A Semi-Automated Functional Test Data Analysis Tool

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Synopsis

The growing interest in commissioning is creating a demand that will increasingly be met by mechanical contractors and less experienced commissioning agents. They will need tools to help them perform commissioning effectively and efficiently. The widespread availability of standardized procedures, accessible in the field, will allow commissioning to be specified with greater certainty as to what will be delivered, enhancing the acceptance and credibility of commissioning. In response, a functional test data analysis tool is being developed to analyze the data collected during functional tests for air-handling units.

The functional test data analysis tool is designed to analyze test data, assess performance of the unit under test and identify the likely causes of the failure. The tool has a convenient user interface to facilitate manual entry of measurements made during a test. A graphical display shows the measured performance versus the expected performance, highlighting significant differences that indicate the unit is not able to pass the test. The tool is described as semi-automated because the measured data need to be entered manually, instead of being passed from the building control system automatically. However, the data analysis and visualization are fully automated. The tool is designed to be used by commissioning providers conducting functional tests as part of either new building commissioning or retro-commissioning, as well as building owners and operators interested in conducting routine tests periodically to check the performance of their HVAC systems.

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Introduction

There is a growing consensus that most buildings do not perform as well as intended and that faults in HVAC systems are widespread in commercial buildings. There is a lack of skilled people to commission buildings and commissioning is widely seen as too expensive and/or unnecessary. There is also a lack of skilled people, and procedures, to ensure that buildings continue to operate efficiently after commissioning.

Functional testing is a key part of the commissioning process and normally consists of a series of performance tests to make sure all the components in the system operate as intended. These include start-up procedures, safety checks and performance tests at different operating points. It is not uncommon for functional testing to be planned and then not actually occur because of time or budget constraints.

One approach to these problems is to wholly or partly automate the functional performance tests procedures, using computer-based methods of fault detection and diagnosis (FDD). Advantages of automation include: saving time by parallel testing, more effective use of skilled personnel, and standardized reporting. The data analysis part of the testing is relatively easy to automate, while the communication between the data analysis tool and the building energy management and control system (EMCS) is harder to automate because of the proprietary communications protocols used by most vendors. So, while fully automated functional testing is a long term goal, the work reported here is focused on the development of a semi-automated tool ─ automated data analysis with manual data entry from the EMCS and/or temporary instrumentation.

In contrast to other functional tests procedures, which emphasize start-up and performance under design conditions, the semi-automated functional tests described here are designed to cover the full range of the system operation. An important objective in designing the tests is to minimize their duration in order to reduce costs and maximize the amount of testing that can be done in the limited time before occupancy. The tests consist of open loop and closed loop tests. The open loop tests check whether the mechanical equipment works properly over the full range of operation. The closed loop tests verify the correct operation of both the mechanical equipment and the control hardware and software, including tuning. In the open-loop tests, the controllers are overridden and the mechanical equipment forced to the desired operating points. In the close-loop tests, a number of different operating points are achieved by manipulating the controller set point.

The automated functional tests described here are limited to HVAC secondary systems. Functional tests procedures have been designed to test three components or subsystems of an air-handling unit (AHU): mixing box, heating coil, cooling coil and supply fan and return fan systems. The methodology employed is similar, though not identical, to that described in Haves *et al.* (1996). The main difference is that the method described here uses simple mathematical models, rather than linguistic rules, to define correct operation.

This paper describes the development of a semi-automated data analysis software tool for the functional tests. It includes a description of the generic tests procedures and analysis methods, the software structure, various analysis modules, the user interfaces, and test examples. The software development is still in progress at the time of writing, so the description of the user interface, visual display and data analysis modules should be taken as being indicative rather than definitive.

Functional tests and a data analysis method

Test sequence

The development of a test procedure for a particular component, subsystem or system starts with the specification of the faults to be detected. Tests procedures were designed with the aim of detecting all the common faults in air handling units relating to routine operation; start-up and safety interlocks have not yet been addressed. For the mixing box, coil/valve, and supply/return subsystems, the major faults of these three subsystems can be classified into five groups (Xu et al., 2005)

- I) Faults detectable at minimum control signal, (e.g. leakage)
- II) Faults detectable at maximum control signal, (e.g. coil fouling, undersized equipment)
- III) Faults detectable because the target component fails to response to change in control signals, (e.g. stuck actuator, wiring problems between controller and actuator)
- IV) Faults occurring across the operating range and detectable from the response of the target components in the middle range of the operation, (e.g. hysteresis, sensor offset)
- V) Faults related to control, (e.g. poorly tuned controller, incorrectly implemented sequence of operations)

The faults are grouped in this way because it is relatively easy to determine which type of fault exists based on a simple analysis of the performance data generated during the tests. For example, if the system fails to turn off completely, there is a Group I fault. If the system fails to achieve the expected capacity, there is a Group II fault. If the system fails to respond at all to the active control signal, there is a Group III fault. If the system fails an open loop test in the middle of the operating range, there is a Group IV fault. If the system passes the open loop tests but fails the closed loop tests, there is a Group V fault. Within each group, a more detailed rule-based fault diagnosis method can be then used to further diagnose the exact fault.

The test procedures are designed to detect all the faults by exercising the systems over their full range of operation. Although the functional tests presented here for the mixing box, fan and coils differ in detail, the general ideas are the same. Faults in Group I, II, and III can be detected by analyzing the performance at each end of the operating range. To test for mismatch between the range of an actuator and a valve or damper, the control signal is changed by a small amount at each end of the range. Mismatch is typically caused by incorrect adjustment of the linkage between the actuator and the valve or damper, though occasionally it is caused by the installation of an actuator with too small a travel. Hysteresis is detected by approaching a selected point in the middle of the operating range from both directions; a significant difference in the output of the system indicates hysteresis. If the models used to analyze the results of the test are steady state models, only measurements taken when the system is close to steady state can be used. At each step, a steady state detector verifies that the system is in steady state before the data are recorded and the test moves on to the next step.

Mixing Box Test Sequence

The test sequence and analysis method for mixing boxes is used here as an example to illustrate how the tests are designed and executed, and how faults are detected and diagnosed. For mixing boxes, the following points need to be measured directly or calculated indirectly during the functional tests:

Measured points

Return air temperature (T_{ret})
Outside air temperature (T_{out})
Mixed air temperature (T_{mix}) (if present and considered reliable)
Supply air temperature (T_{sup}) (used when mixed air temperature sensor is missing or unreliable, subtract assumed/calculated temperature rise across supply fan to estimate mixed air temperature)
Demanded damper position (u)

Calculated Point

Outside air fraction

$$OAF = \frac{Tmix - Tret}{Tout - Tret} \tag{1}$$

Figure 1 and Table 1 illustrates the identification of the different fault groups from the measured outside air fraction (*OAF*) from an open loop test. The mixing box is exercised by applying a series of step changes to the demanded damper position, ranging from 0 to 100% and then back to 50%. At each step, the outside air fraction is calculated in order to identify the presence of one or more faults. The identification can either be performed by comparing the measured outside air fraction at different operating points or by comparing the deviations of the measured outside air fractions to those predicted by a reference model.

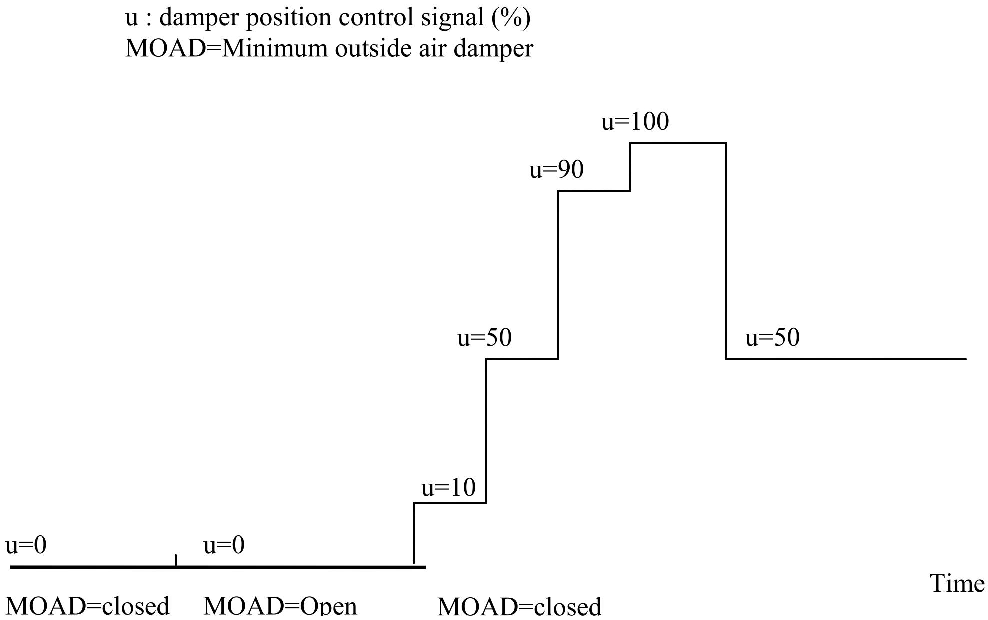


Figure 1: Mixing box open loop step test sequence

Table 1 Mixing box open loop test sequence

Step	Actions	Explanations	What to expect
1	Fix both the supply and the return fan speeds at their design values, turn off both heating and cooling coils, and check whether the difference between the outside air temperature and the return air temperature exceeds a minimum value of 10 °F	If the temperature difference is too small, the outside air fraction calculation is uncertain because of the uncertainties in the temperature measurements. The fan speed is fixed to minimize the pressure fluctuation in the air intake plenum. If the supply air temperature is used to calculate mixed air temperature, the heating and cooling coils must be turned off, preferably with isolating valves as well as the control valves	The supply and return airflow should be relatively stable with the fixed fan speeds.
2	Disconnect the controller from the control loop	This allows the user to override the demanded damper position in order to perform the open loop test.	
3	Command the minimum outside air damper fully closed (if present), set the demanded economizer damper position signal to zero (u=0), wait until the system is stable and then enter the observed performance data into the software tool	This step determines whether either of the dampers is leaking	The observed OAF should be close to zero. If it exceeds the acceptable value, this indicates unacceptable leakage of either the minimum outside air damper or the economizer outside air damper

4	If there is a minimum outside air damper, command it fully closed, set the demanded economizer damper position signal to zero, wait until the system is stable and then enter the observed performance data into the software tool	If there is a minimum outside air damper, this step is to determine the actual minimum outside flow	If there is a minimum outside air damper, the observed OAF should be close to the design value. If the leakage observed in Step 3 is small and the calculated OAF is much higher or lower than the design requirement, the minimum outside air damper is not sized or operating properly.
5	If there is a minimum outside air damper, command it fully closed. Set the demanded economizer damper position signal to u=10%, wait until system is stable and enter the required performance data into the tool	This is to test whether there is a mismatch of the damper and the actuator such that the damper fails to move significantly when the actuator moves from 0 to 10%	OAF should be slightly higher than zero. If OAF is unchanged from the last step, there is a mismatch between the damper(s)t and the actuator.
6	Set the demanded economizer damper position signal to u=50%, wait until system is stable and enter the required performance data into the tool	This is to test for substantial non-linearity that would lead to controllability problems.	The OAF should be within the lower and upper limits of acceptability.
7	Set the demanded economizer damper position signal to u=90%, wait till system stable and enter the required performance data to the software	This is to test whether there is any mismatch of actuator and damper at the upper end of the range of operation.	The OAF should be slightly less than 100%.
8	Set the demanded economizer damper position signal to u=100%, wait till system stable and enter the required performance data to the software	This is to test whether the recirculation damper exhibits significant leakage.	The OAF should be acceptably close to 100%.
9	Set the demanded economizer damper position signal to u=50%, wait till system stable and enter the required performance data to the software	This is to test whether there is significant hysteresis.	The value of the observed OAF should be acceptably close to the value observed in Step 6.
10	Remedy any faults detected and repeat the test		
11	Unlock the fan speeds, turn back on the heating and cooling coils if necessary, and reactivate the control loop	This is to restore system back to the conditions before the tests	The system should operate as before

Figure 2 and Table 2 show the test sequence for the closed loop tests. If the open loop tests have been performed, the closed loop tests are just used to verify that the control software is working properly and only three steps are required for testing the mixing box (*OAF*=10%, *OAF*=50%, *OAF*=90%). If the open loop tests have not been performed, two additional steps are required (*OAF*=0, *OAF*=100%). It may be more efficient to combine a closed loop mixing box test with closed loop tests of the heating coil and cooling coil (if present), particularly if the mixing box is controlled by the supply air temperature loop rather than by a separate mixed air temperature loop. However, for the purpose of illustration, only the mixing box portion of an air handling unit closed loop test will be presented here.

The set-points for the supply air temperature are calculated from the expected outside air fraction at each step by rearranging Equation 1 and accounting for fan heat to yield Equation 2.

$$T_{sup} = OAF(T_{out} - T_{ret}) + T_{ret} + \Delta T_{fan} \tag{2}$$

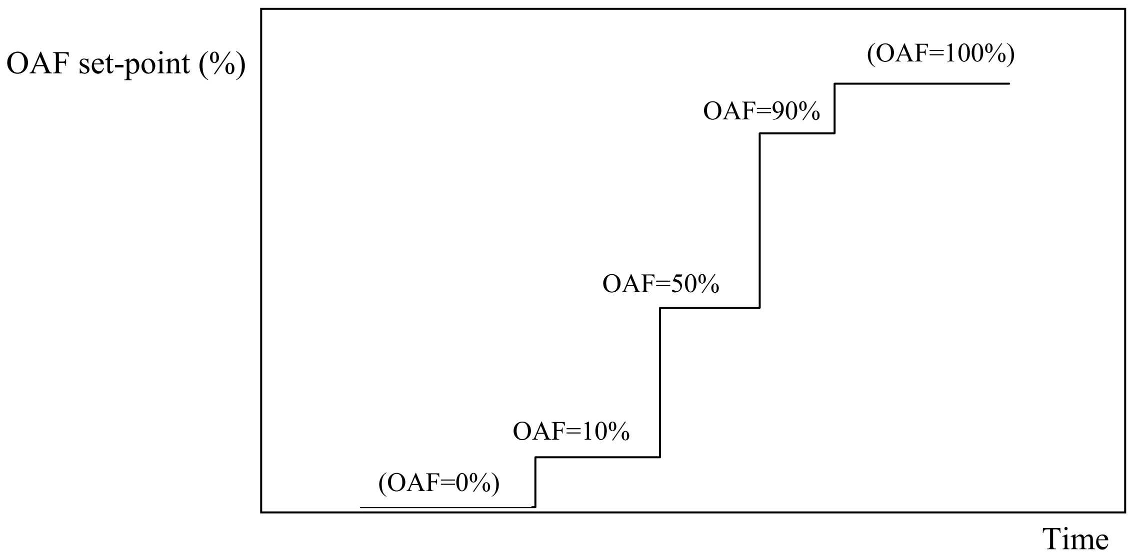


Figure 2: Mixing box closed loop test sequence

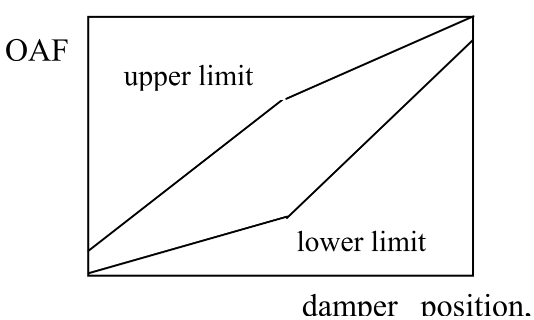
Table 2: Mixing box closed loop test sequence

Step	Actions	Explanation	What to expect
1	Fix both supply and return fan speeds at their design values. If only the mixing box is being tested, turn off both heating and cooling coils. Check whether the difference between the outside air temperature and the return air temperature exceeds a minimum value of 10 °F. Close the minimum outside air damper.	Blocking the water flows to the coils avoids the problem of damper leakage being masked by coil valve leakage. If the temperature difference is too small, the outside air fraction calculation is uncertain because of the uncertainties in the temperature measurements. The fan speed is fixed to minimize the pressure fluctuation in the air intake plenum. The minimum outside air damper is closed in order to test the economizer outside air damper for leakage.	The supply and return airflow should be relatively stable with the fixed fan speeds.

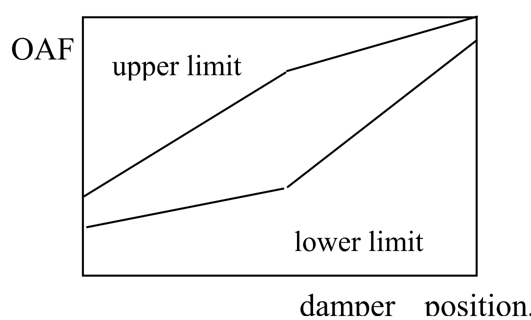
2	Increase the gain of the controller by a factor equal to the ratio of the largest return-outside temperature difference at which the loop will be active to the current return-outside temperature difference. Both the proportional gain and the integral gain should be increased (also the derivative gain if it is non-zero). If the integral time rather than the integral gain is used for tuning, it should not be altered.	Increasing the controller gain allows the loop to be tested for stability under worst case conditions.	
3	(This step is only performed if the open loop test has not been performed.) Reset supply air temperature to the value corresponding to OAF=0, wait until system is stable and enter the observed performance data to the software. If system fails to stabilize, this observation should also be entered into the tool.	This is to test the performance at the operating point where the mixing box should provide 0% outside air and the coil valves should be closed.	The mixing box control signal u should be zero and the actual supply air temperature (or mixed air temperature) should meet set-point. If $u \neq 0$, there is a temperature sensor error, the estimate of fan temperature rise is incorrect or, if the coils are active, there is valve leakage.
4	Reset supply air temperature to the value corresponding to OAF=10%, wait until system is stable and enter the observed performance data to the software. If system fails to stabilize, this observation should also be entered into the tool.	This is to test performance at an operating point where there is a risk of unstable control	The control should be stable and the response to the set-point change should not exhibit any control signal reversals, neither should it be too sluggish.
5	Reset supply air temperature to the value corresponding to OAF=50%, wait until system is stable and enter the observed performance data to the software. If system fails to stabilize, this observation should also be entered into the tool.	This is to test performance at an operating point where there is a risk of unstable control	The control should be stable and the response to the set-point change should not exhibit any control signal reversals, neither should it be too sluggish.
6	Reset supply air temperature to the value corresponding to OAF=90%, wait until system is stable and enter the observed performance data to the software. If system fails to stabilize, this observation should also be entered into the tool.	This is to test performance at an operating point where there is a risk of unstable control	The control should be stable and the response to the set-point change should not exhibit any control signal reversals, neither should it be too sluggish.

7	(This step is only performed if the open loop test has not been performed.) Reset supply air temperature to the value corresponding to OAF=100%, wait until system is stable and enter the observed performance data to the software. If system fails to stabilize, this observation should also be entered into the tool.	This is to test the performance at the operating point where the mixing box should provide 100% return air and the coil valves should be closed.	The mixing box control signal *u* should be 100% and the actual supply air temperature (or mixed air temperature) should meet set-point. If $u \neq 100\%$, there is a temperature sensor error, the estimate of fan temperature rise is incorrect or, if the coils are active, there is valve leakage.
8	If necessary, retune the controller and repeat the test.		
9	Turn back on the heating and cooling coil if necessary. Reduce the controller gain by the factor used to increase it in Step 2. Restore control of the minimum outside air damper (if present).	This is to restore the system to its original operating condition.	The system should operate correctly.

At each of the test steps described above, the performance data are analyzed in real time after they are entered into the tool. Faults are detected by comparing the observed performance at each step to the performance predicted by a model of correct operation configured using design information and/or manufacturer's data. Figure 3 shows the empirical model of the mixing box used in the tool. The model defines the acceptable range of performance for different damper positions. The values at each end of the operating range are determined by the maximum acceptable leakage for the dampers. The values in the middle of the operating range are determined by the maximum acceptable variation in system gain over the operating range, arbitrarily taken to be 3:1. Differences between observed and acceptable performance that exceed the uncertainty associated with sensor errors indicate the presence of a fault. The tool uses rules based on the symptoms presented in Table 3 to diagnose the nature of the faults that are detected. If a major fault is detected, the software tool immediately generates an alarm so that the user can stop the test if desired. In Table 3, $\Delta OAF(u)$ indicates the difference between the observed and the acceptable outside air fraction at damper position *u*.



(a)



(b)

Figure 3: Mixing box correct operation model, (a) minimum outside air damper closed or absent, (b) minimum outside air damper open

Table 3: Fault diagnoses

Fault Group	Causes	Symptoms
Group I	Leaking outside air damper	$\Delta OAF(u=0) > 0$
	Oversized minimum outside air damper	$\Delta OAF(u=0) > 0$
Group II	Outside air damper stuck closed or partially closed	$OAF(u=0) = OAF(u=10\%) = OAF(u=50\%)$
	Exhaust air damper stuck closed or partially closed	$\Delta OAF(u=50\%) < 0$
	Leaking return air damper	$\Delta OAF(u=100\%) < 0$
	Return air damper stuck open or partially open	$\Delta OAF(u=100\%) < 0$
Group III	Common actuator stuck	$OAF(u=0) = OAF(u=10\%) = OAF(u=50\%) = OAF(u=90\%) = OAF(u=100\%)$
	Actuator wiring or controller output failure	$OAF(u=0) = OAF(u=10\%) = OAF(u=50\%) = OAF(u=90\%) = OAF(u=100\%)$
	Sensor offset/failure	$\Delta OAF(u=0) = \Delta OAF(u=10\%) = \Delta OAF(u=50\%) = \Delta OAF(u=90\%) = \Delta OAF(u=100\%) \neq 0$
Group IV	Hysteresis in actuator(s) or damper linkage(s)	$OAF(u=50\%$ increasing$) \neq OAF(u=50\%$ decreasing$)$
	Damper actuator range mismatch	$OAF(u=0) = OAF(u=10\%)$ or $OAF(u=90\%) = OAF(u=100\%)$
	Excessive non-linearity	$\Delta OAF(u=50\%) \neq 0$
Group V	Poor loop tuning	Oscillation or sluggish response when *OAF* =10%, 50% or 90% in closed loop tests
	Control program error	Failure to meet the set-points in closed loop tests

Software tool description

Software structure

Figure 4 shows the internal structure of the software. A data-driven approach has been adopted to make it easy to add or remove modules. At the center of the tool is a database, where all data are stored, including measurements, model predictions and analysis results. The other modules read and/or write to the database. The prototype version of the tool runs on a laptop PC.

At the top of the diagram is the data entry module which handles manual entry of test measurements from the system under test. The data are then passed through a preprocessor where they are checked and converted into the appropriate units. After the data for each new test step are entered, they are processed by the analysis modules. On the right side of the diagram is the SPARK simulation tool (SPARK 2005) that uses a model of the system under test to predict the correct operation performance. The simulated performance data are saved in the database in real time. The comparator is used to compare the simulated and measured performance and generate fault alarms. The fault diagnosis module uses IF-THEN rules and fuzzy inferencing to generate fault diagnoses. Fuzzy logic is a convenient method of applying linguistic rules to continuous systems.
At the bottom of Figure 4 there are several output modules that can be used to visualize the performance and generate tests report. Two data visualization methods are used in the tool. The results of the open loop tests are presented as X-Y plots of a normalized output variable, e.g. outside air fraction, *vs.* control signal to display the symptoms of hardware faults such as leakage. The closed loop test results are presented as time series plots in order to display controllability problems such as hunting or sluggish response to set-point changes. Both the visualization and the report routines run in parallel with the data analysis routines, providing a continuously updated display of the analysis results as the test is performed.

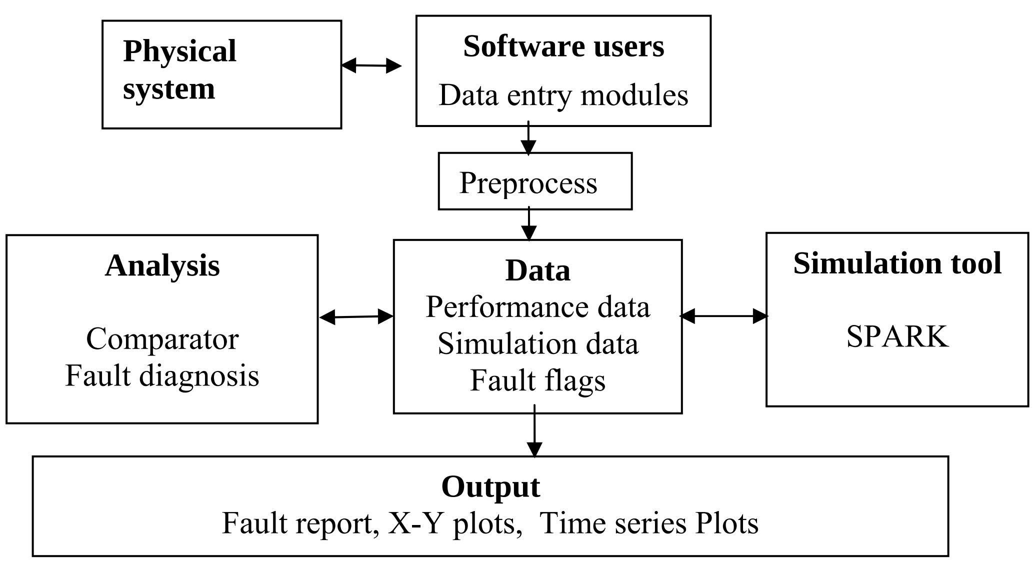


Figure 4: Data analysis software tool internal structure

User interface: Starting a project

Figure 5 shows the main menu of the software tool. The users can start a new project or open an existing project using the File menu. The project setup menu is used to select the component or subsystem to be tested – mixing box, heating coil, cooling coil or fan/duct system. The project configuration can be saved and used again.

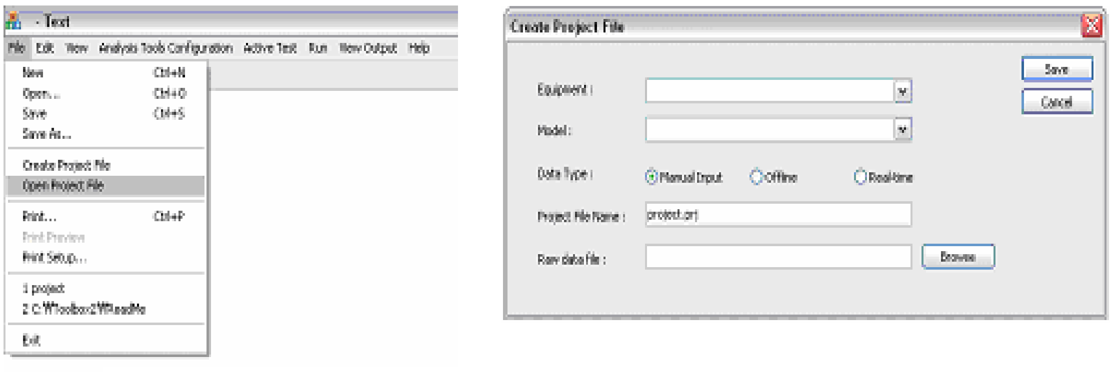


Figure 5: Project set-up interface

Conducting a test

Once the project setup and configuration are complete, the functional test is performed, typically by using a laptop computer to override the control system output or to change the set-point. Data can be entered after each step of the test or all the data can be entered together at the end of the test, whichever is more convenient for the user. If the data are entered after each step, the tool can analyze the data entered up to that point in time and potentially flag a major fault, e.g. no response to the changing control signal, that indicates that there is no point in continuing with the test.

An important output module is the test report in the text format. The test report consists of three parts. The first part contains general information about the test and also the performance data entered by the user. The second part shows the (partial) fault analysis at each step. The last part is a summary of the results of the complete test, including a numerical measure of the confidence that the operation is correct or incorrect and that particular faults have been diagnosed.

Summary

A software tool for functional test data analysis has been developed. The tool uses generic step test sequences to detect and diagnose major faults of key components in air handling units. The tool is semi-automated, in that the data analysis and fault diagnosis are automated but the performance data need to be entered manually. The software has a flexible data-driven structure and so that different analysis, communication and output modules can be added easily in future. The tool is still under development. This paper uses the example of the mixing box to explain the analysis method and some of the features of the user interface. Field testing of the tool by commissioning agents is planned to start in the summer of 2005.

Acknowledgements

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