5996) = 0.5840[W] \quad (4.15)$$

The theoretical power is 0.5840[W] for this system under the constrains.

Chapter 5

Conclusions

Along of this thesis, the fundamental equations of ventilation system were developed in order to control them. Once these equation were known, the control in ventilation systems could be applied where all parameters were known. If the parameters were unknown, had to be estimated. In this thesis, it was shown how to estimate the parameters under different conditions of noise. In noisy conditions, more tests were necessary to do in order to get the same results than non-noisy conditions. In this project, 12 tests were enough to reach a good estimation under noise conditions. On the one hand, with 5% and 10% of noise, the results with sensors in the valves had some error and large deviation, therefore they did not reach a good estimation. On the other hand, with 1% and 0,1% the results were very close to the real value and with a low deviation, therefore a good estimation was reached. This is the reason why sensors with low error are needed to estimate the parameters in ventilation systems, when they are only in each output valve. In the estimation it was considered that the structure of pipes is known. In systems where the structure is unknown, this parameter estimation cannot be applied leaving this field for futures studies.

In systems where the structure is known, after the estimation of parameters, different control strategies can be applied and the energy consumption can be compared. In the figure 5.1, the theoretical energy consumption in one day (8 hours) can be seen. Moreover in this figure is shown, the different consumption depending on the use of the meeting room. In the system where there is no control, the consumption is the same but in the system with controlled valves the consumption change in a wide range. This can be done with different rooms but since the meeting room is the place where people make the reunions, usually the use of it is lower than the office where people is working (due to this, this comparison was considered).

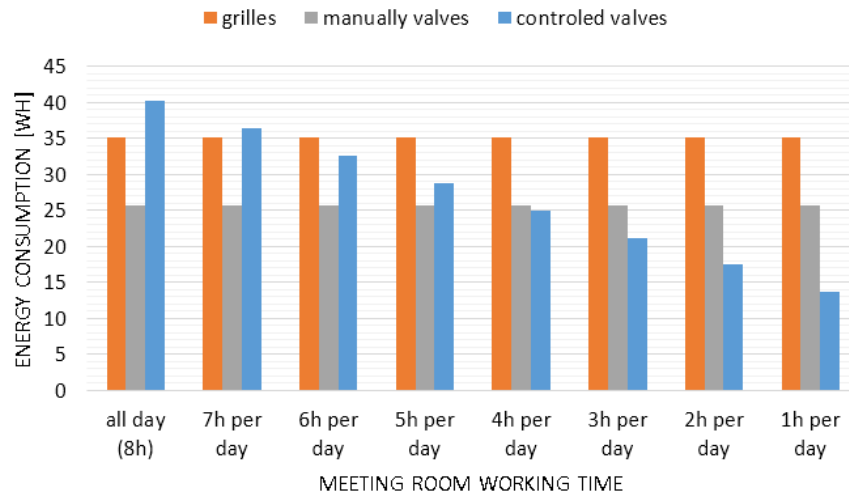


Figure 5.1: Change of energy consumption depends on working time in meeting room

It can be seen in this figure that most of times, the largest energy consumption is produced when exit grilles are used. Another point to take into account is the noise that produce the incoming air in the grilles. In the analysis made in the comparison chapter, it can be seen that with grilles the air incoming in the first office is higher than the IDA1, therefore this could produce noise in the office(depends on the design) and workers could be uncomfortable.

Manually valves have a better energy consumption than exit grilles. The energy saving of this system in comparison with exit grilles is 36.77%. The fan is running in the minimum energy consumption to introduce the enough air (IDA1). As it was stated before, the valves have the same size than the exit grilles in order to change the system (exit grilles to manually valves or controlled valves) as less as possible (change that should be done in a real office).

The controlled valves have the worst energy consumption in the case of 8 hours working. This is due to the drop pressure in these valves is higher than the noncontrolled valves (it can be seen in figure 4.3 and 4.4). Therefore, the fan has to put more pressure in the system to get the same amount of air. Following the equation of the power of the fan (4.3), more pressure for an equal amount of air, more power is required, therefore more energy is consumed. There are some other valves with different sizes that give less drops pressure, therefore less energy is consumed. However this project was

done following the same dimension in the exit devices (exit grilles and valves).

Following with this study, it can be seen that control valves give less energy consumption per day in comparison with manually valves when the meeting room is used less than 5 hours (it will be profitable when the use of the meeting room is below 5 hours). In the case where the meeting room has just 1 hour of use per day, the energy saving of controlled valves in comparison with exit grilles is 158,32%. If now it is compared with manually valves, the energy saving is 88,87%. In case of offices like this, it can be seen that with use of controlled valves, money can be saved. In offices where people work at different hours, or where people work longer time than others, the use of controlled valves will result in a saving of energy consumption and thus of money. At the same time, with controlled valves less CO_2 is emitted, due to they are consuming less energy.

Chapter 6

Problem formulation and time schedule

Initial problem formulation and time schedule

Nowadays, most ventilation systems in use are being calibrated manually. Due to this fact and the need to ensure sufficient ventilation in all rooms, the systems are normally running at much higher capacity than is really needed. This is why there are good opportunities to achieve large energy saving by introducing optimal control strategies with the aim of ensuring sufficient air ventilation at minimum energy consumption. In order to facilitate this, ventilation systems with valves situated at each exit grill will be considered as this opens up for local control of the ventilated air.

This project is part of a larger ELFORSK project, with SDU as one of the partners. The part of the project located at SDU is aimed at modeling, parameter identification and control of arbitrary ventilation systems.

All of this studies will be done under the ventilation standards.

What will be done in this project

Research:

The first step will be to research about different ventilation systems to get enough knowledge about this topic. Some research about optimal control will be done (together with energy consumption) to see the goal of the project.

Modeling:

The second part that will be considered in this project is how to model ventilation systems. The first steps will consist on research about what types of variables are involved in this systems, as pressure losses, conservation of

mass and so on. After this, some general values of these variables could be added from different suppliers of this components. Finally, a small ventilation system model will be done to work with.

State space:

When model is built, the next step in the project is start with put the ventilation system model in state variables. Right after, some simple controls of this system will be done. Simple control is considered as a change on the quantity of air in the system in different work points.

Optimal control:

After these simple controls, some research about different optimal control strategies will be done. These optimal control strategies will be put in ventilation system model to see how they are working, some simulations in Simulink will be done to show in a graph. In this way, the differences of performance between, manually controlled systems and electrically controlled system can be easily seen.

Delimitation

This project will be focus on control and modeling of ventilation systems. Nothing about parameter identification, neither calibration will be done. A lot of things more can also be controlled, like the quantity of CO_2 in the air (so depends of this, you will introduce more quantity of new air or less), temperature inside of your office, humidity and so on. But all of these parameters will not be considered since there is no time for everything, so this could be a new line of study for another bachelor thesis.

The next figure shown the risks from the initial plan schedule.

Risk	Description	Plan B
1	If there is a lot of problems in use of optimal control and it cannot be apply to the modeling	define some points of study to compare controlled systems and manual ventilation systems and verify that it is possible to go to this points with the valves through the control.

Figure 6.1: Risk 1

Explanations about the changes

Following the time plan the first two tasks were done without any change. Initially, it was thought that there is no problem in the third task, only in the optimal control task. When it was working in state space task, it was realized that there was not possible to apply the optimal control strategies, since a steady state air flow was considered. Therefore the task in the project had to be changed, consequently the time schedule. After the change, the new tasks are shown in the final time schedule. The parameter estimation task was solved without any problem, it was used the equations from the model, with the testing data to estimate the parameters with non-linear least squares method (different way than actually was solved). But when some noise was added (compare different estimations task), it was realized that some equations became inconsistent. The equation that gives inconsistent results was equation 6.1.

$$\min_x \|F(x)\|_2^2 = \min_x (F_1(x)^2 + F_2(x)^2 + \dots + F_n(x)^2) \quad (6.1)$$

where n is the number of equations of the system and x the parameters to estimate. This function minimizes the value over the change of x .

Therefore the non-linear least squares method was used in a different way (how it was explained). In this way, the noise is not introduced in the model equations, therefore the results are more reliable. This change induced to delay the parameter estimation schedule, consequently the comparison between different estimations was delayed. The computer time of working with equation 6.1 is around 1 second and the computer time to work with the actual equations is between 48 minutes and 2 hours 23, depend on the number of considered tests (in some estimates with noise, the computer time reached around 4 hours). Since 10 estimates for each percent of noise (4 different) and for each number of test (3 different) 120 estimations were done, therefore the delay was about one week from the time schedule.

Final problem formulation and time schedule

Nowadays, most ventilation systems in use are being calibrated manually. Due to this fact and the need to ensure sufficient ventilation in all rooms, the systems are normally running at much higher capacity than is really needed. This is why there are good opportunities to achieve large energy saving by introducing optimal control strategies with the aim of ensuring sufficient

air ventilation at minimum energy consumption. In order to facilitate this, ventilation systems with valves situated at each exit grill will be considered as this opens up for local control of the ventilated air.

This project is part of a larger ELFORSK project, with SDU as one of the partners. The part of the project located at SDU is aimed at modeling, parameter identification and control of arbitrary ventilation systems.

All of this studies will be done under the ventilation standards.

What will be done in this project

Research:

The first step will be to research about different ventilation systems to get enough knowledge about this topic. Some research about optimal control will be done (together with energy consumption) to see the goal of the project.

Modeling:

The second part that will be considered in this project is how to model ventilation systems. The first steps consist on research about what types of variables are involved in this systems, like pressure losses, conservation of mass and so on. After this, some general values of these variables can be added from different suppliers of this components. Finally, a small ventilation system model will be done to work with.

Research about parameter estimation:

It will be research about how to do the estimates and the different types of estimation that can be done. Also, different methods to solve the estimate will be search.

Parameter estimation:

Since there is no office available, the values that should be taken from the office will be generated. In order to generate these values the equations of the system have to be solved. Some algorithm will be found to solve these equations. With this generated data will be done the estimation. Different noise will be added to the generated data to see the influence in the estimations. Finally the different estimation will be compared.

Comparison between different control strategies:

When the parameters of one system are know (after the estimation), the system can be controlled with controlled valves, therefore the system with controlled valves can be compared with others systems as output grilles and manually valves system. In this comparison will be shown the energy consumption with different strategies.

Delimitations

This project will be focus parameter estimation, modeling of ventilation systems and compare different control strategies. It will not be done nothing

about optimal control, neither calibration. A lot of things more can also be controlled, like the quantity of CO_2 in the air (so depends of this, you will introduce more quantity of new air or less), temperature inside of your office, humidity and so on. But all of these parameters will not be considered since there is no time for everything, so this could be a new line of study for another bachelor thesis.

The next figure shown the risks from the final plan schedule.

Risk	Description	Plan B
2	If there is bad parameter estimation with one method	Try to use other methods or simpler systems

Figure 6.3: Risk 2

Week	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Task1 - Research																			
1.1 Research about ventilation systems																			
1.2 Research about VAV and optimal control																			
Task2 - Modeling																			
2.1 Modeling																			
2.2 Develop a ventilation system to work with																			
Task3 - Research																			
Research about parameter estimation																			
Task4 - Parameter estimation																			
4.1 Solve equations																			
4.2 Solve parameter estimation																			
4.3 Compare different estimations																			
Task5 - Comparison																			
Comparison between different control strategies																			
Task6																			
Writing the final report																			
Task7																			
Hand in the final report																			end

Figure 6.4: Final time schedule

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Appendix A

Model equations

Here all equations from the model are shown. Each equation is the balance of energy between the fan and each output exit to the office. Depending on the output device the equation change and because of that a function f was introduced. This function f is different with valves and exit grilles, it is explained below of the equations.

$$\begin{aligned} & A - B * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\ & - K_1 * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\ & \quad - K_2 * (Q_{v1} + Q_{v2} + Q_{v3})^2 - K_3 * Q_{v1}^2 - f = 0 \quad (\text{A.1}) \end{aligned}$$

$$\begin{aligned} & A - B * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\ & - K_1 * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\ & \quad - K_2 * (Q_{v1} + Q_{v2} + Q_{v3})^2 + Q_{v3}^2 - f = 0 \quad (\text{A.2}) \end{aligned}$$

$$\begin{aligned} & A - B * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\ & - K_1 * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\ & \quad - K_2 * (Q_{v1} + Q_{v2} + Q_{v3})^2 - K_4 * Q_{v3}^2 - f = 0 \quad (\text{A.3}) \end{aligned}$$

$$\begin{aligned} & A - B * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\ & - K_1 * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\ & \quad - K_5 * (Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\ & \quad - K_6 * (Q_{v4} + Q_{v5} + Q_{v6})^2 - K_7 * Q_{v4}^2 - f = 0 \quad (\text{A.4}) \end{aligned}$$

$$\begin{aligned}
& A - B * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\
& - K_1 * (Q_{v1} + Q_{v2} + Q_{v3} + Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\
& \quad - K_5 * (Q_{v4} + Q_{v5} + Q_{v6} + Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 \\
& - K_9 * (Q_{v7} + Q_{v8} + Q_{v9} + Q_{v10} + Q_{v11})^2 - K_{10} * (Q_{v10} + Q_{v11})^2 - f = 0
\end{aligned} \tag{A.11}$$

Equations for exit valves

When it is working with valves, the equations were explained in model development chapter. Therefore, the next function is used in this study for valves:

$$f(Q_{vj}, K_{vj}, a_j) = a_j Q_{vj}^{K_{vj}} \tag{A.12}$$

Equations for exit grilles

In order to make the comparison between different systems, it was seen that the exit grilles have different drop pressure equation. Therefore it was checked which type of function have them and the next function was found(parabolic):

$$f(Q_{gj}, K_{gj}) = K_{gj} Q_{gj}^2 \tag{A.13}$$

Appendix B

Model estimation

This appendix will be in the back of the project in a CD.

Q_values

The code to calculate with the inputs, the outputs values (the test done in appendix D)

Function_newton

This folder contains the Newton method used to solve the non-linear equations.

code_lsq

This folder contains the code to estimate the parameters and inside of this estimation is using the “vmodel function”

vmodel

This folder contains the algorithm to give back the $F(x,z)$ to non-linear least squares method.

Appendix C

Model estimation with noise

This appendix will be in the back of the project in a CD.

Noise influence

This folder contains all the estimations made with different noise percents and different number of tests considered.

sensor_with_noise

This folder contains the algorithm to generate the different amount of air in each valve with noise, using the real values from appendix D.

code_lsq

This folder contains the code to estimate the parameters with noise and inside of this estimation is using the “vmodel function” (from folder “vmodel”). But now the values of the amount of air are taken with noise from “sensor_with_noise”.

vmodel

This folder contains the algorithm to give back the $F(x,z)$ to non-linear least squares method (same as without noise).

Function_newton

This folder contains the Newton method used to solve “vmodel”

Appendix D

Table of test

In this appendix all the tests done in order to make the estimation are shown. 24 test were done and different numbers of test were analyzed to see which one is a good approximation.

Test	1	2	3	4	5	6	7	8	9	10	11	12
Input Kv1	2	1	2	2	2	2	2	2	2	2	2	2
Input Kv2	2	2	1	2	2	2	2	2	2	2	2	2
Input Kv3	2	2	2	1	2	2	2	2	2	2	2	2
Input Kv4	2	2	2	2	1	2	2	2	2	2	2	2
Input Kv5	2	2	2	2	2	1	2	2	2	2	2	2
Input Kv6	2	2	2	2	2	2	1	2	2	2	2	2
Input Kv7	2	2	2	2	2	2	2	1	2	2	2	2
Input Kv8	2	2	2	2	2	2	2	2	1	2	2	2
Input Kv9	2	2	2	2	2	2	2	2	2	1	2	2
Input Kv10	2	2	2	2	2	2	2	2	2	2	1	2
Input Kv11	2	2	2	2	2	2	2	2	2	2	2	1
Output Qv1[l/s]	23.2645	137.3373	12.4763	14.5580	19.9737	19.5460	19.9737	20.6603	20.3914	19.9028	20.3914	20.6603
Output Qv2[l/s]	23.3109	14.5871	156.2793	14.5871	20.0136	19.5851	20.0136	20.7016	20.4322	19.9425	20.4322	20.7016
Output Qv3[l/s]	23.2645	14.5580	12.4763	137.3373	19.9737	19.5460	19.9737	20.6603	20.3914	19.9028	20.3914	20.6603
Output Qv4[l/s]	20.9264	15.8676	14.9594	15.8676	111.9979	11.1440	12.7093	16.4471	15.9365	14.9767	15.9365	16.4471
Output Qv5[l/s]	20.9682	15.8993	14.9893	15.8993	12.7347	124.6847	12.7347	16.4800	15.9683	15.0066	15.9683	16.4800
Output Qv6[l/s]	20.9264	15.8676	14.9594	15.8676	12.7093	11.1440	111.9979	16.4471	15.9365	14.9767	15.9365	16.4471
Output Qv7[l/s]	20.1603	15.2868	14.4118	15.2868	14.5654	13.7249	14.5654	99.4931	10.3988	10.9597	12.7253	13.5986
Output Qv8[l/s]	20.2006	15.3173	14.4406	15.3173	14.5945	13.7523	14.5945	11.7936	108.5664	10.9816	12.7507	13.6258
Output Qv9[l/s]	20.3613	15.4391	14.5554	15.4391	14.7105	13.8617	14.7105	13.7342	12.8521	122.5219	12.8521	13.7342
Output Qv10[l/s]	20.2006	15.3173	14.4406	15.3173	14.5945	13.7523	14.5945	13.6258	12.7507	10.9816	108.5664	11.7936
Output Qv11[l/s]	20.1603	15.2868	14.4118	15.2868	14.5654	13.7249	14.5654	13.5986	12.7253	10.9597	10.3988	99.4931

Table D.1: Test in model 1/2

Test	13	14	15	16	17	18	19	20	21	22	23	24
Input Kv1	1	2	2	2	2	2	2	2	2	1	2	2
Input Kv2	2	1	2	2	2	2	2	2	2	2	1	2
Input Kv3	1	2	1	2	2	2	2	2	2	1	2	1
Input Kv4	2	1	2	1	2	2	2	2	2	2	1	2
Input Kv5	2	2	1	2	1	2	2	2	2	1	2	1
Input Kv6	2	2	2	1	2	1	2	2	2	2	1	2
Input Kv7	2	2	2	2	1	2	1	2	2	2	2	1
Input Kv8	2	2	2	2	2	1	2	1	2	2	2	2
Input Kv9	2	2	2	2	2	2	1	2	1	2	2	2
Input Kv10	2	2	2	2	2	2	2	1	2	2	2	2
Input Kv11	2	2	2	2	2	2	2	2	1	2	2	2
Output Qv1[l/s]	89.5525	11.5432	12.9503	19.1953	18.6323	18.7521	19.5157	19.6270	19.5157	77.1770	11.2820	12.5150
Output Qv2[l/s]	11.0288	133.7758	12.9762	19.2336	18.6696	18.7896	19.5547	19.6663	19.5547	10.0503	127.7912	12.5400
Output Qv3[l/s]	89.5525	11.5432	115.2503	19.1953	18.6323	18.7521	19.5157	19.6270	19.5157	77.1770	11.2820	109.3875
Output Qv4[l/s]	14.3915	77.0988	9.5003	72.5777	9.9309	10.7565	14.1830	14.4147	14.1830	8.9502	51.9972	8.5387
Output Qv5[l/s]	14.4203	10.0437	90.6170	9.6772	99.0170	10.7780	14.2114	14.4435	14.2114	80.4256	7.9256	73.1998
Output Qv6[l/s]	14.3915	10.0237	9.5003	72.5777	9.9309	86.3441	14.1830	14.4147	14.1830	8.9502	51.9972	8.5387
Output Qv7[l/s]	13.8647	11.1230	11.1246	13.0055	67.3981	8.7958	57.7894	8.4868	9.3246	10.3093	10.0382	51.6388
Output Qv8[l/s]	13.8924	11.1452	11.1468	13.0315	9.2503	77.6745	8.4350	72.3128	9.3433	10.3299	10.0582	7.8934
Output Qv9[l/s]	14.0029	11.2338	11.2355	13.1351	10.4436	10.3722	88.6905	9.9211	88.6905	10.4120	10.1382	8.7454
Output Qv10[l/s]	13.8924	11.1452	11.1468	13.0315	10.3612	10.2904	9.3433	72.3128	8.4350	10.3299	10.0582	8.6764
Output Qv11[l/s]	13.8647	11.1230	11.1246	13.0055	10.3405	10.2699	9.3246	8.4868	57.7894	10.3093	10.0382	8.6591

Table D.2: Test in model 2/2

Appendix E

Study of 24 test

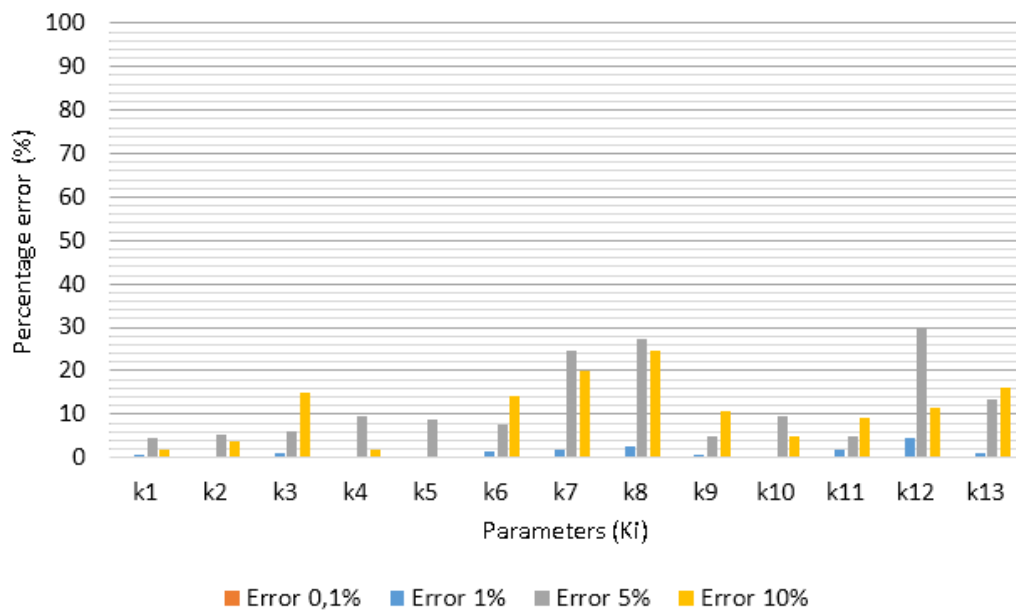


Figure E.1: Mean of estimate parameters with 24 test

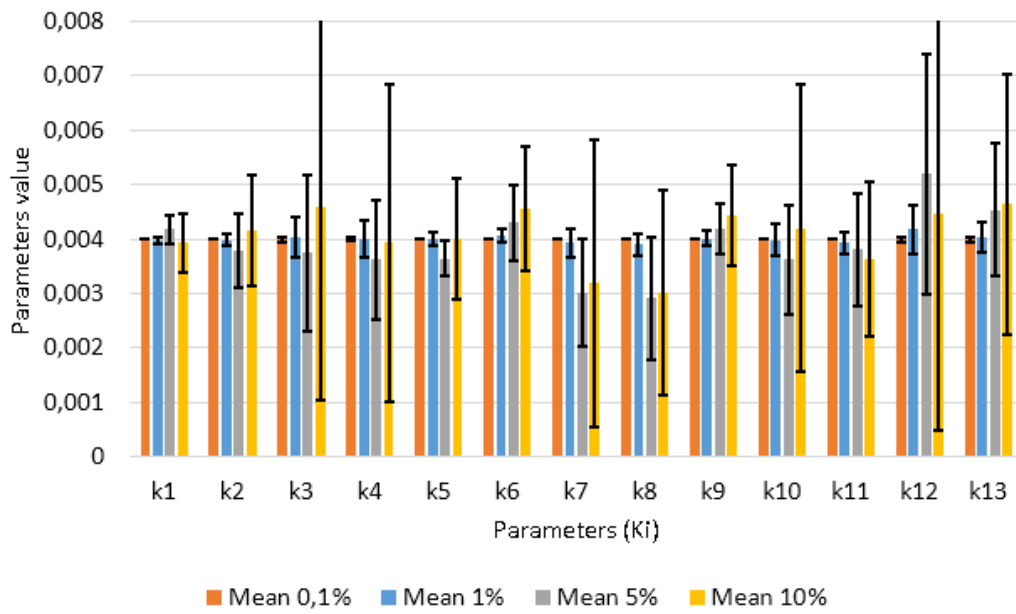


Figure E.2: Standard deviation of estimate parameters with 24 test

Appendix F

Others calculus

This appendix will be in the back of the project in a CD.

Exit electrical valves

- Kvj_Evalues

This folder contains the code to get the calculus of different K_{vj} with different A and the solutions in different cases.

- Function_newton

This folder contains the Newton method used to solve the non-linear equations from “Kvj_Evalues”.

Exit manual valves

- Kvj_Mvalues

This folder contains the code to get the calculus of different K_{vj} with different A and the solutions in different cases.

- Function_newton

This folder contains the Newton method used to solve the non-linear equations from “Kvj_Mvalues”.

Exit grilles

- Kgj_exitgrilles

This folder contains the code to get the calculus of different Q_{gj} with different A and the solutions in different cases.

- Function_newton

This folder contains the Newton method used to solve the non-linear equations from “Kgj_exitgrilles”.

Simplified model calculus

- Q_values

This folder contains the code to calculate the different Q_{vj} from the simplified system.

- parameter_estimation

This folder contains the code to estimate K_i from the simplified system. This algorithm needs the Q_{vj} from the “Q_values” algorithm and the K_{vj} previously used in the “Q_values” algorithm.

- Function_newton

This folder contains the Newton method used to solve the non-linear equations from “Q_values”. Also the Newton method was used to estimate the parameters since there is no noise.