Prognostic & Health Management (PHM) Tool for Robot Operating System (ROS)

USER GUIDE

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1. Introduction

Nowadays, prognostics-aware systems are increasingly used in many systems and it is critical for sustaining autonomy. All engineering systems, especially robots, are not perfect. Absence of failures in a certain time is the perfect system and it is impossible practically. In all engineering works, we must try to predict or minimize/prevent failures in the system. Failures in the systems are generally unknown, so prediction of these failures and reliability of the system is made by prediction process. Reliability analysis is important for the improving the system performance, extending system lifetime, etc. Prognostic and Health Management (PHM) includes reliability, safety, predictive prognostic, fault detection / isolation, advanced diagnosis, component lifecycle tracking, health reporting and information management, etc.

Reliability generally shows how successful a system is in performing its intended function. In order to increase the system performance, intensive studies are carried out on reliability models and analytical tools. It is true that the consequences of unreliability in engineering can be very costly and often tragic. In a changing world, reliability becomes more important to ensure that systems operate with high performance and gain functionality. Reliability engineering is applied in many fields such as defense industry, robotics industry, aerospace industry etc. The current generation of mobile robots have poor reliability. In order to design more reliable robots, we need analytical tools for predicting robot failure.

This study proposes Prognostic and Health Management (PHM) tool infrastructure using a model-based methodology for robotic systems. The main objective of this study is “Development of the General Prognostic and Health Management Tool” for ROS. The scope of this guide is processes and methodologies for conducting hazard rate of equipment, reliability predictions for electronic and mechanical systems. A comprehensive and systematic study of the different reliability models and analytical tools for various systems are also given. Furthermore, reliability, remaining useful life (RUL), and the probability of task completion of the robot (PoTC) are estimated in this tool. In this report, reliability and PoTC of the system is calculated by using hazard rate of the mechanical and electrical components, configuration of the robot (series, parallel, etc.). Results show that system reliability depends on hazard rate of all components in the system, their configurations, usage time and some environmental conditions (temperature, load, humidity, etc.). PoTC is the task completion probability of the robot that depends on the calculated reliability and distance travelled along the task.

This document is a user manual for PHM Tool. In this document, all operations that can be done on the interface are explained on the screenshots. In Section 2 describes the summary of the work that can be done on the PHM Tool. In Section 3, it is mentioned how to use PHM Tool. How to download, launch and usage of PHM Tool are explained in sections 3.1, 3.2 and 3.3 respectively. In Section 3.4 and 3.5, it is mentioned how to work on "Robot Configuration Setup" and "Monitoring and Analysis" tabs, respectively.

1.1. PrognostIc Health Management

A team of robots must be capable of knowing their health and making decisions about improving their reliability. Robotic systems are increasingly used in various fields. While it is important to realize autonomous behavior in the pioneering applications of robots, maintaining autonomy becomes more important with the use of robotic systems. Estimation of reliability is very important to suppress the possible errors of robotic systems and increase the success and health of robotic systems [1].

Prognostic and Health Management (PHM) includes logistics, safety, reliability, mission criticality, and economic applicability. The PHM of the components or systems has both diagnostics and prognostic: Diagnosis is the process of detecting or isolating of faults, and prognostic is the prediction of the future situation or the remaining useful life (RUL) depending on the current situation and historical conditions. Prognostic is also based on failure of equipment after a breakdown period which can be used in the event of failure to prevent system failure and minimize operating costs. Concisely, diagnosis is related to the current state of any subsystem, and prognostic is related to the future state of the subsystem [2].

Fault-tolerant control architectures have been developed for maintainability; however, they are generally diagnostic-based. In contrast, prognostic-based strategies can predict risks before failure. The prognostic conscious system aims to integrate information about health and future working conditions into the process of selecting subsequent actions for the system. There are serious difficulties in dealing with prognostics. Prognostics deal with built-in data. The calculation cost of the internal diagnostics is limited in the robot, resulting in a limited number of sensors. These sensors generate thousands of signals or data streams while the robot is in motion. These signals are continuously sent to the main panel. It requires high storage capacity, resulting in high costs. Using this prognostic information, the system can make some kind of decision, such as replacing the component before failure, extending component life through load reduction or task switching, and optimally planning or re-planning a route. Some of the features a PHM system should have;

- Fault detection / isolation
- Advanced diagnosis
- Predictive prognostic
- Rule and failure time estimates
- Component lifecycle tracking
- Health reporting and information management
- Usage tracking.

2. Scope of Prognostics and Health Management (PHM) Tool for ROS

PHM tool is model-based user interface which the user creates his system using various mechanical and electrical equipment’s, but can also calculates the reliability, failure rate and probability of task completion (POTC) of the created system. In addition, the PHM Tool offers the user the ability to formulate his own components and add them to the system. PHM Tool can also work with a real robot. Data from the sensors on the real robot are published via ROS topics. By subscribing to these topics in the PHM Tool, the system's failure rate, reliability and POTC values are calculated together with the data which is obtained from the sensors.

PHM Tool is a modular interface. The user can create his own system using various electrical and mechanical equipment’s with this tool. The failure rate of the system is calculated as a result of the configuration of this equipment.

Failure rate values of equipment’s are calculated using “Hazard Rate Calculation Algorithms” in the 5th section of the PHM Tool Model Based [3] document in PHM Tool. Electrical and mechanical equipment’s in the PHM Tool are given in Table 1. Failure rate calculation formulas of all equipment’s in this table are included in PHM Tool Model Based [3] document.

Electrical Equipment	Mechanical Equipment
Capacitor	Spring
Diode	Gears
Inductor	Bearing
Transistor	Actuators
Fuse	Shafts
Resistor	Electric Motors
Rotating Devices, Motors	Mechanical Couplings
Relays	Battery
Connectors, General	

Connectors Sockets	
Quartz Crystals	

Table 1: Electrical and Mechanical Equipments in PHM Tool

In PHM Tool, the reliability of the system has been calculated using the "Reliability Estimation Algorithms" which is located in part 3 of the reference [3] document. The reliability of the system is calculated by the physical arrangements of each item that creates the system. Thus, the effect of the failure rate value of each item on the system is modeled.

Physical arrangements of the items in the system are made in 2 ways in the PHM Tool:

- Series
- Parallel

In a series configuration when the failure of any item results in a system failure. Accordingly, for the functional success of a series system, all items must operate successfully during the intended task period of the system.

In a parallel configuration, only failure of all items results gives system failure. Accordingly, the success of only one item will be sufficient to guarantee the success of the system.

Accelerated life test (ALT) models given which is used in different conditions in order to calculate reliability analysis in this tool. Formulas for ALT models used in the interface are located in section 4 of the PHM Tool Model Based [3] document. The user can perform reliability analysis by choosing one of the following models:

- Exponential Distribution
- Curve Distribution

$$R\ (Reliability) = e^{-(\lambda * t)} \qquad (1)\ *$$

$$POTC = R^{d} \qquad (2)$$

**Exponential Distribution ALT model formula*

The unit of time (t) in the formula used to calculate the reliability of the system should be hour or second. The unit of distance (d) in the formula used to calculate the POTC should be km or m. In PHM Tool the user has the opportunity to select any of these units. In section 8 of Figure 3.26, when the user chooses any of these units (m/s or km/h), reliability and POTC values are calculated according to the selected units.

After the system is configured, the system must be started for analysis. There are 3 types of analysis available in PHM Tool:

- Hazard Rate Analysis
- Reliability Analysis
- Task Completion Analysis

In the "Hazard Rate Analysis" and "Reliability Analysis" sections, the graphs of the calculated hazard rate and reliability values are plotted in real time. At the same time, the user can add the sensor data that are read from ROS topics in to the appropriate modules. Thus, besides the nominal values, a sensor-based hazard rate and reliability values should be calculated.

Nominal: The calculated hazard rate and reliability value of the system without adding any environmental condition.

Sensor based: Hazard rate and reliability values calculated by adding sensors to the modules in the system.

- *In PHM Tool, calculation of sensor-based hazard rate and reliability values are done using temperature sensors only. These calculations' formulas are located in FailureRateCalculation class. In order to make these calculations by adding other sensor types (load, humidity, etc.), the sensor type must be specified as input by the user in the interface. Since PHM Tool is open source software, the user can make the necessary arrangements in the interface and create the necessary functions in the FailureRateCalculation class.*

In the "Task Completion Analysis" tab, the calculated reliability value is used. In order to calculate the POTC value, the task sent for the mobile robot must come to PHM Tool. POTC value, total time and distance values are estimated before realizing the robot task by applying Predict analysis as soon as the task arrives. After estimation, besides the total time and distance values, nominal and sensor based POTC values are calculated and displayed on the interface and POTC values are added graphically. In addition, the incoming task can be used to calculate advanced simulation by adding it to the list of tasks in the "Prognostic Analysis" tab. The robot transmits distance and time values to PHM Tool after finishing the current task. POTC value is calculated as nominal and sensor based by applying actual analysis. The calculated POTC values are displayed in the interface along with the total time and distance values, and POTC values are added graphically.

3. How to Use PHM Tool?

This section describes the system requirements for the use of the PHM Tool, the structure of the tool and how to use the tool.

In section 3.1, the system requirements for the use of PHM Tool and the required libraries when using the PHM Tool are mentioned. It is also mentioned how the PHM Tool is downloaded and launched.

In section 3.2, the general structure of PHM Tool is described with flowcharts.

In section 3.3, general description of the "Robot Configuration Setup" tab in PHM Tool and how to work in this tab are explained together with the screenshots of the application.

In section 3.4, general description of the " Monitoring and Analysis " tab in PHM Tool and how to work in this tab are explained together with the screenshots of the application.

3.1. PHM Tool Tutorial

This section describes how to download the dependencies required for the installation of PHM Tool and run PHM Tool.

First, a workspace needs to be created. If there is no workspace, a workspace should be created by following the instructions in the [Create a workspace]() link.

If the workspace has been created, you should go to the workspace directory in the terminal.

```
$ cd ~/catkin_ws/src
```

Then Phm Tool is downloaded.

```
$ git clone "https://github.com/inomuh/phm_tools.git"
```

The required PyQT5 and matplotlib dependencies must be downloaded for Phm Tool to work after it is downloaded.


```
$ sudo apt-get install python3-pyqt5
$ sudo apt-get install python3-matplotlib
```

Because it is high in size, go to the rosbag file (.zip) and extract.

```
$ cd ~/catkin_ws/src/phm_tools/phm_rosbag
$ unzip rosbag_sample.bag.zip
```

After downloading the dependencies, go to the workspace and compile it.

```
$ cd ~/catkin_ws
$ catkin_make
$ catkin_make install
```

After compiling the workspace, start to run PHM Tool. A new terminal is opened and roscore is opened.

```
$ roscore
```

A new terminal opens after running the roscore command. Phm Tool is run in this terminal.

```
$ roslaunch phm_start phm_start.launch
```

To configure the system, you can follow the document or watch the video in the Phm Tools link. Sensors from rosbag should be added to the system after configuring the system.

A new terminal opens, goes to the location where rosbag is and opens the rosbag. Sensors are added to the modules as in the video.

```
$ cd ~/catkin_ws/src/phm_tools/phm_rosbag
$ rosbag play rosbag_sample.bag
```

For Task Completion Analysis, task data must come from the smach included in the simulation package. If there is no simulation, the "Task Completion Analysis" tab can be applied with the following commands.

For Predict Analysis and Prognostic Analysis in Real Time Analysis, messages must be published from /robot_task_list topc.

```
$ rostopic pub /robot_task_list std_msgs/String "data: '[[4.25, 2.18, 0.305032286643936], [4.25, 3.1, 0.34244299963151925], [4.25, 2.18, 0.3130261708222558], [5.55, 3.54, 0.25665934871261936], [7.29, 3.53, 0.3099463716242755], [10.34, 3.91, 0.33396332918153804], [11.05, 3.67, 0.34579751666395014], [11.42, 2.76, 0.34335229915257853], [11.42, 1.93, 0.32025931883120473], [10.97, 1.08, 0.2732565117783081], [8.16, 0.82, 0.3424904966267803], [6.35, 0.83, 0.3364506314969207], [4.26, 0.68, 0.30230026016025063]]'" -1
```

For Actual Analysis in Real Time Analysis section, messages from /task_time and /task_position topics must be published.

```
$ rostopic pub /task_time std_msgs/String "data: '[7.070728063583374, 7.325403928756714, 3.0024330615997314, 5.1106040477752686, 10.97532606124878, 12.948495864868164, 3.0029280185699463, 17.01675295829773, 3.674638032913208, 4.787661075592041, 4.183042049407959, 4.751224040985107, 16.489573001861572, 10.011996984481812, 17.285614013671875]'" -1
```

```
$ rostopic pub /task_position std_msgs/String "data: '[[4.173425111935546, 0.6996212725439405], [4.252327779615457, 1.7887780478495028], [4.254796821506879, 2.986813819580745], [4.254796821506879, 2.986813819580745], [4.075966735712705, 2.45786878651297], [5.296776265140758, 3.2377047247386685], [7.186286384259671, 3.4575905505176574], [7.186286384259671, 3.4575905505176574], [10.02707803637877, 3.834368378077772], [10.713219522235965, 3.6906226762430725], [11.321258808297841, 3.0485739135240486], [11.451096448575916, 2.271822575810481], [11.191486774449103, 1.4076532146026228], [8.491930981852743, 0.7301303113520736], [6.714700980072448, 0.7608179284539074], [4.405262763785259, 0.5861917110532081]]'" -1
```

3.2. Usage of PHM Tool

Different operations are performed on each tab in the PHM Tool. The operations performed on each tab are described in detail in this section.

Basically 2 different operations are performed in the PHM Tool:

- Robot Configuration
- System Analysis and Monitoring

Robot configuration operations are performed in “Robot Configuration Setup” tab. The flowchart of the operations performed on the “Robot Configuration Setup” tab is shown in Figure 3.1.

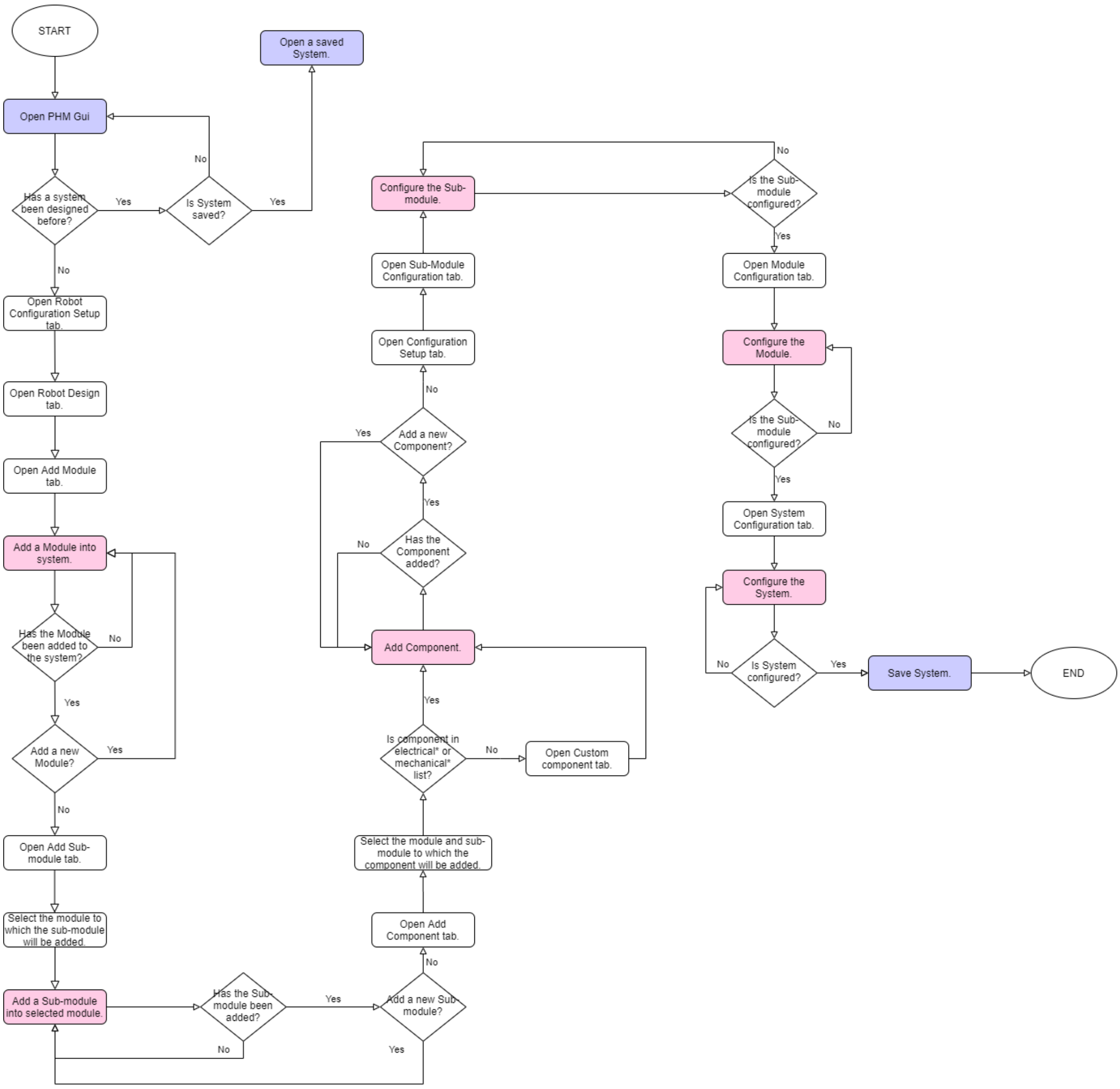


Figure 3.1 Flowchart of "Robot Configuration Setup" tab

System analysis and monitoring operations are performed in “Monitoring and Analysis” tab. The flowchart of the operations performed on the “Monitoring and Analysis” tab is shown in Figure 3.2.

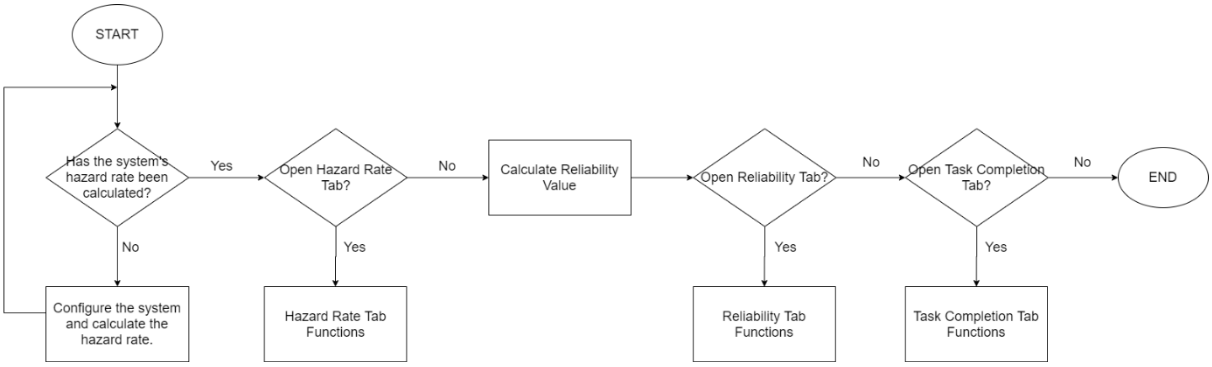


Figure 3.2 Flowchart of "Monitoring and Analysis" tab

3.3. Robot Configuration Setup Tab

It is the tab where the parts (modules, sub-modules, components) in the robot are added, created and configured. Since PHM TOOL is a modular tool, the modules and submodules in the robotic system must be created at the interface. Therefore, these processes will be worked on the “Robot Design” tab (see Section 3.3.1).

The configuration of each component, sub-module and module is derived by defining their serial or parallel relationships with each other. In this way, the failure rate values of the sub-modules, modules and system are calculated. The configuration process will be run in the “Configuration Setup” tab (see Section 3.3.2).

The user can save a system he created and configured in this tab, or load a system he previously saved to PHM Tool. Saving and loading operations are performed by using the "Save" and "Load" buttons on the "Robot Configuration Setup" tab (see Section 3.3.3).

3.3.1. Robot Design Tab

In this section, creating a module, sub-module and component in PHM Tool for a robotic system and adding them into the system will be explained.

3.3.1.1. Add Module Tab

Modules compose the top level of the system. Therefore, modules must be determined first when creating a system. “Add Module” tab is the tab where modules are added to the system.

The flowchart of the operations done in “Add Module” tab is shown in Figure 3.3.

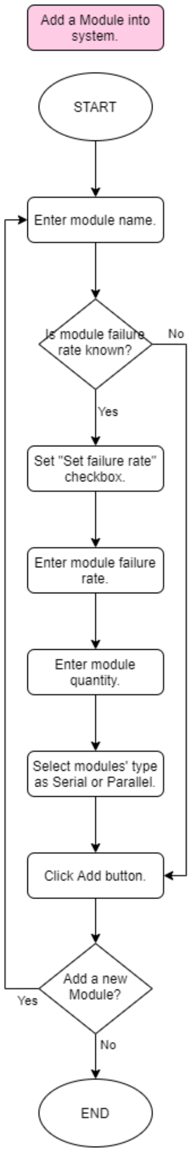


Figure 3.3 Flowchart of Add Module tab

Adding modules into the system is done in 2 different ways: Adding modules with zero failure rate and entering the failure rate value by user.

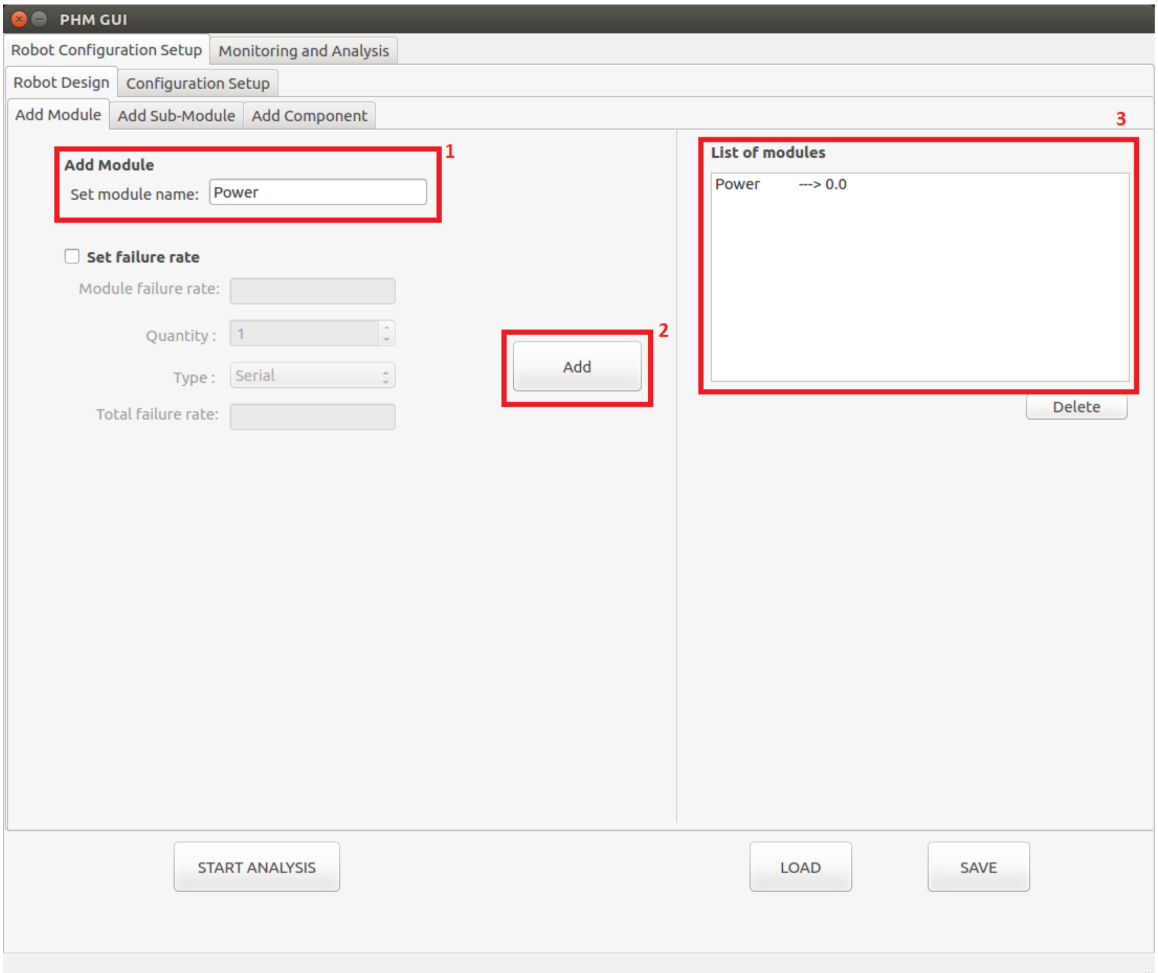


Figure 3.4 Adding module with 0 failure rate

Module with "0 failure rate value" can be added into the system. When the module is added in this way, the failure rate of the module is calculated after the configuration process. If it is desired to add a module in this way, there should be at least 1 sub-module under the module. The failure rate value of the module will be calculated after the configuration of these sub-modules.

In Figure 3.4, the process of adding modules with 0 failure rate value is shown.

- In box 1, the name of the module to be added to the system is entered.
- In box 2, the module is added to the system by clicking the "Add" button.
- In section 3, the modules added to the system are listed together with their failure rate values.

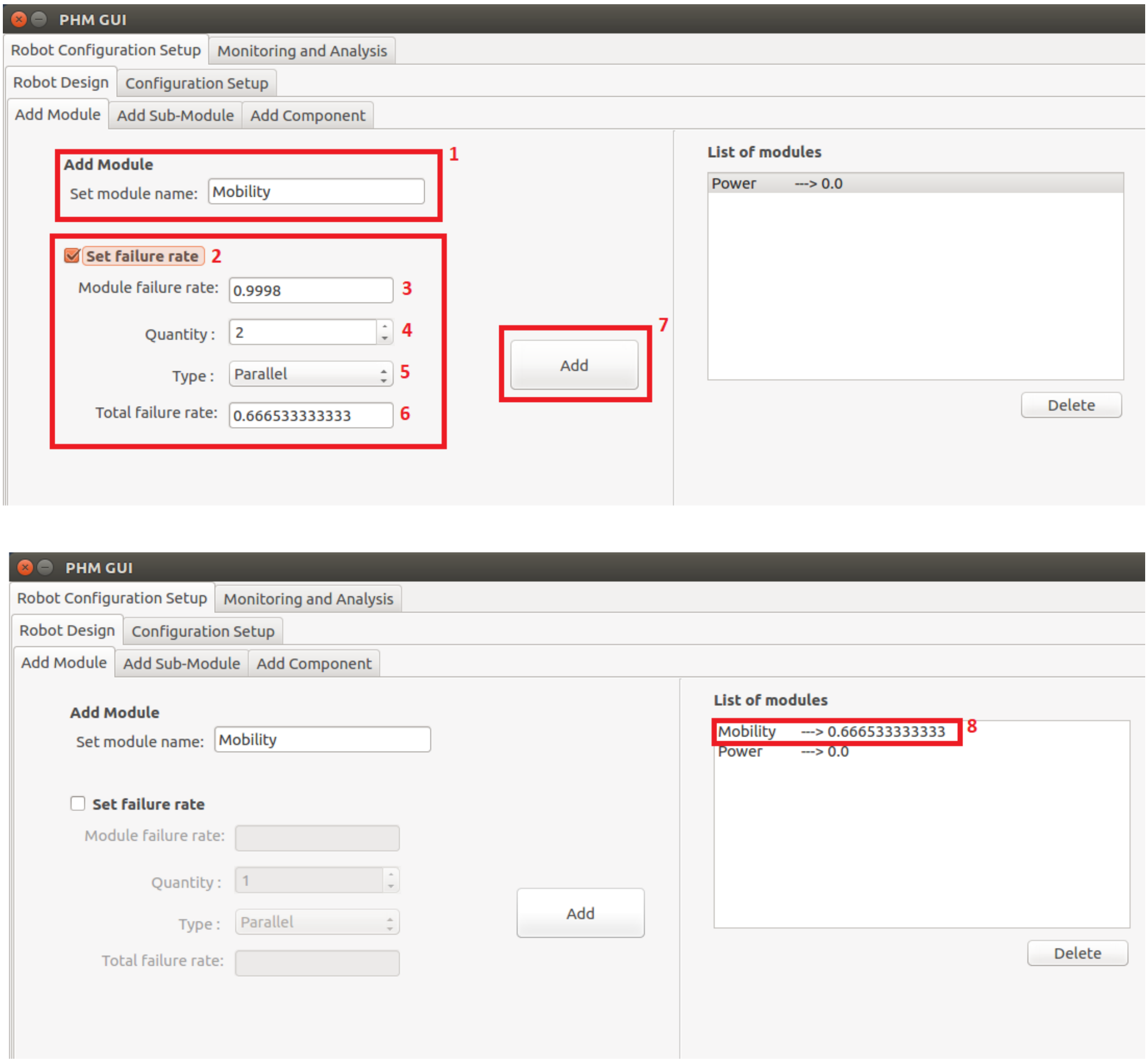


Figure 3.5 Entering the module's failure rate value by user

The module can be added to the system by entering the failure rate of the module by the user. When the module is added in this way, its configuration is not needed to calculate the module's failure rate. Therefore, it is not expected to have a sub-module under the module.

In Figure 3.5, the operation of adding the module's failure rate value by the user is shown.

- In box 1, the name of the module to be added to the system is entered.
- By checking the checkbox in section marked with 2, the user activates the relevant section.
- In section marked with 3, failure rate value of the module is entered.
- In section marked with 4, the number of the added module will be entered.
- In section marked with 5, serial or parallel states of the added modules are entered according to each other. If the module quantity is 1, selecting this section as series or parallel will not change the total failure rate value.
- In section marked with 6, it shows the total failure rate of the module.
- By clicking the "Add" button in box 7, the module is added to the system with the calculated failure rate value.

- In box 8, the added modules are listed with the calculated failure rate value.

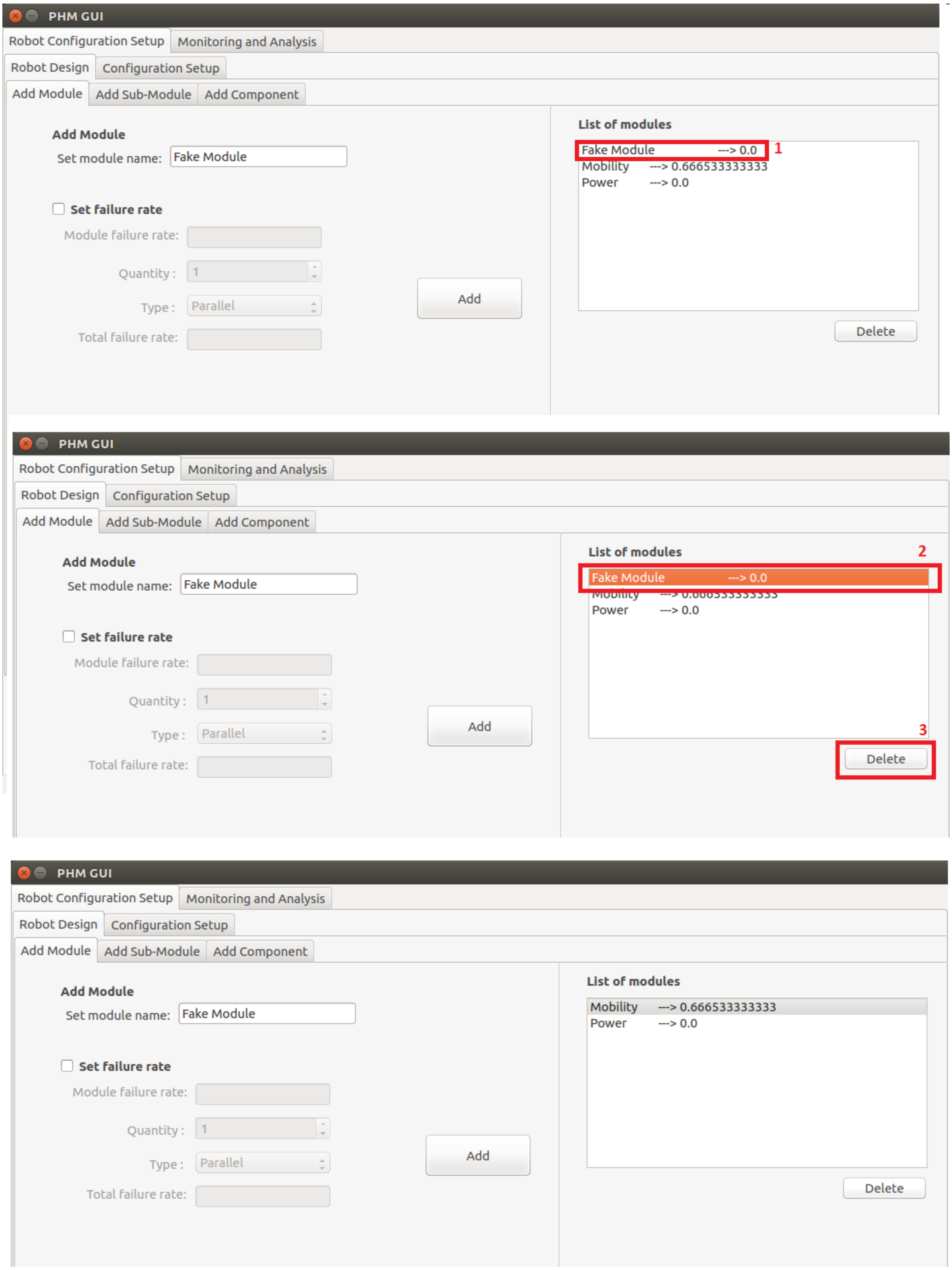


Figure 3.6 Deleting the added module from the system

The deletion of a module loaded in the system is shown in Figure 3.6.

- Suppose the module to be deleted is “Fake Module” (Box 1).
- In box 2, the module to be deleted is selected from the list.
- In box 3, the module is removed from the system by clicking the “Delete” button.

3.3.1.2. Add Sub-Module Tab

Sub-modules compose the second level of the system. Therefore, sub-modules must be determined after determining the modules. “Add Sub-Module” tab is the tab where sub-modules are added to the system.

The flowchart of the operations done in “Add Sub-Module” tab is shown in Figure 3.7.

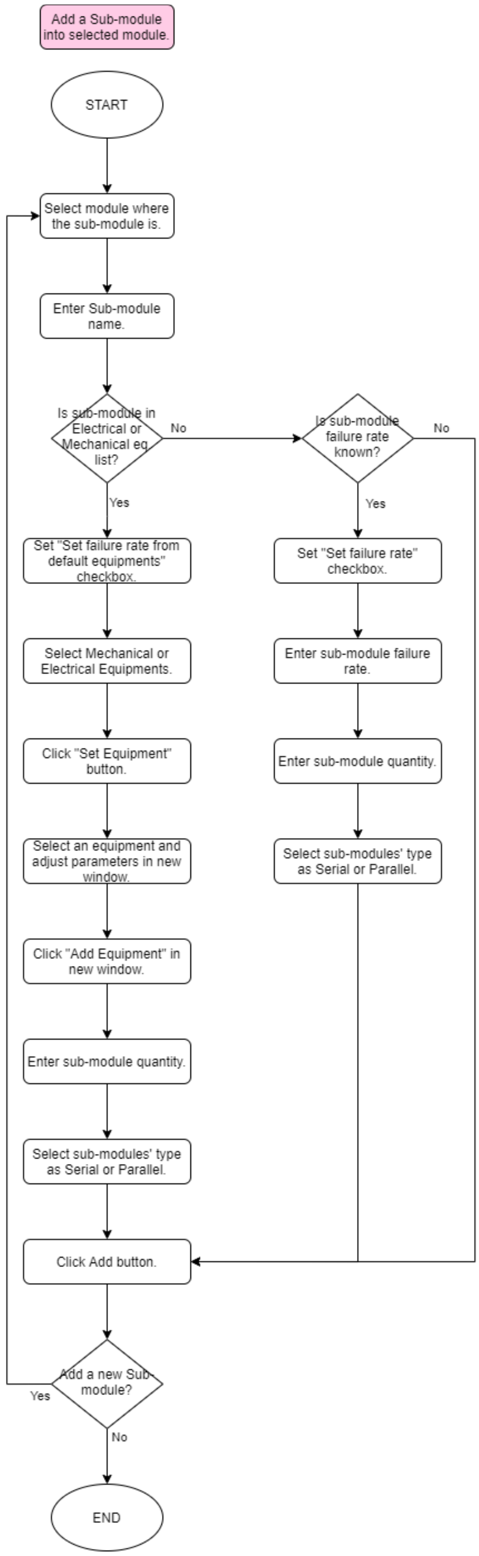


Figure 3.7 Flowchart of Add Sub-Module tab

Sub-modules are added to the system in 3 different ways: Adding sub-modules from the given equipment list (Table 1), adding sub-modules with zero failure rate and entering the failure rate value by user.

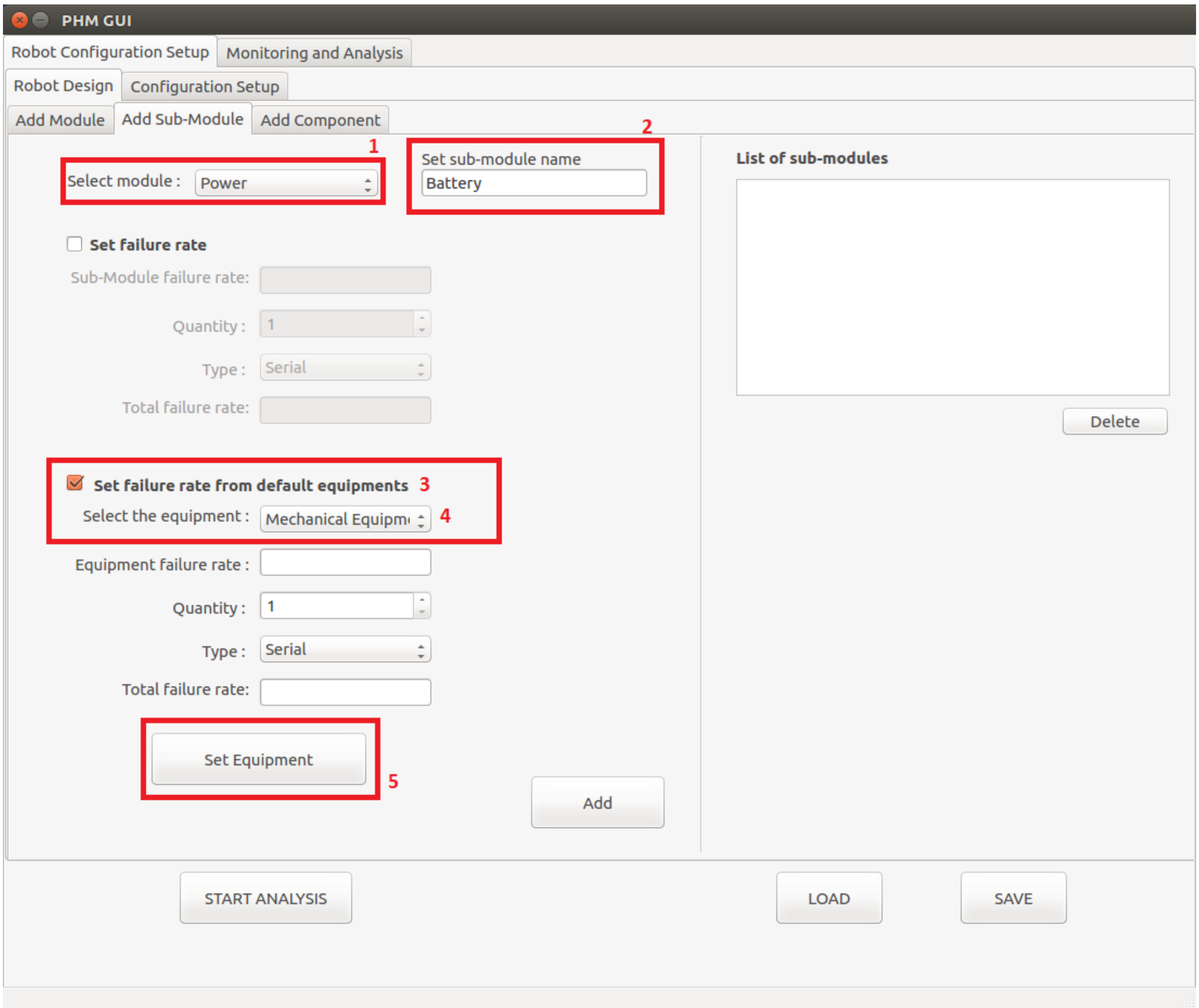


Figure 3.8 Adding sub-module as equipment

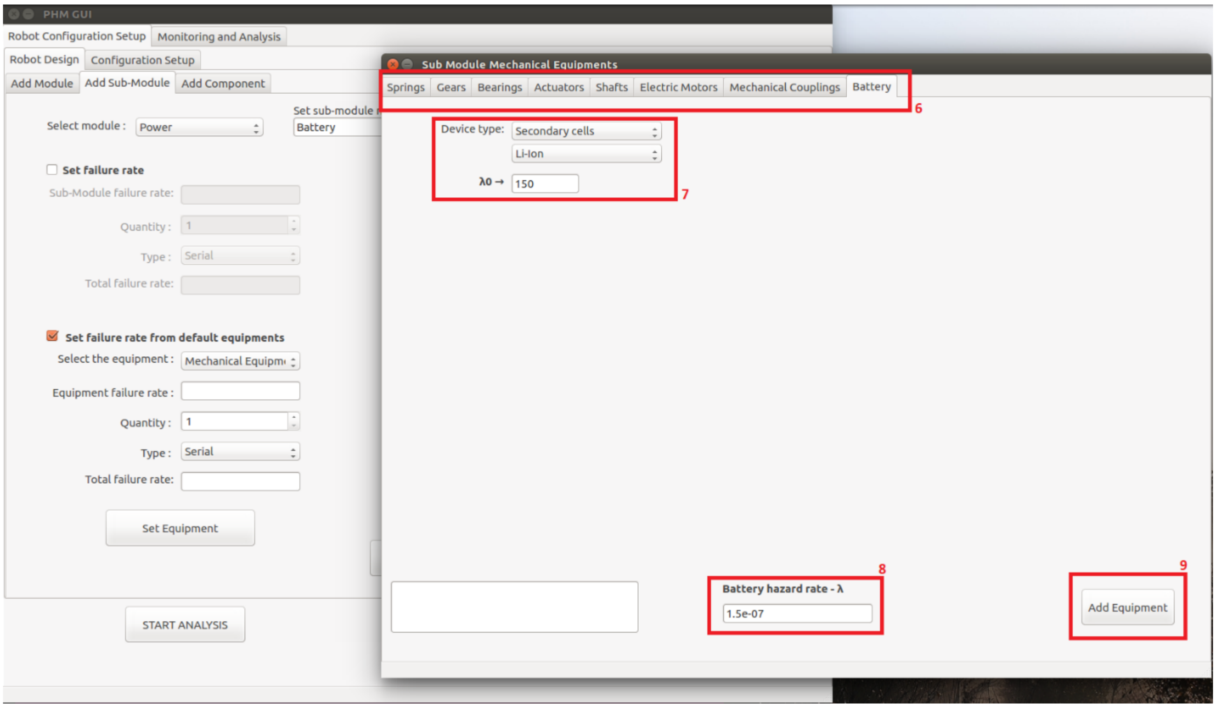
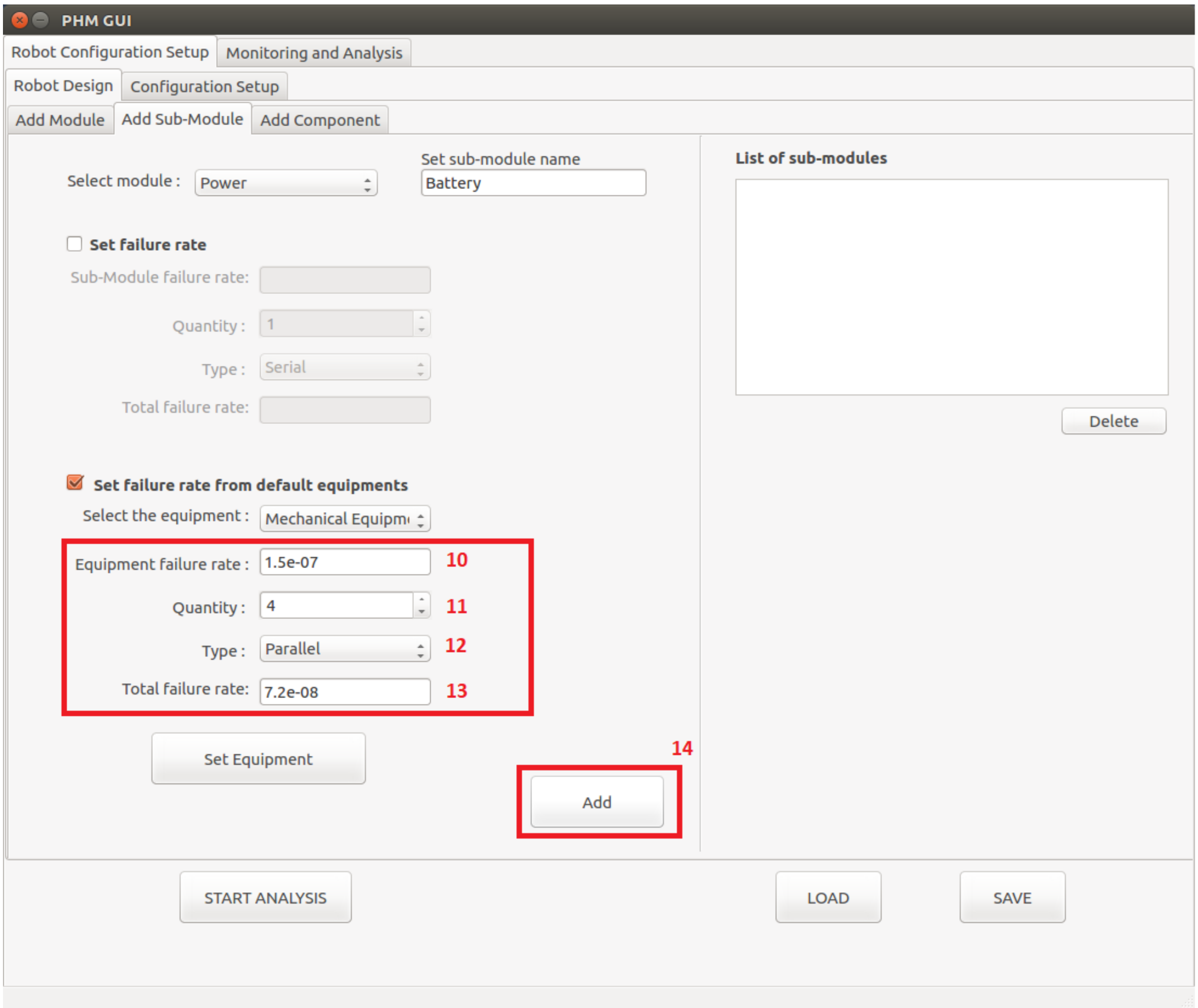


Figure 3.9 Equipments and their parameters in PHM Tool



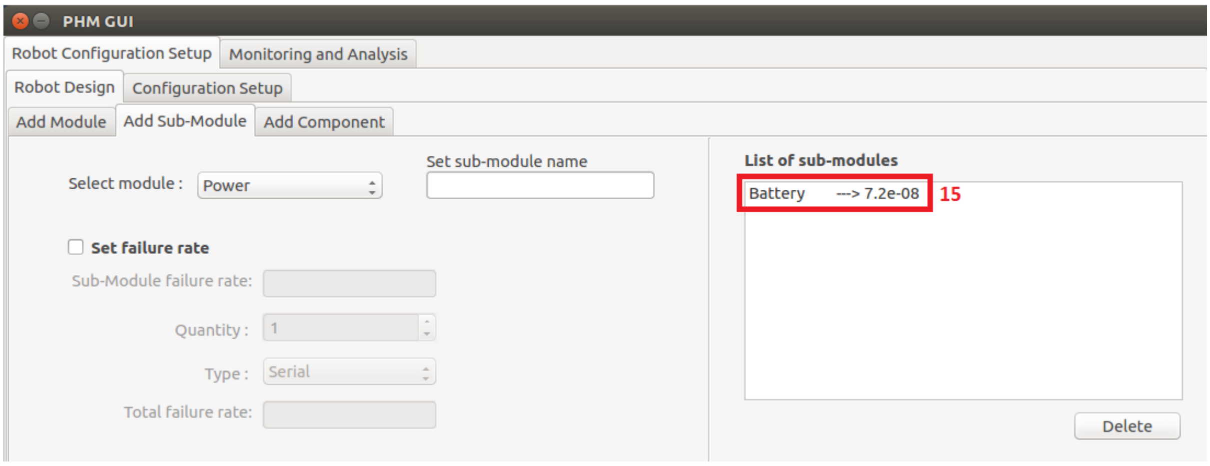


Figure 3.10 Adding sub-module into the system

A sub-module to be added to the system can be an electrical or mechanical equipment. In this case, the user can calculate the failure rate of the sub-module by selecting one of the equipments in the PHM Tool. All of the equipments in the PHM Tool are given in Table 1. The Figure 3.8, Figure 3.9 and Figure 3.10 show the addition of one of the equipments in the PHM Tool as a sub-module.

- In box 1, under which module the sub-module to be added is selected.
- In box 2, the name of the sub-module to be added is entered.
- In section amrked with 3, the checkbox here is checked, if the added sub-module is electrical or mechanical equipment.
- In section marked with 4, it is checked whether the added sub-module is in electrical or mechanical equipments.
- By clicking the “Set Equipment” button in box 5, you can go to the equipment selection window.
- In box 6, one of the equipments is selected.
- In box 7, the parameters of the selected equipment are arranged. Here you can see the parameters of the “Battery” equipment.
- In box 8, failure rate value of the equipment can be seen.
- By clicking the “Add Equipment” button in box 9, the failure rate value of the equipment is added to the section 10.
- In section marked with 10, the failure rate value of a single equipment is shown.
- In section marked with 11, sub-module (equipment) quantity is entered.
- In section marked with 12, serial or parallel states of the added sub-modules are entered according to each other. If the sub-module quantity is 1, selecting this section as series or parallel will not change the total failure rate value.
- In section marked with 13, the total failure rate of the sub-module is shown.
- By clicking the “Add” button in box 14, the sub-module is added to the system with the calculated failure rate value.
- In box 15, the added sub-module is listed.

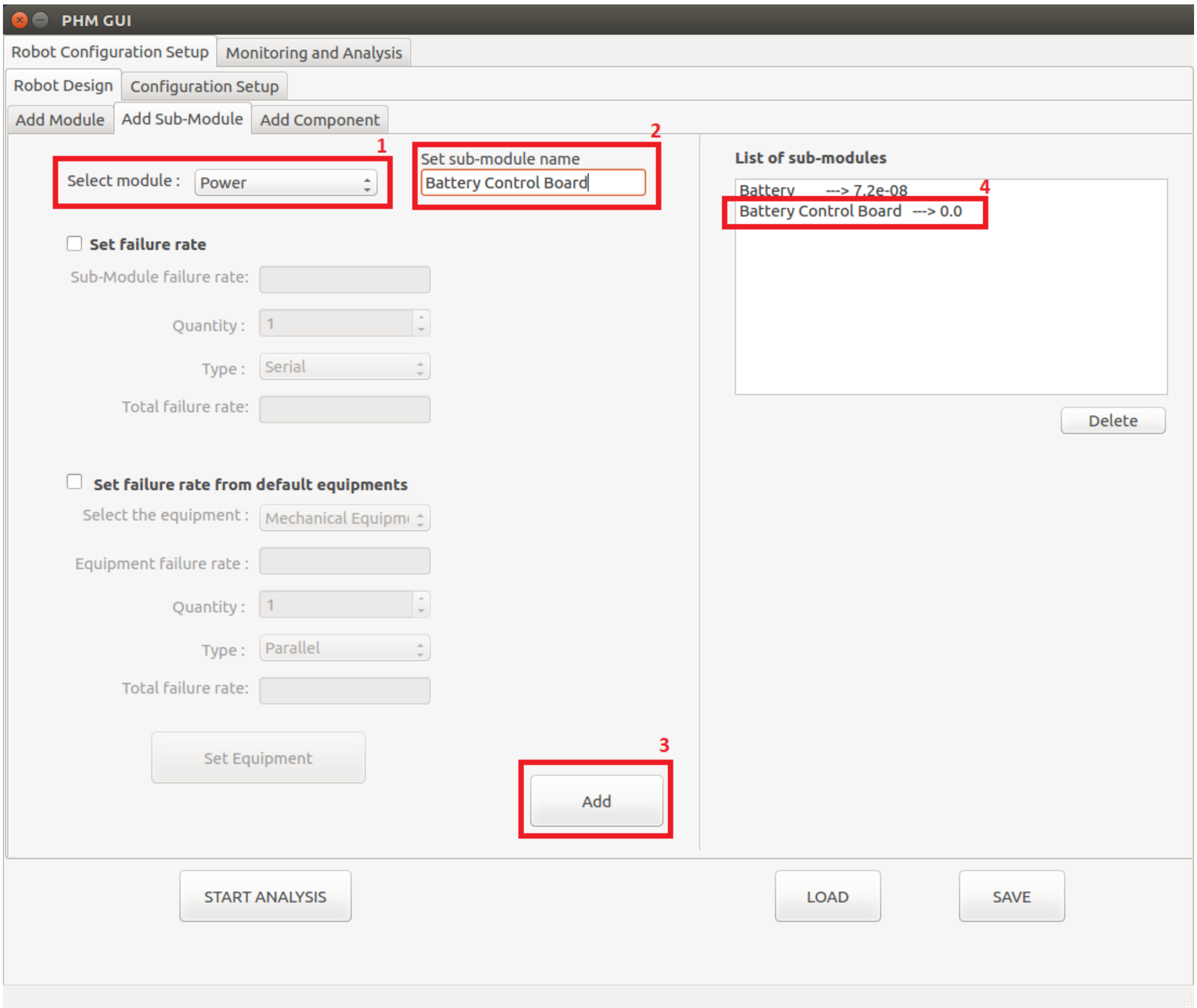


Figure 3.11 0 Adding sub-module with 0 failure rate

Sub-module can be added with 0 failure rate value. When a sub-module is added in this way, the failure rate of the module is calculated after the configuration process. Figure 3.11 shows the process of adding sub-modules with 0 failure rate value.

- In box 1, under which module the sub-module to be added is selected.
- In box 2, the sub-module name is entered.
- By clicking the “Add” button in box 3, the sub-module is added under the module selected in section 1.
- In box 4, the sub-modules added to the system are listed together with their failure rate values.

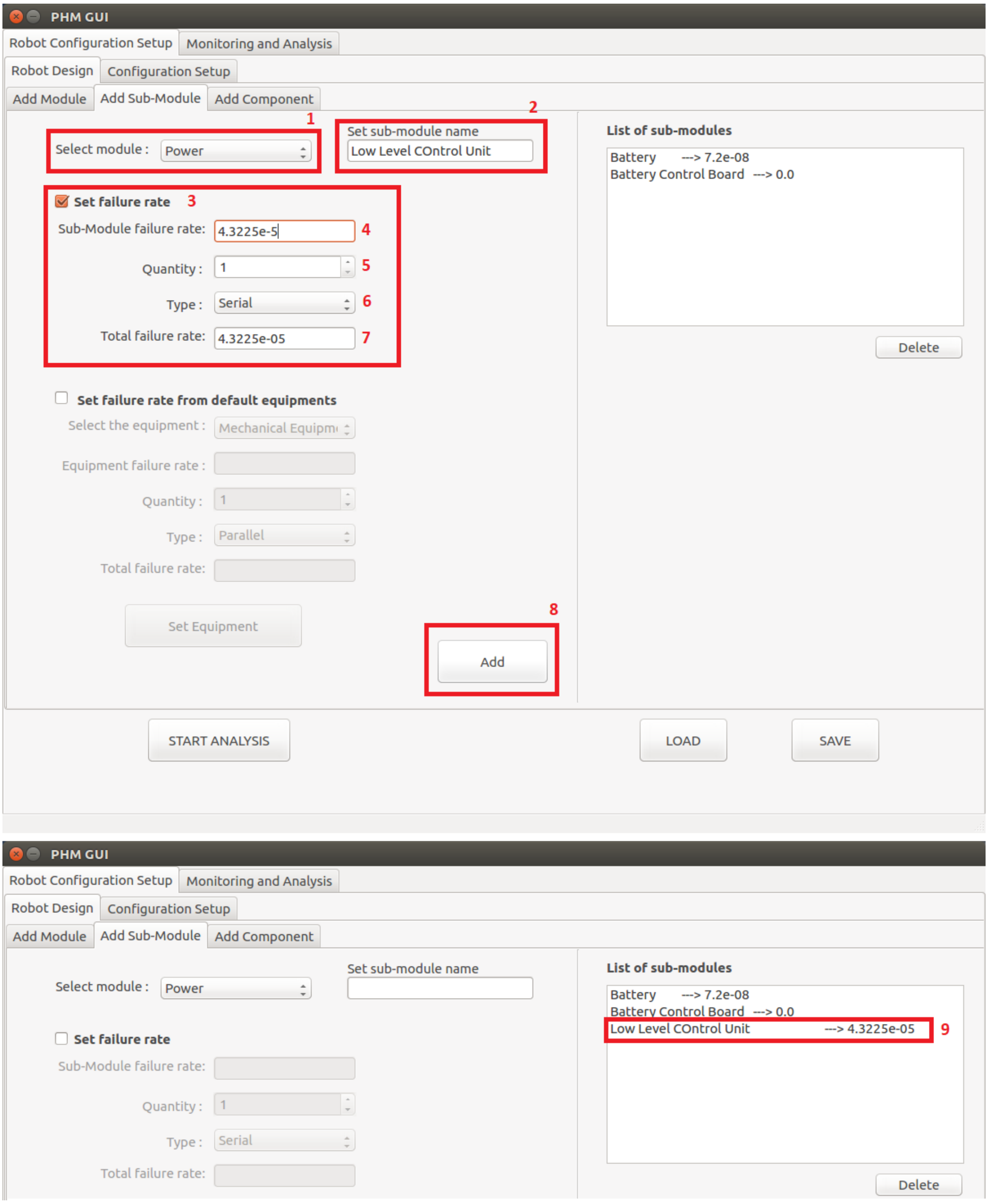


Figure 3.12 Entering the sub-module's failure rate value by user

The sub-module can be added under the selected module by entering the failure rate by the user. When the sub-module is added in this way, its configuration is not required to calculate the failure rate of the sub-module. In Figure 3.12, the operation of adding the sub-module's failure rate value by the user is shown.

- In box 1, under which module the sub-module to be added is selected.

- In box 2, the sub-module name is entered.
- By checking the checkbox in section marked with 3, the user activates the relevant section.
- In section marked with 4, the failure rate value of the sub-module is entered.
- In section marked with 5, the number of the added sub-module will be entered.
- In section marked with 6, serial or parallel states of the added sub-modules are entered according to each other. If the sub-module quantity is 1, selecting this section as series or parallel will not change the total failure rate value.
- In section marked with 7, the total failure rate of the sub-module is shown.
- By clicking the "Add" button in box 8, the sub-module is added under the module selected in section 1 with the calculated failure rate value.
- In box 9, the sub-modules added to the system are listed together with their failure rate values.

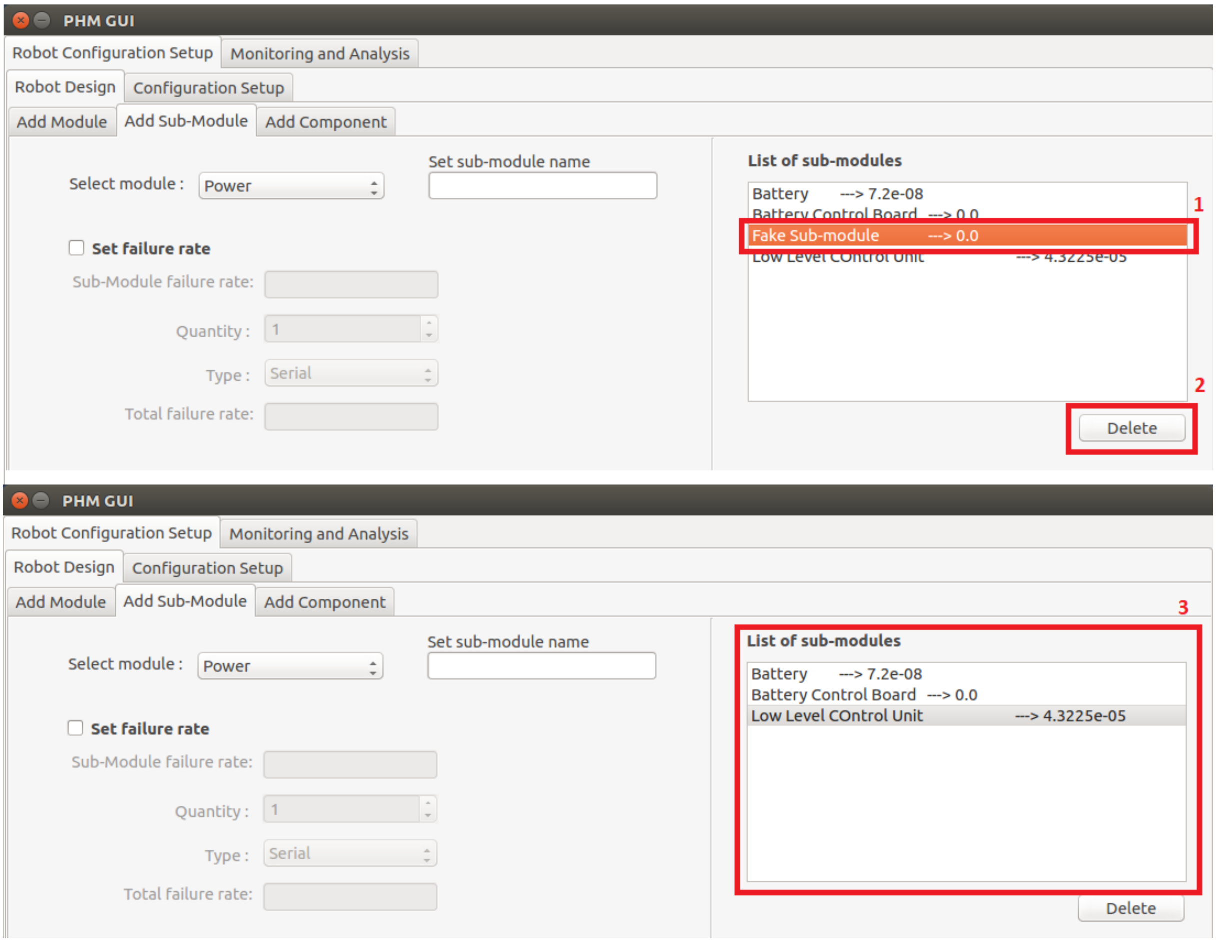


Figure 3.13 Deleting the added sub-module from the system

The deletion of a sub-module which is added to the selected module is shown in Figure 3.13. Let's assume that the sub-module to be deleted is "Fake Sub-module".

- In box 1, the sub-module to be deleted is selected from the list.
- By clicking the "Delete" button in box 2, the sub-module is removed from the system.
- Deleted sub-modules are removed from the list in box 3.

3.3.1.3. Add Component Tab

Components compose the third level of the system. Therefore, components must be determined after determining the sub-modules. “Add Component” tab is the tab where components are added to the system.

The flowchart of the operations done in “Add Component” tab is shown in Figure 3.14.

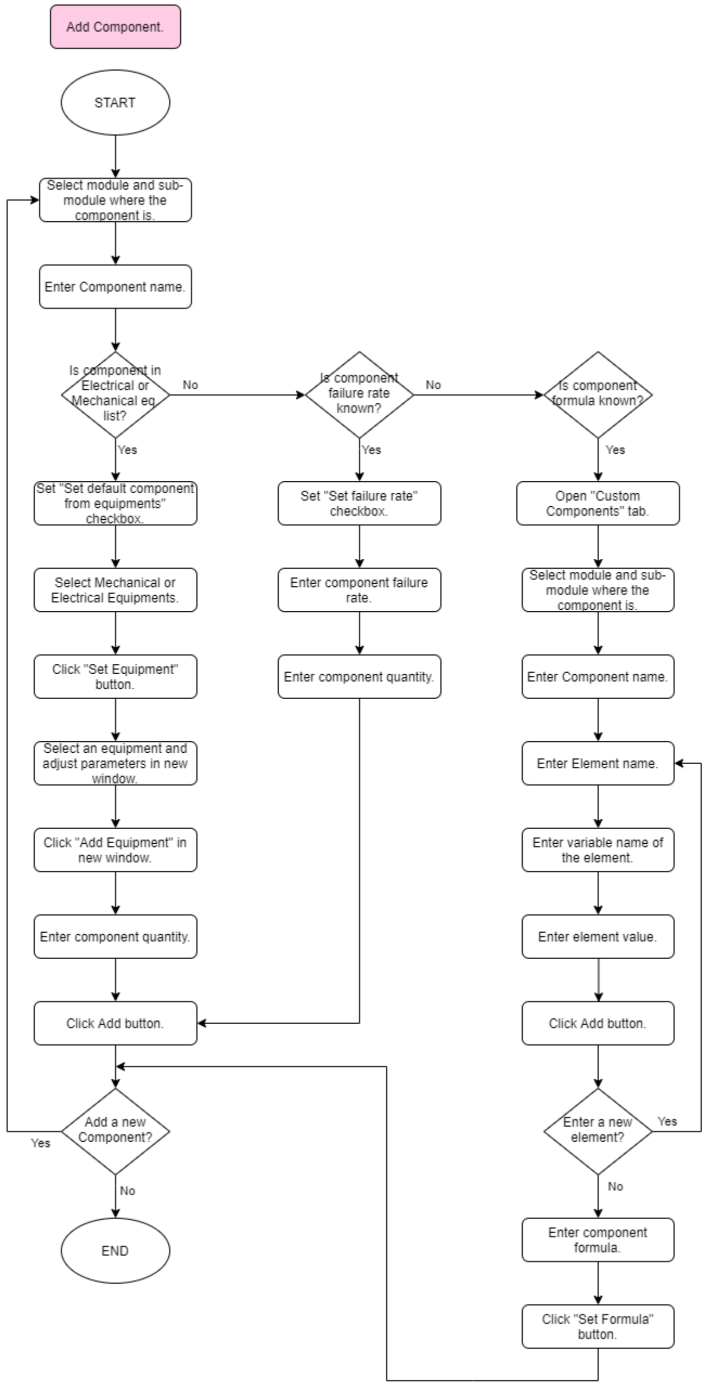


Figure 3.14 Flowchart of Add Component tab

Components are added to the system in 3 different ways: Adding components from the given equipment list (Table 1), entering the failure rate value by user and entering the failure rate calculation formula of the component.

3.3.1.3.1. Default Components Tab

In this tab, the components are added from the given equipment list and by entering failure rate value by the user.

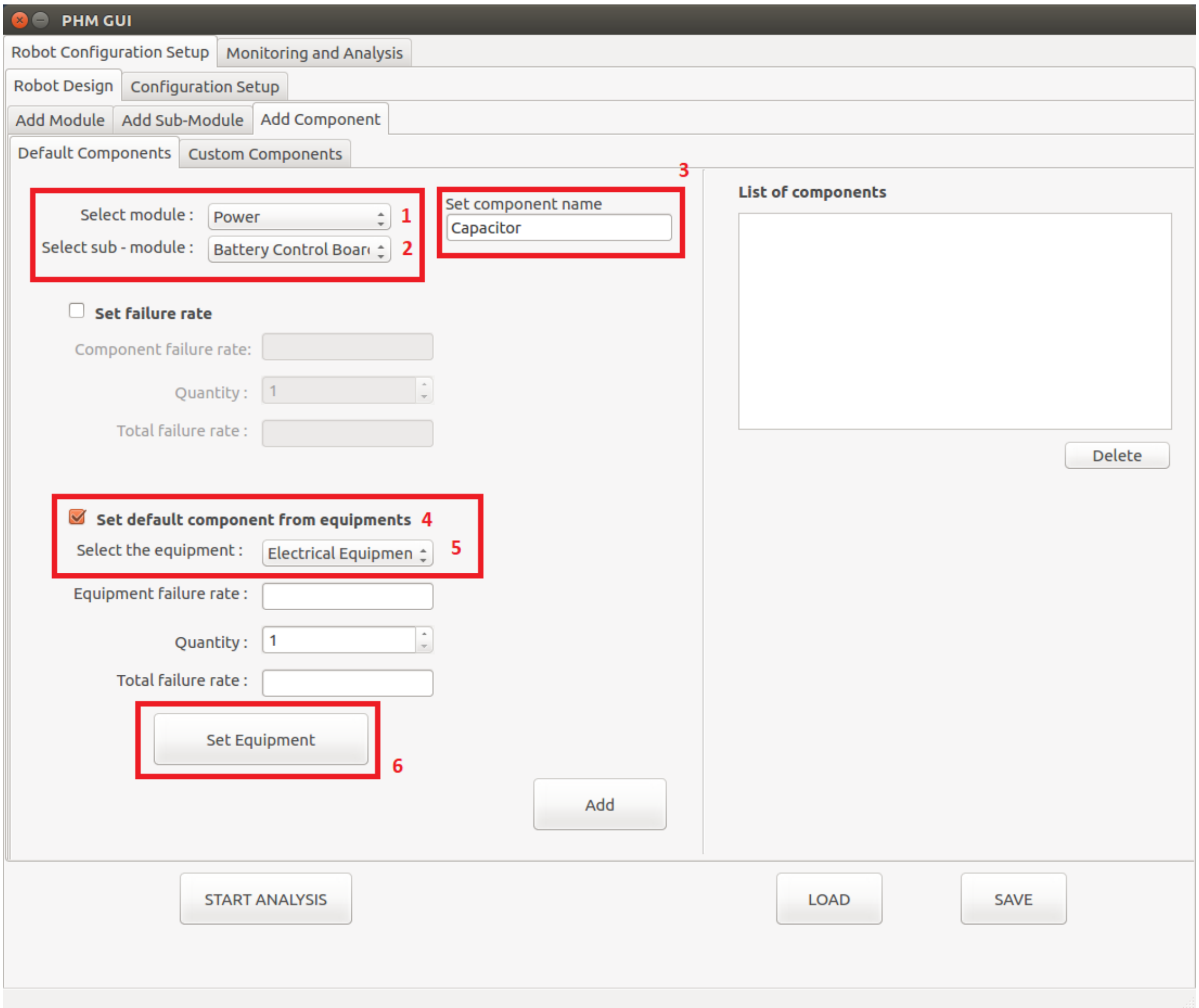


Figure 3.15 Adding a component from equipment list (a)

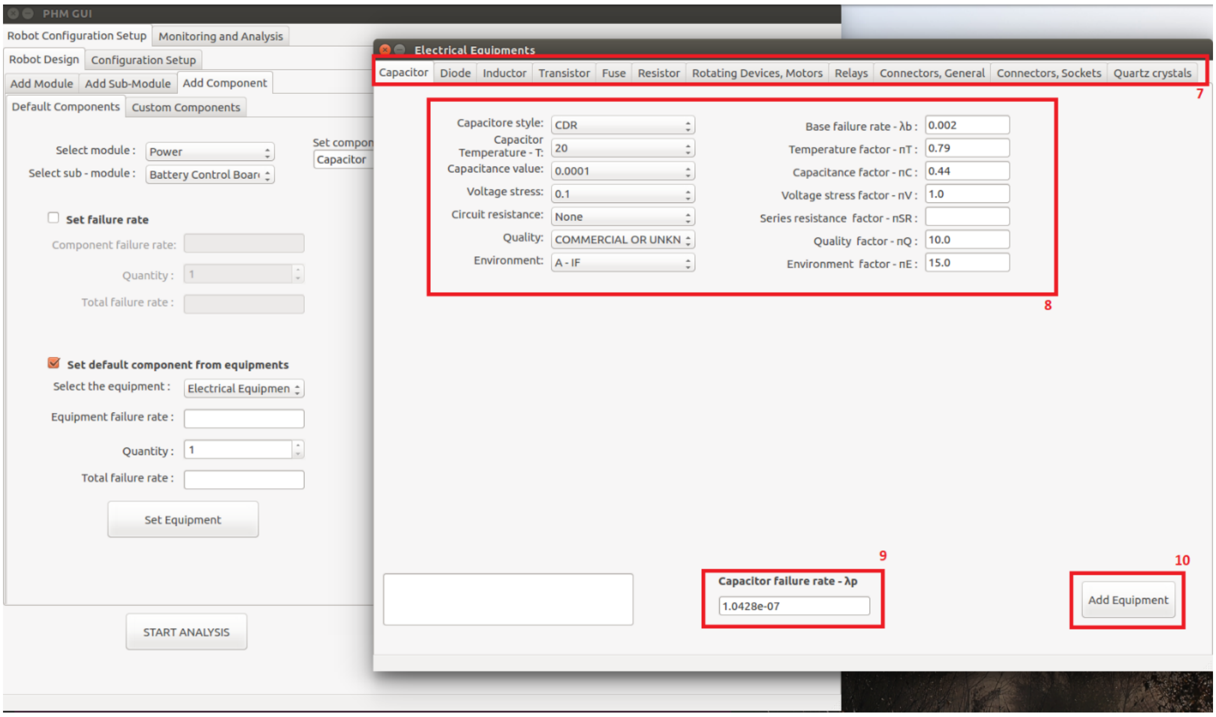


Figure 3.16 Adding a component from equipment list (b)

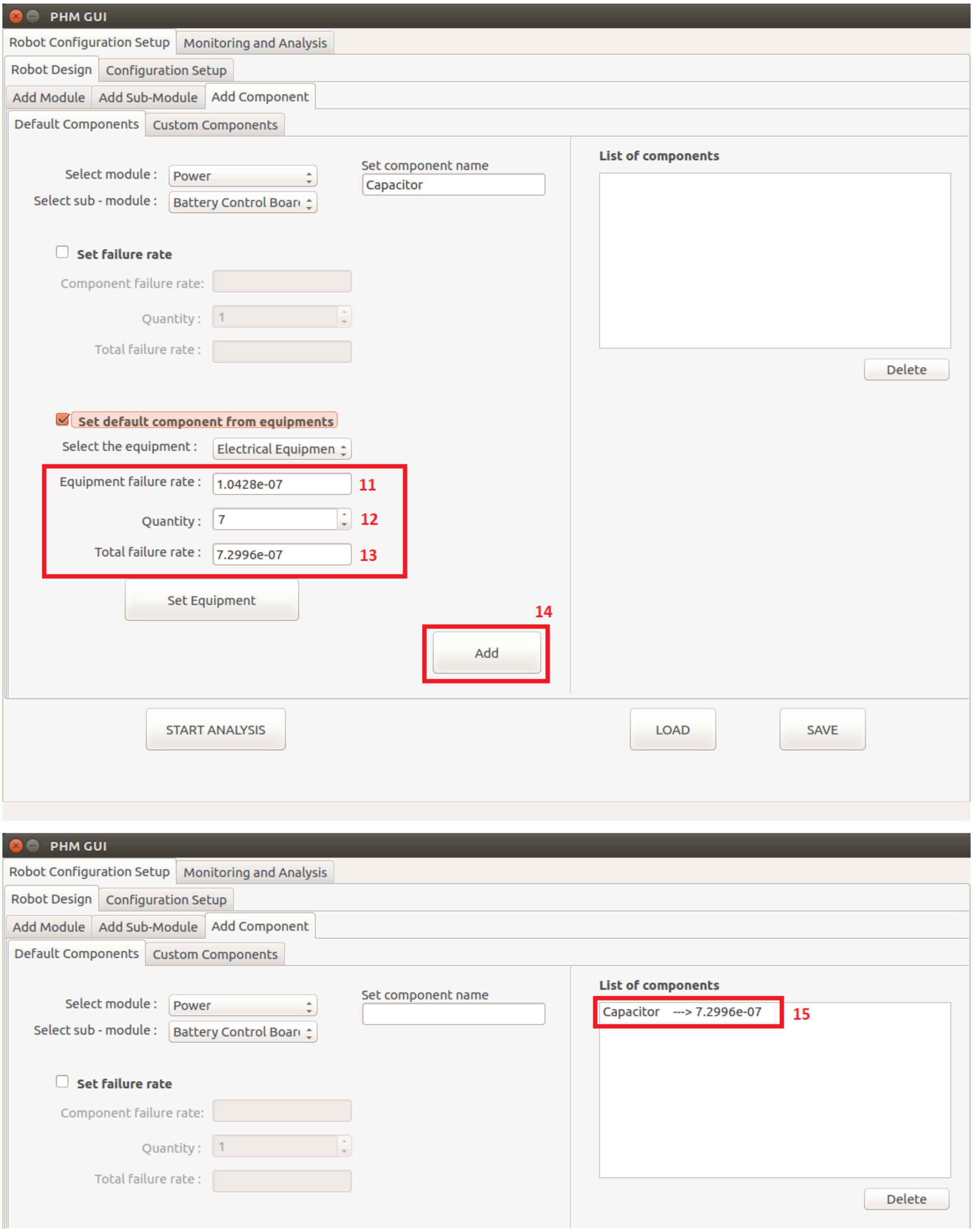


Figure 3.17 Adding a component from equipment list (c)

A component to be added to the system can be an electrical or mechanical equipment. In this case, the user can calculate the failure rate of the component by selecting one of the equipments in the PHM Tool. All of the equipments in the PHM Tool are given in Table 1. The Figure 3.15, Figure 3.16 and Figure 3.17 show the addition of one of the equipments in the PHM Tool as a component.

- In section marked with 1, under which module the component to be added is selected.
- In section marked with 2, under which sub-module the component to be added is selected.
- In box 3, the name of the component to be added is entered.
- In section marked with 4, the checkbox here is checked, if the added component is electrical or mechanical equipment.
- In section marked with 5, it is checked whether the added component is in electrical or mechanical equipments.
- By clicking the “Set Equipment” button in box 6, you can go to the equipment selection window.
- In box 7, one of the equipment is selected.
- In box 8, the parameters of the selected equipment are arranged. Here you can see the parameters of the “Capacitor” equipment.
- In box 9, failure rate value of the equipment can be seen.
- By clicking the “Add Equipment” button in box 10, the failure rate value of the equipment is added to the section marked with 11.
- In section marked with 11, the failure rate value of a single equipment is shown.
- In section marked with 12, component (equipment) quantity is entered.
- In section marked with 13, the total failure rate of the component is shown.
- By clicking the “Add” button in box 14, the component is added to the system with the calculated failure rate value.
- In box 15, the added component is listed.

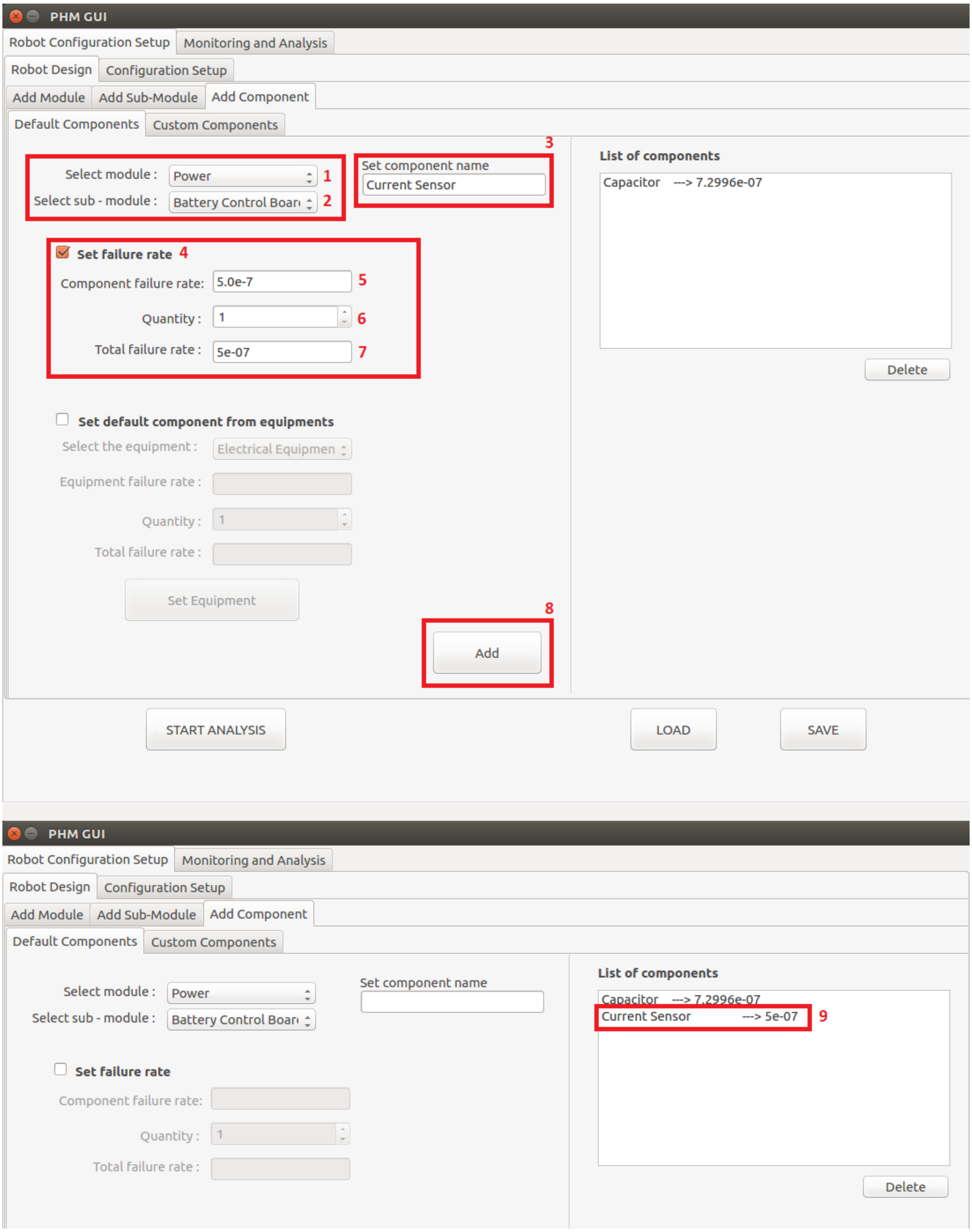


Figure 3.18 Entering the component's failure rate value by user

The component can be added under the selected module and selected sub-module (Figure 3.18, section 1 and section 2) by entering the failure rate by the user. When the component is added in this way, its formulation is not required to calculate the failure rate. In Figure 3.18, the operation of adding the component's failure rate value by the user is shown.

- In section marked with 1, under which module the component to be added is selected.
- In section marked with 2, under which sub-module the component to be added is selected.
- In box 3, the name of the component to be added is entered.
- By checking the checkbox in section marked with 4, the user activates the relevant section.
- In section marked with 5, the failure rate value of the component is entered.
- In section marked with 6, the number of the added component will be entered.
- In section marked with 7, the total failure rate of the component is shown.
- By clicking the “Add” button in box 8, the component is added under the selected module and selected sub-module (Figure 3.18, section 1 and section 2) with the calculated failure rate value.
- In box 9, the components added to the system are listed together with their failure rate values.

3.3.1.3.2. Custom Components Tab

If the component that the user wants to add into the system is not in Table 1 and the user knows the failure rate calculation formula of the component, it should be worked on the “Custom Components” tab.

Adding a custom component is basically done in 2 steps: Entering the failure rate calculation parameters of the component and writing the failure rate calculation formula of the component using these parameters.

The process of entering the failure rate calculation parameters of the component is shown in Figure 3.19 and the process for writing the failure rate calculation formula of the component using these parameters is shown in Figure 3.20.

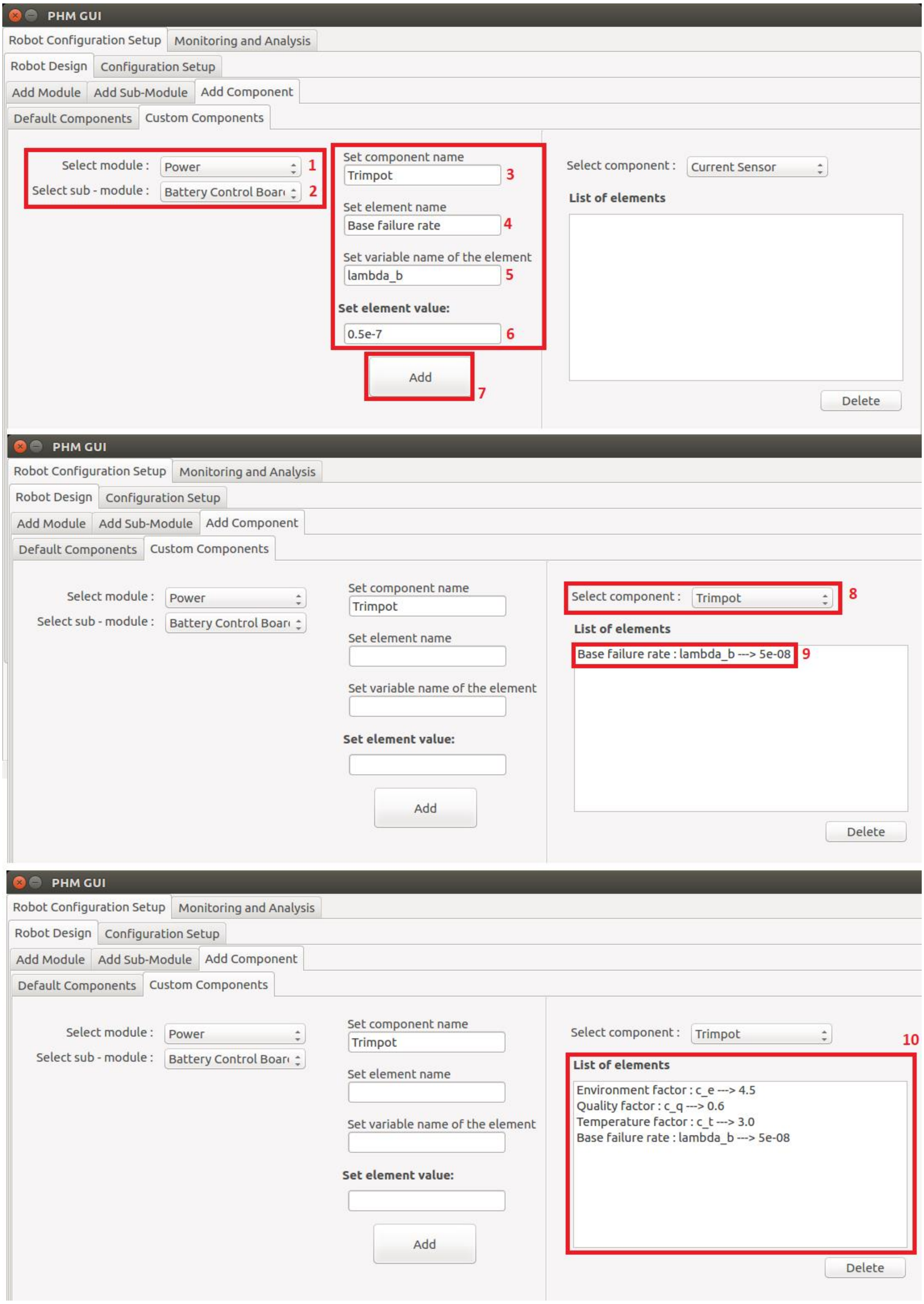


Figure 3.19 Adding parameters of a custom component

- In section marked with 1, under which module the component to be added is selected.
- In section marked with 2, under which sub-module the component to be added is selected.
- In section marked with 3, the name of the component to be added is entered.
- In section marked with 4, the name of the parameter of the custom component is entered.
- In section marked with 5, the variable name of the parameter belonging to the custom component is entered.
- In section marked with 6, the value of the parameter belonging to the custom component is entered.
- By clicking the “Add” button in box 7, a parameter belonging to the component is added.
- In box 8, the added component is selected.
- In box 9, the parameter added to the component is listed.
- In box 10, all parameters added to the component are displayed in this way.

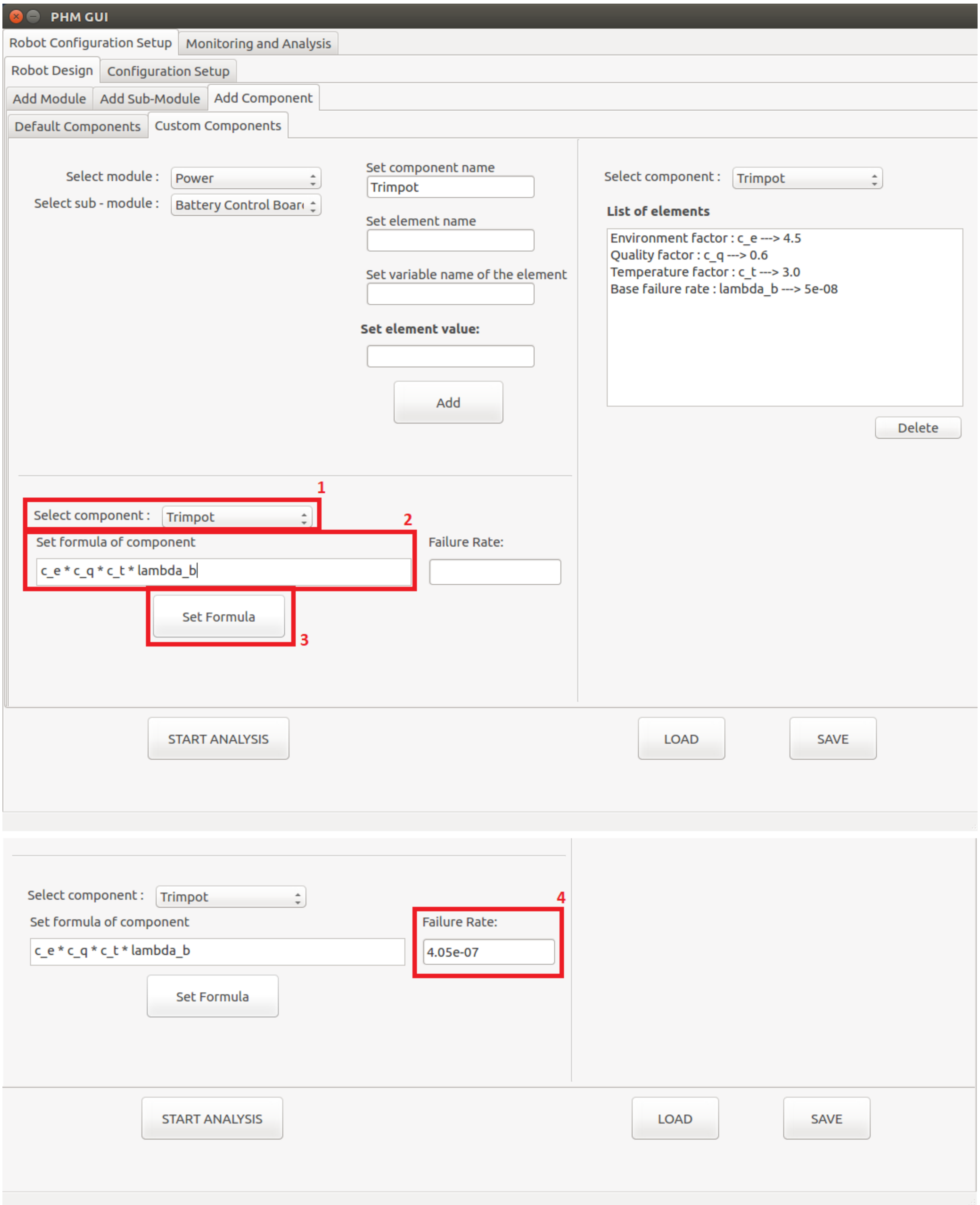


Figure 3.20 Writing the failure rate calculation formula of a custom component

The process of writing the failure rate calculation formula of the component using these parameters is described in here (Figure 3.19).

- In box 1, the component whose will be entered is selected.

- In box 2, the formula of the component is entered using the variable names of the parameters of the component.
- The failure rate value of the component is calculated according to the entered formula and parameter values by clicking the “Set Formula” button in box 3.
- In box 4, the new calculated failure rate value of the component is shown.

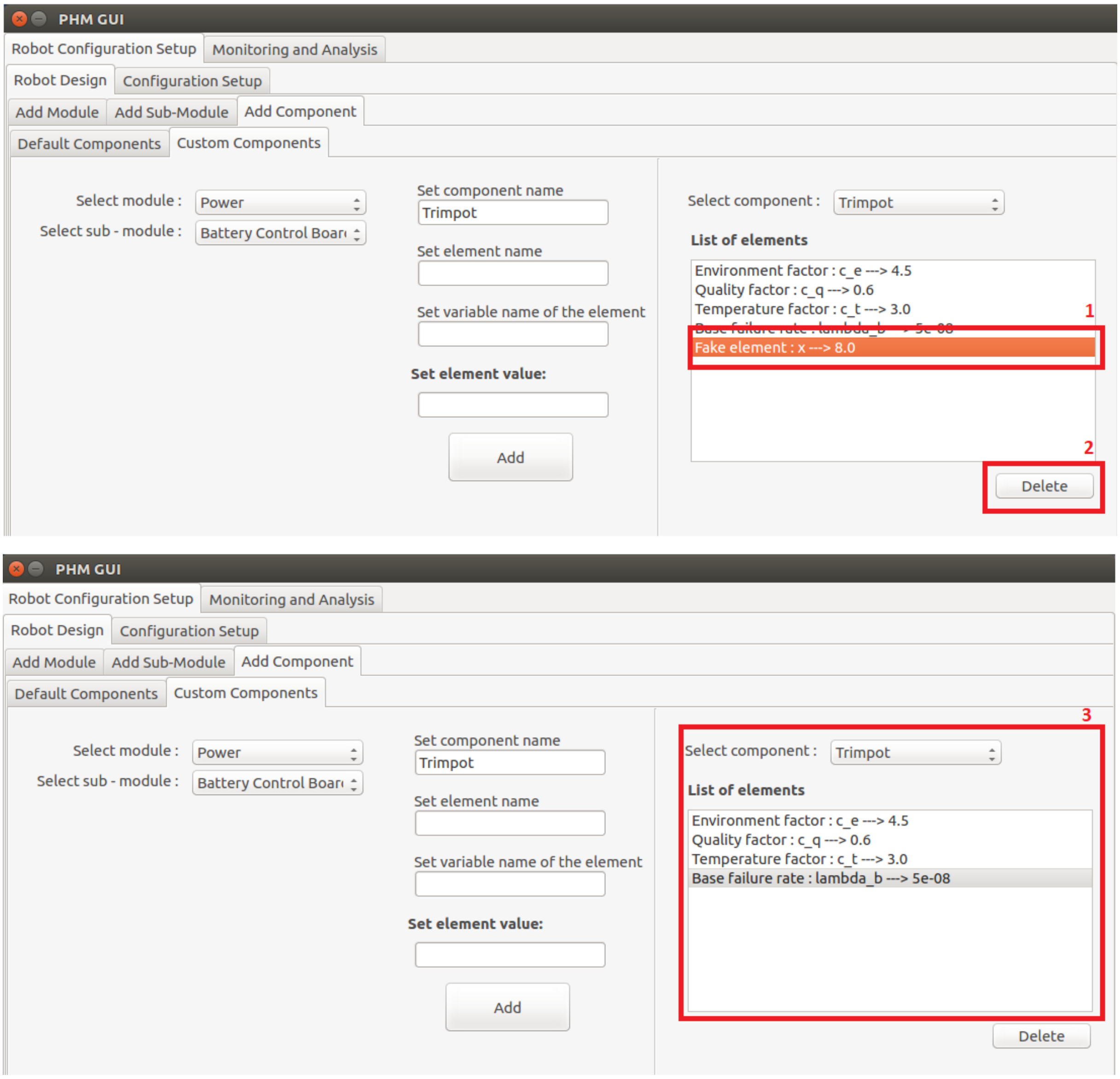


Figure 3.21 Deleting the added parameter from the custom component

The deletion of a parameter which is added to the selected component is shown in Figure 3.21. Let's assume that the parameter to be deleted is “Fake element”.

- In box 1, the parameter to be deleted is selected from the list.
- By clicking the “Delete” button in box 2, the parameter is removed from the component.
- Deleted parameters are removed from the list in box 3.

3.3.2. Configuration Setup Tab

In this section, how to configure the components, submodules and modules which are created in the "Robot Design Tab" tab and how their serial-parallel relations with each other are realized in the PHM Tool.

3.3.2.1. Sub Module Configuration Tab

It is the tab where the components under the sub-module are configured. As a result of configuring the components, the failure rate of the sub-module is calculated. The flowchart of the operations done in “Sub-Module Configuration” tab is shown in Figure 3.22.

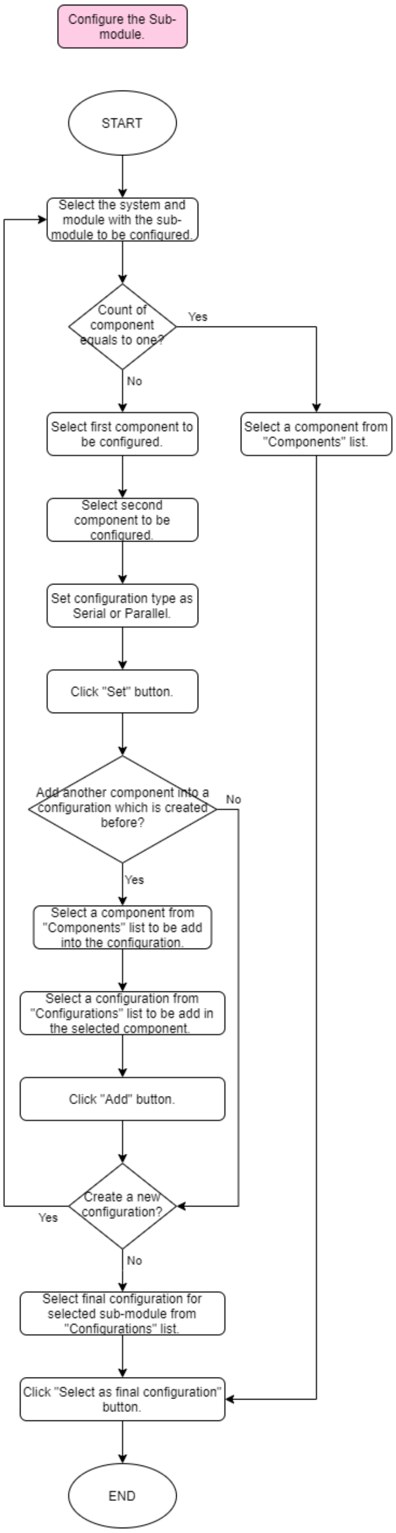


Figure 3.22 Flowchart of Sub-Module Configuration tab

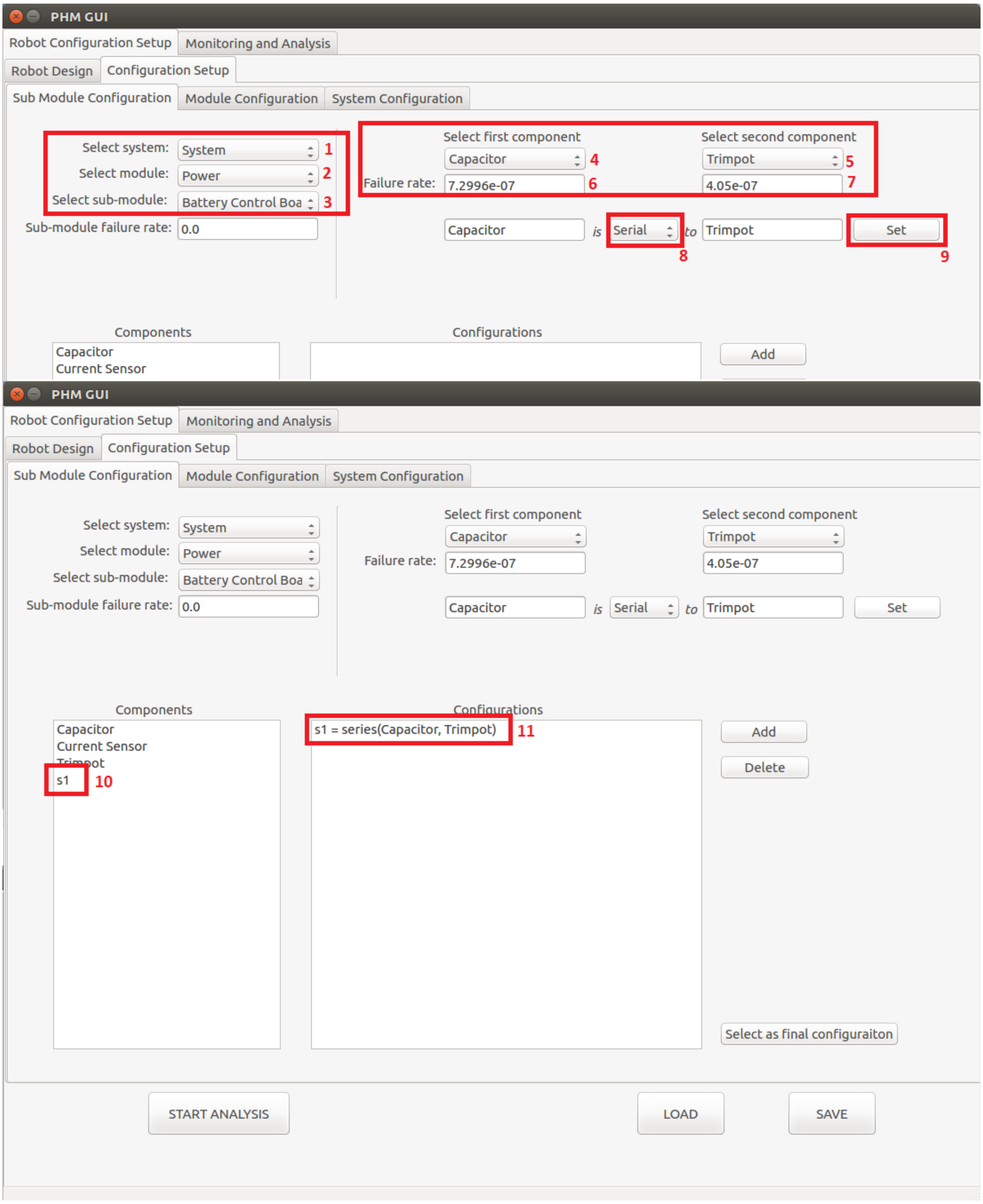


Figure 3.23 Configuration of two components

Figure 3.23 shows how to configure the two components.

- In section marked with 1, the system is selected.
- In section marked with 2, one of the modules under the system is selected.
- In section marked with 3, a sub-module is selected to be configured.

- In sections marked with 4 and 5, the components to be configured are selected.
- In sections marked with 6 and 7, failure rate values of the selected components are shown.
- In box 8, the state of the two components relative to each other is selected as serial or parallel.
- By clicking the “Set” button in box 9, two components re configured as serial or parallel.
- In box 10, the configuration name is displayed.
- In box 11, the entire configuration is displayed.

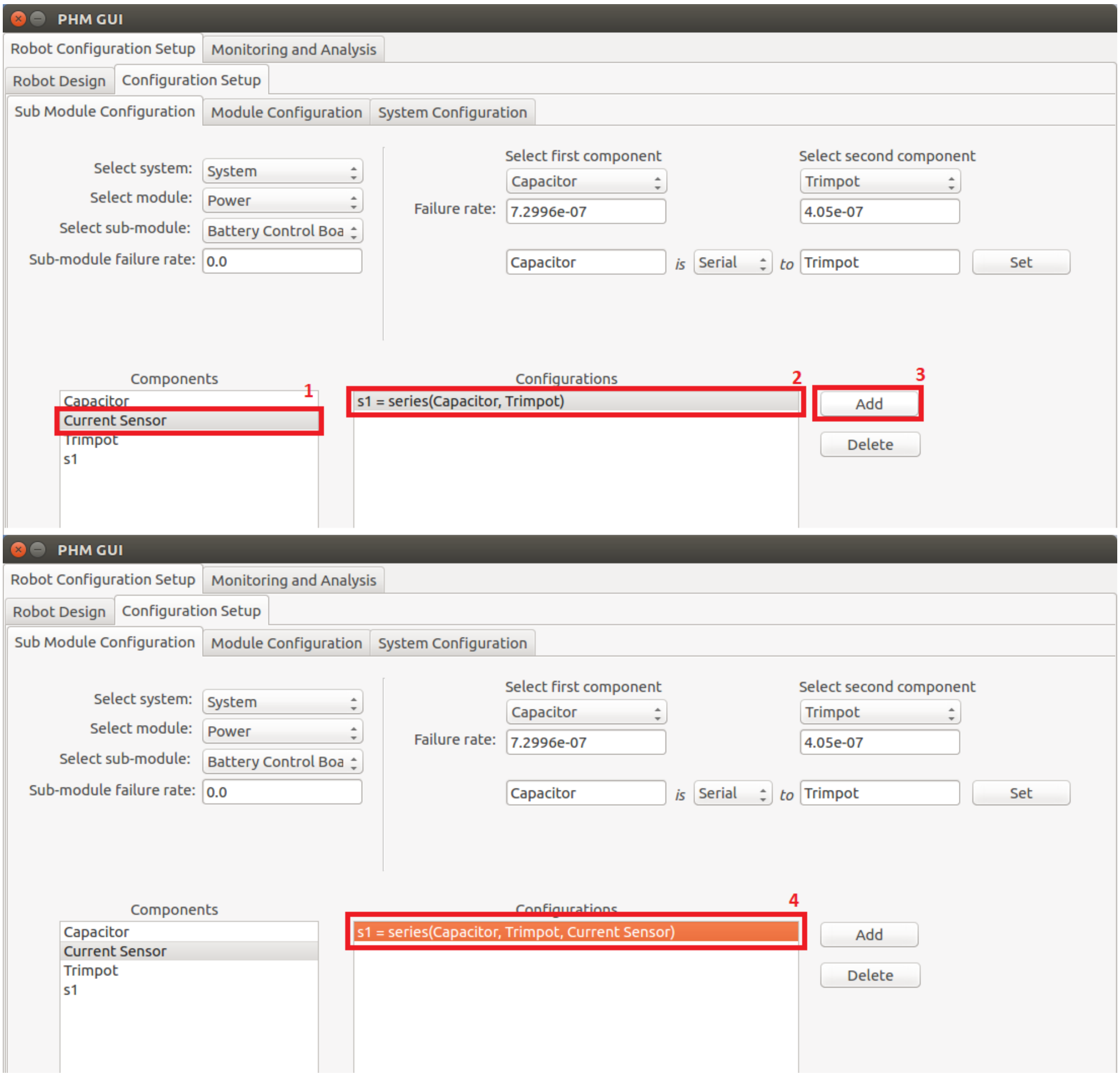


Figure 3.24 Adding an another component into a configuration

Components in the “Components” list can be added to a previously created configuration. This process is shown in Figure 3.24.

- In box 1, component is selected.
- In box 2, a configuration is selected to add the component which is selected in section 1.
- By clicking the “Add” button in box 3, the selected component is added into the selected configuration.

- In box 4, it is seen that the selected component is added to the selected configuration.

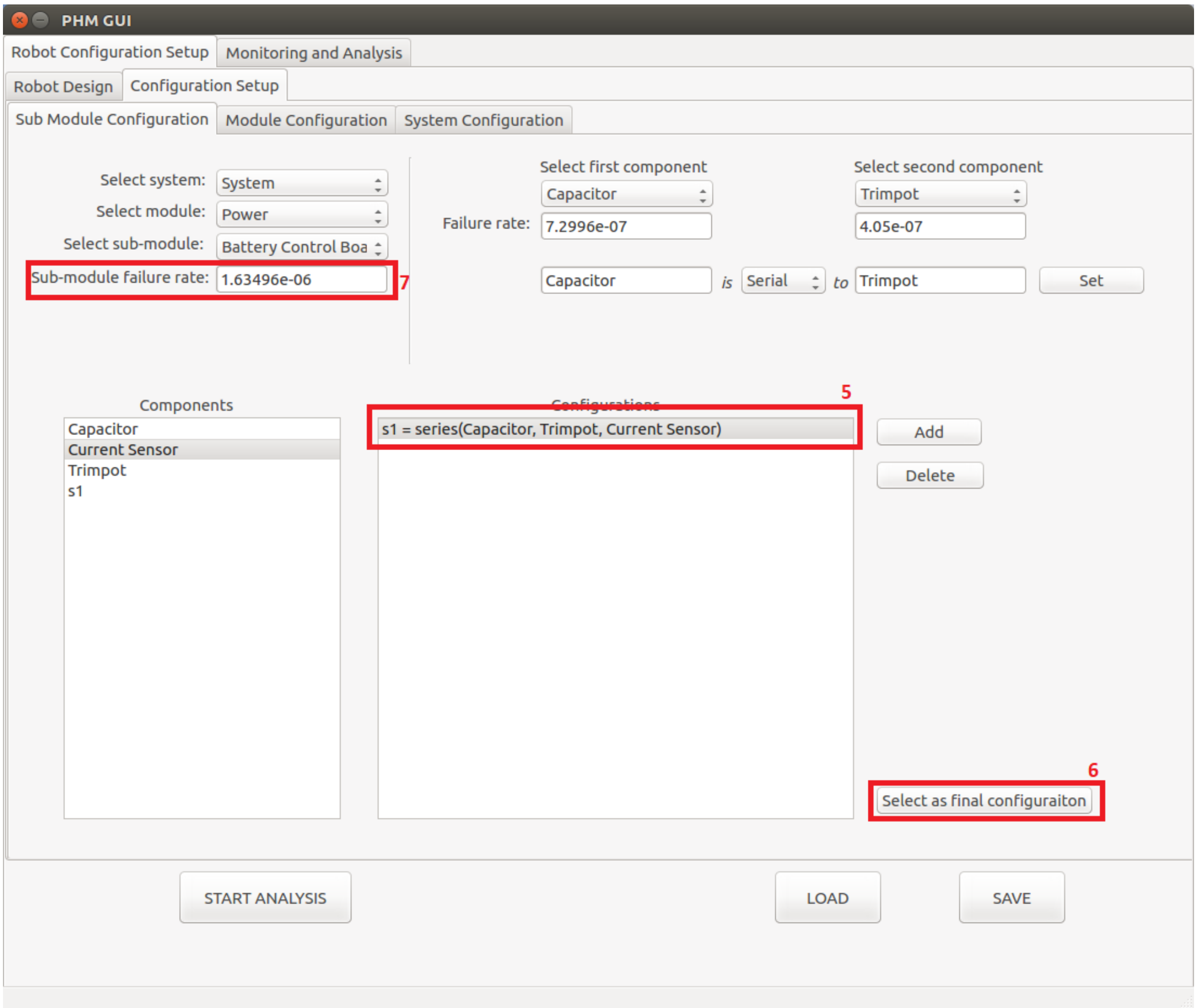


Figure 3.25 Setting the sub-module's failure rate after configuration

In order to assign the failure rate value of the sub-module, it is necessary to decide which of the configurations is "Final Configuration". The process of assigning the failure rate value of the sub-module is shown in Figure 3.25.

- In box 5, the configuration of the sub-module is selected.
- By clicking the "Select as final configuration" button in box 6, the failure rate value of the sub-module is assigned.
- In box 7, the failure rate of the sub-module is shown after selection.

❖ *If the selected configuration is "Serial"; the configuration names are "s1, s2, etc."*

❖ *If the selected configuration is "Parallel"; the configuration names are "p1, p2, etc."*

- *If the final configuration to be made is only one component, the element to be the final configuration is selected from the "Components" list. Then click "Select as final configuration" button.(See the video in the [One component as a final configuration](#) link)*

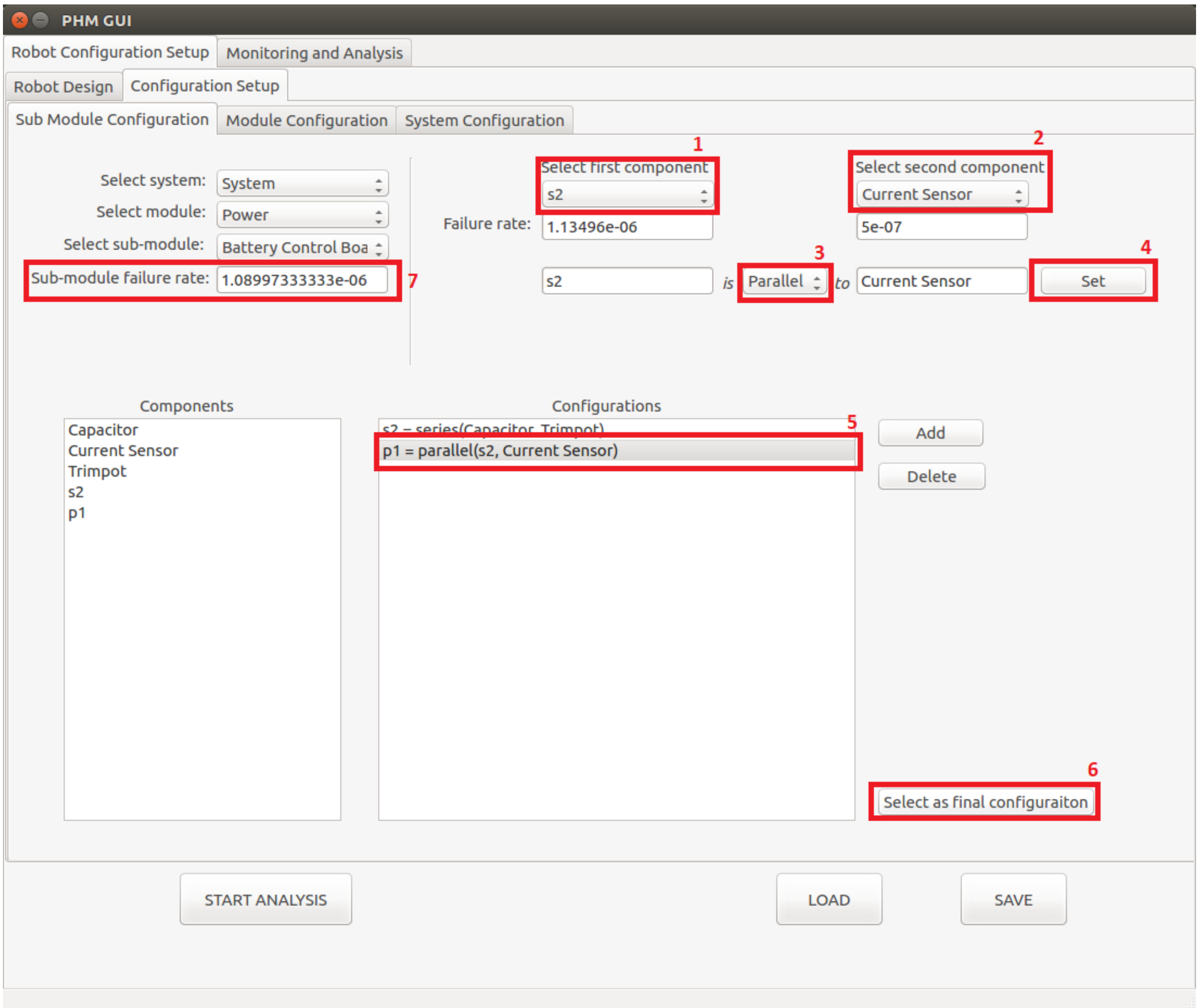


Figure 3.26 Configuration of a component with a previously done configuration

- *There are two lists named "Components" and "Configurations" in the interface. In the "Components" list, the components and created configurations are located under the selected sub-module. Because in some cases, components can be configured together with the created configurations (See Figure 3.26, section 5).*

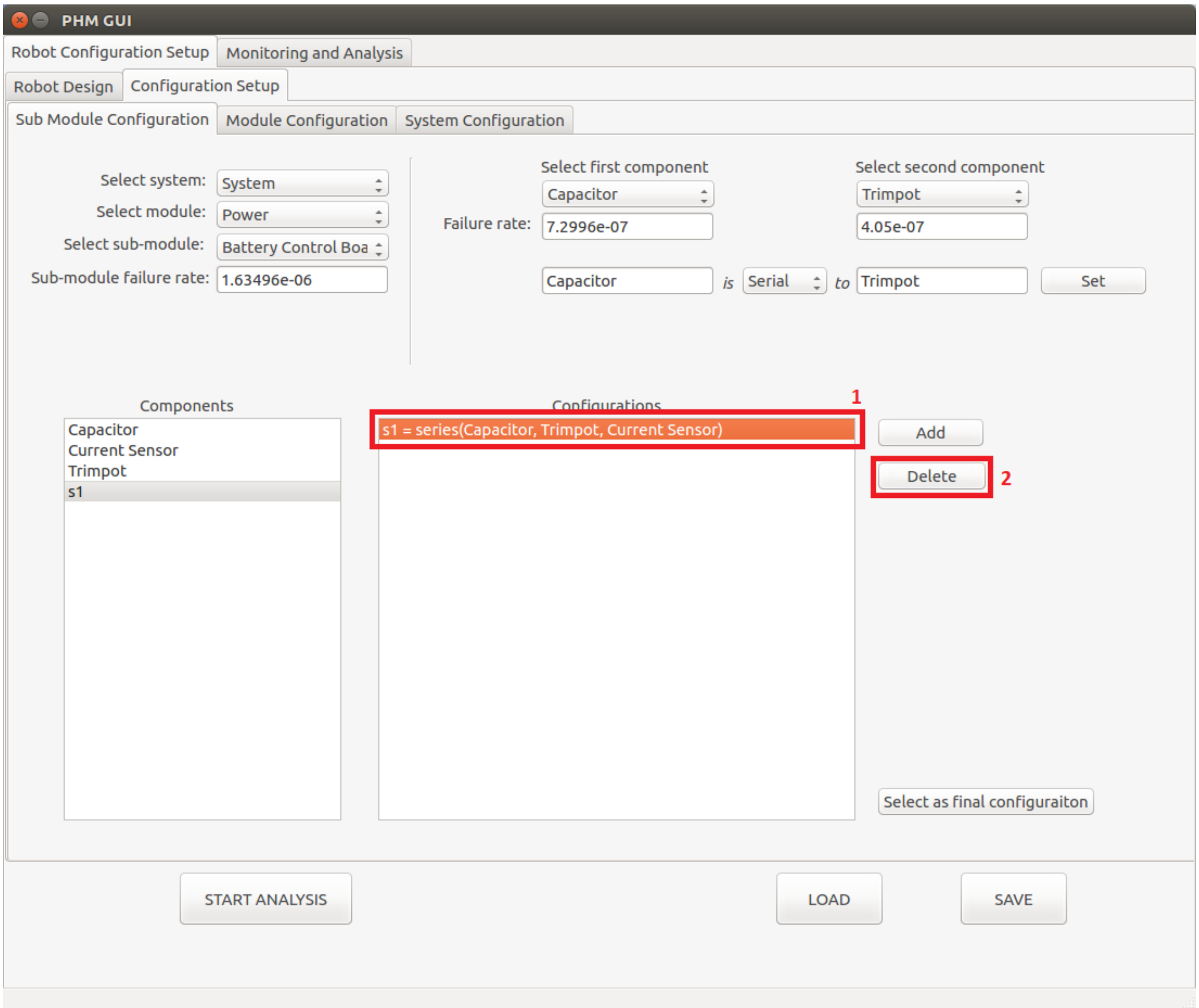


Figure 3.27 Deleting a configurtion

The process of deleting a created configuration is shown in Figure 3.27.

- In section 1, the configuration to be deleted is selected.
- Clicking the “Delete” button in section 2 will delete the selected configuration.

3.3.2.2. Module Configuration Tab

It is the tab where the sub-modules under the module are configured. As a result of configuring the sub-modules, the failure rate of the module is calculated. The flowchart of the operations done in "Module Configuration" tab is shown in Figure 3.28.

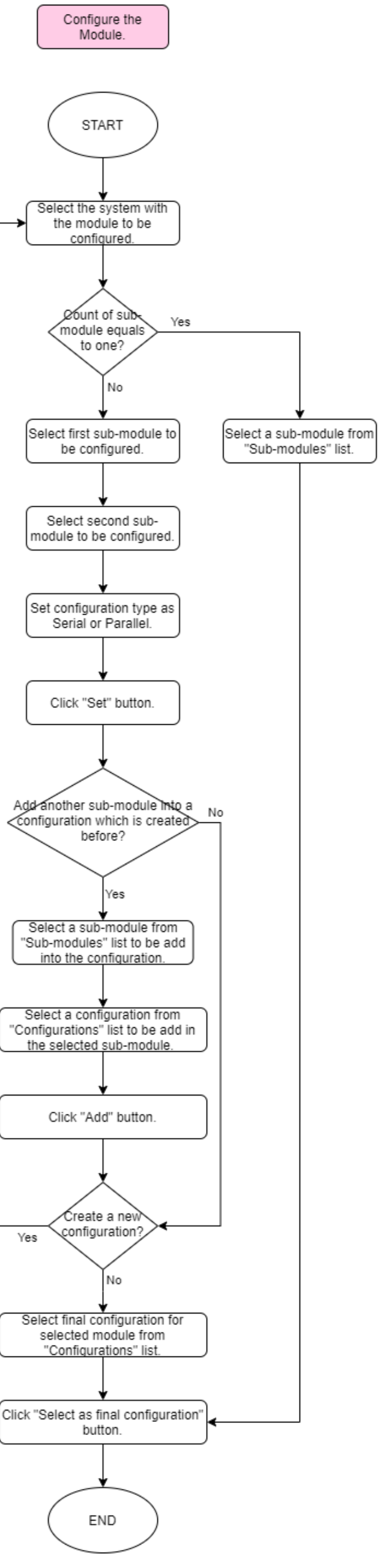


Figure 3.28 Flowchart of Module Configuration tab

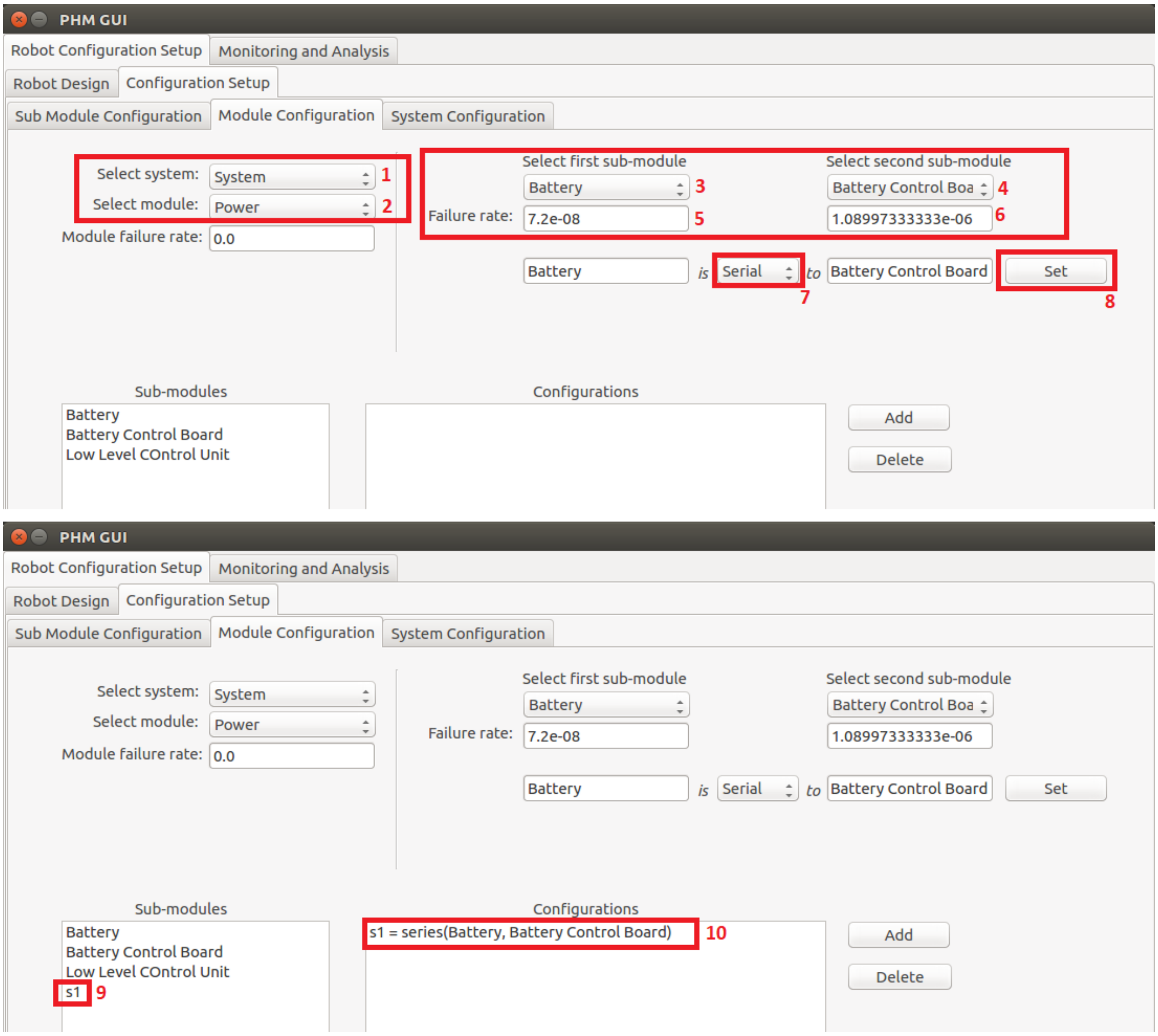


Figure 3.29 Configuration of two sub-modules

Figure 3.29 shows how to configure the two sub-modules.

- In section marked with 1, the system is selected.
- In section marked with 2, a module is selected to be configured.
- In sections marked with 3 and 4, the sub-modules to be configured are selected.
- In sections marked with 5 and 6, failure rate values of the selected sub-modules are shown.
- In box 7, the state of the two sub-modules relative to each other is selected as serial or parallel.
- By clicking the “Set” button in box 8, two sub-modules are configured as serial or parallel.
- In box 9, the configuration name is displayed.
- In box 10, the entire configuration is displayed.

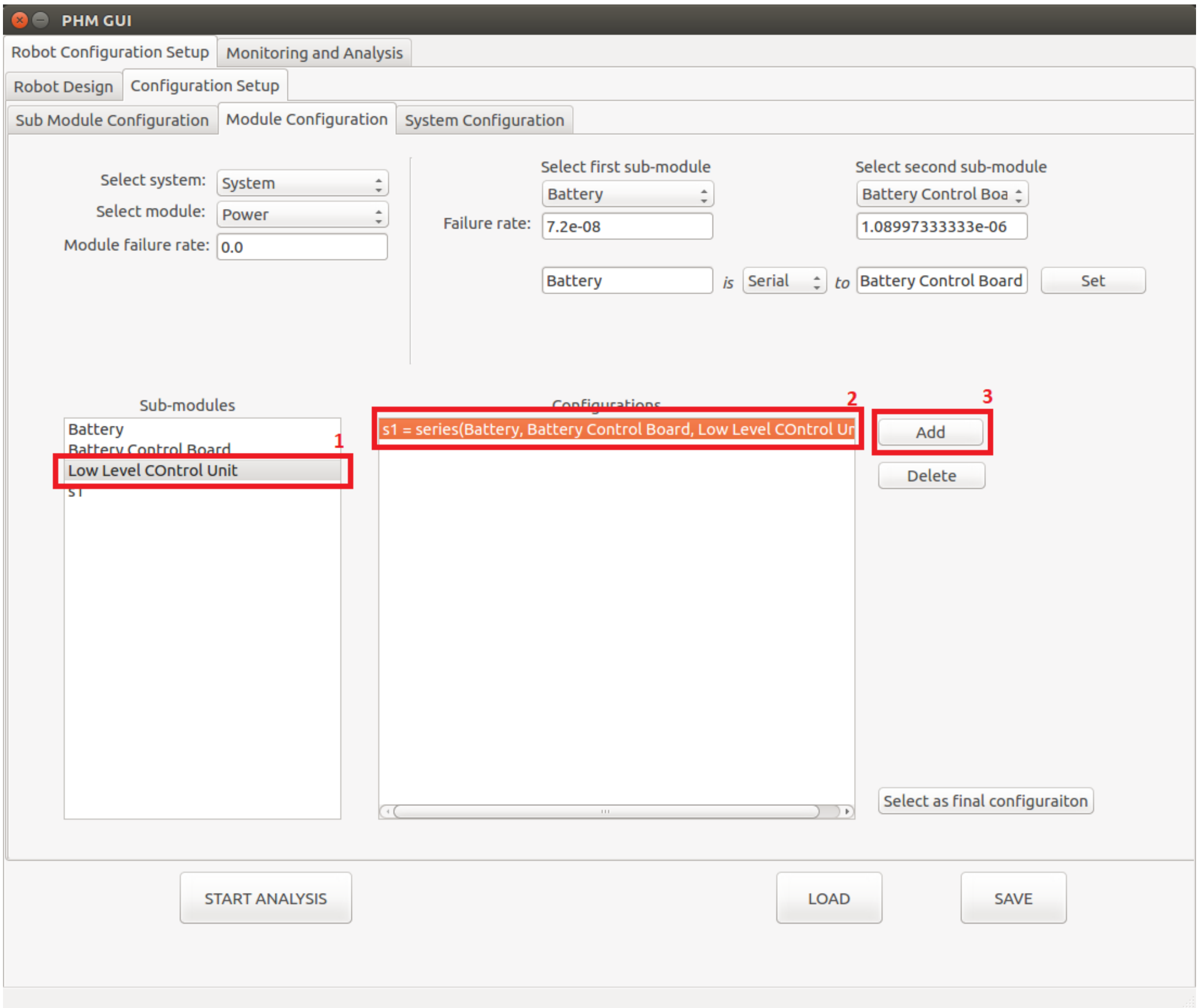


Figure 3.30 Adding an another sub-module into a configuration

Sub-moudules in the “Sub-modules” list can be added to a previously created configuration. This process is shown in Figure 3.30.

- In box 1, sub-module is selected.
- In box 2, a configuration is selected to add the sub-module which is selected in section 1.
- By clicking the “Add” button in box 3, the selected sub-module is added into the selected configuration.

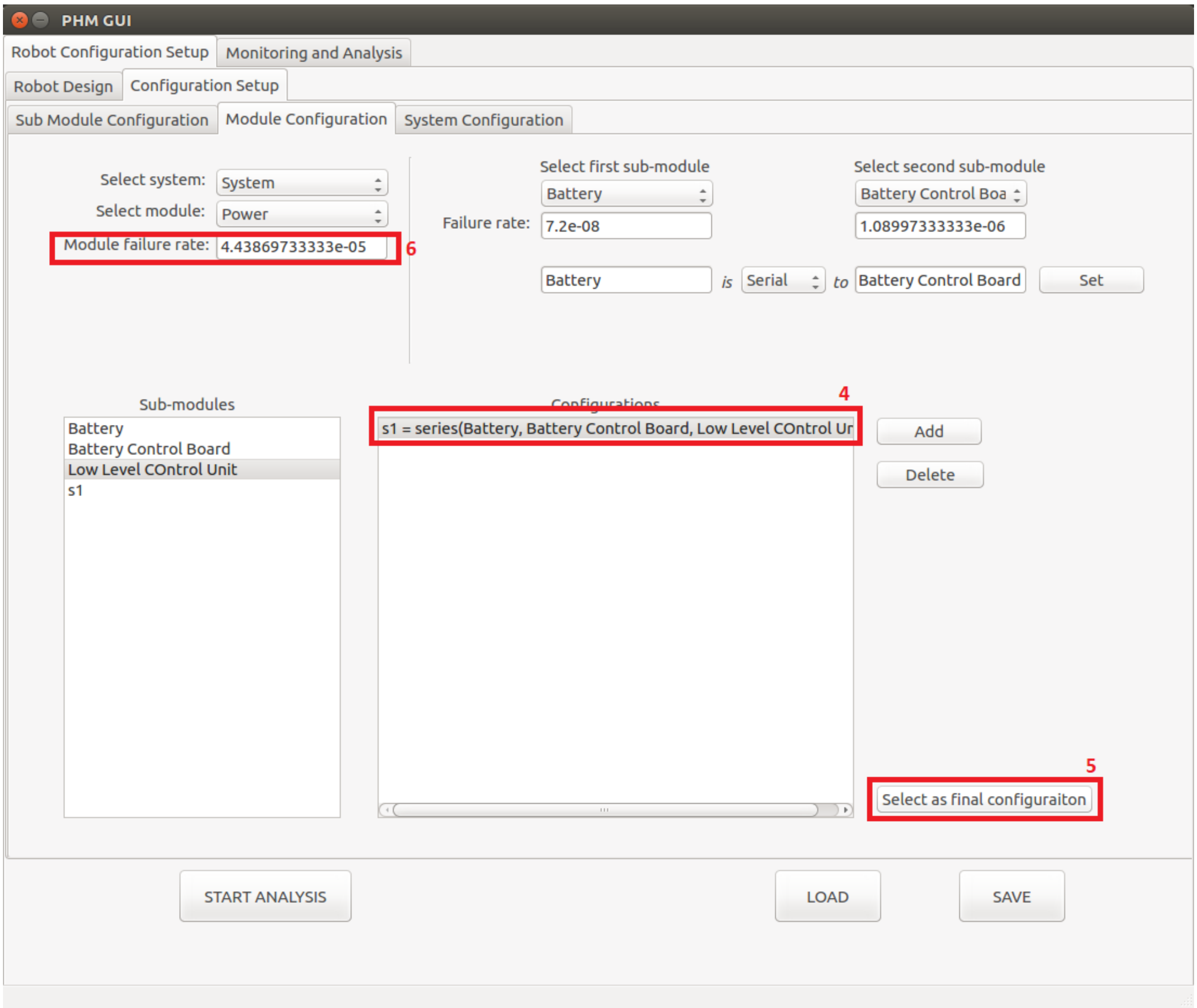


Figure 3.31 Setting the module's failure rate after configuration

In order to assign the failure rate value of the module, it is necessary to decide which of the configuration is "Final Configuration". The process of assigning the failure rate value of the module is shown in Figure 3.31.

- In box 4, the configuration of the module is selected.
- By clicking the "Select as final configuration" button in box 5, the failure rate value of the module is assigned.
- In box 6, the failure rate of the module is shown after selection.

3.3.2.3. System Configuration Tab

It is the tab where the modules under the system are configured. As a result of configuring the modules, the failure rate of the overall system is calculated. The flowchart of the operations done in "Module Configuration" tab is shown in Figure 3.32.

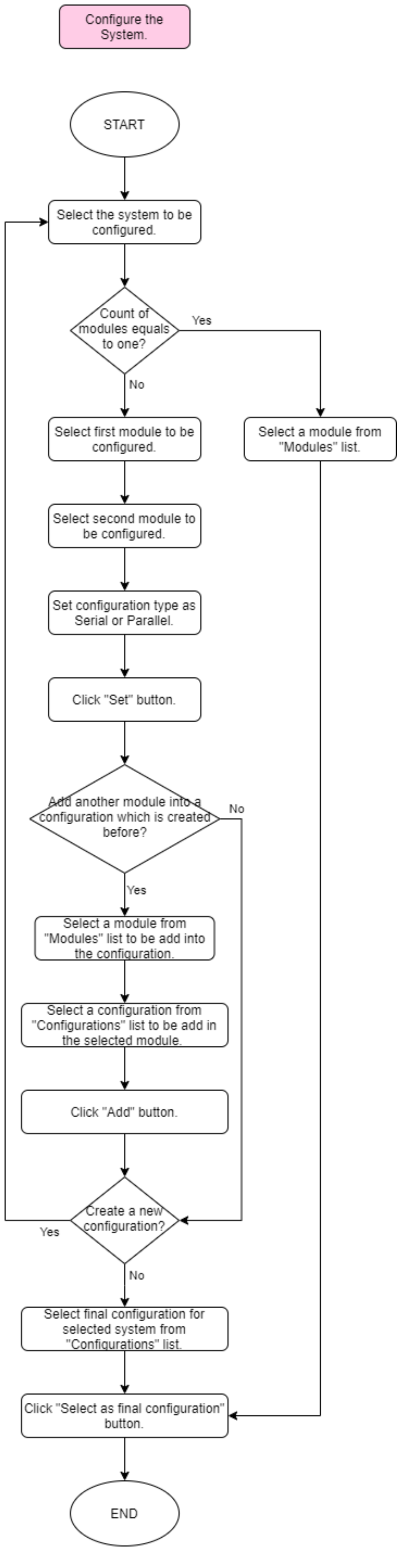


Figure 3.32 Flowchart of System Configuration tab

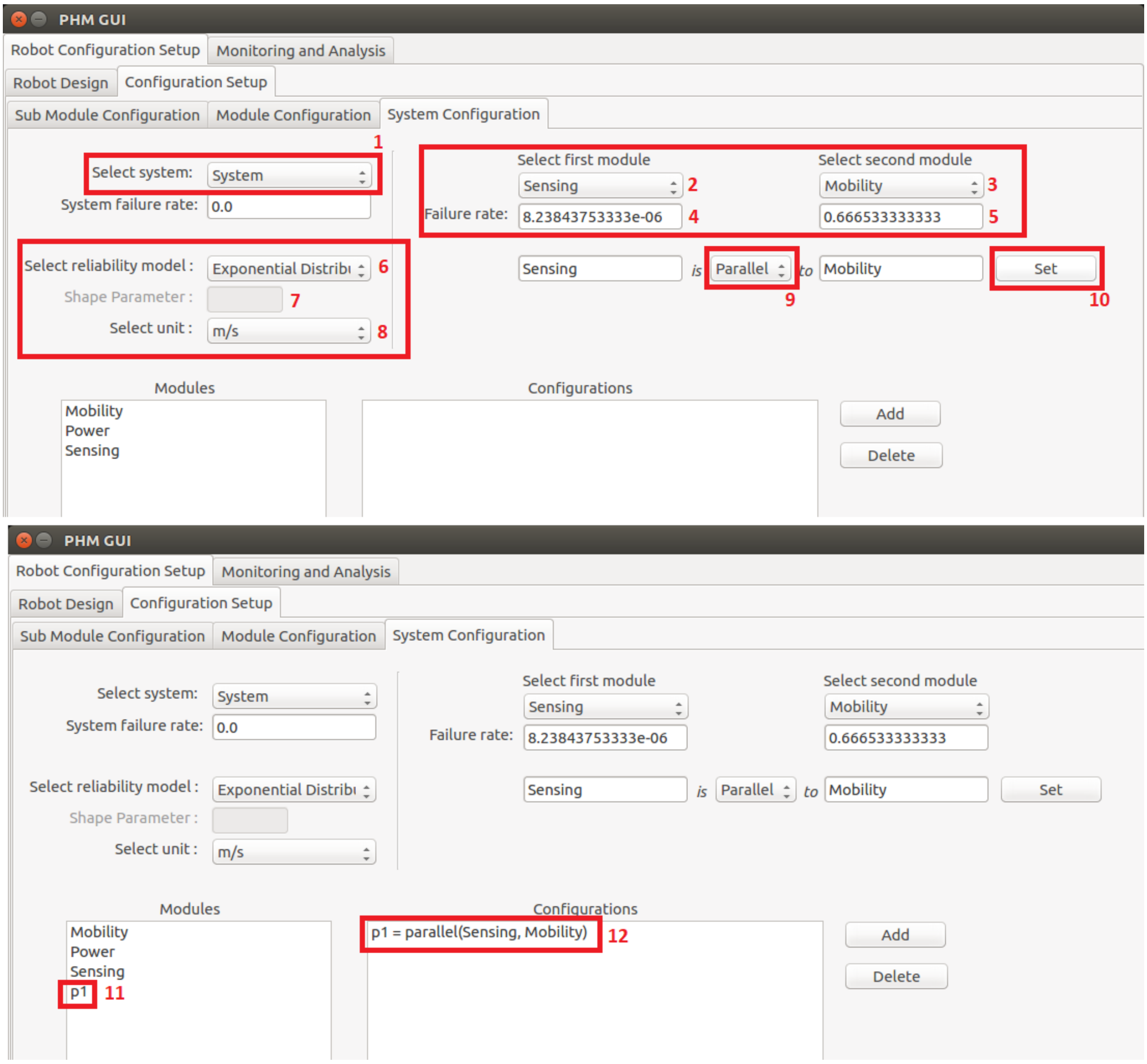


Figure 3.33 Configuration of two modules

Figure 3.33 shows how to configure the two modules.

- In box 1, the system is selected.
- In sections marked with 2 and 3, the modules to be configured are selected.
- In sections marked with 4 and 5, failure rate values of the selected modules are shown.
- In section marked with 6, one of the reliablity models is selected.
- In section marked with 7, shape parameter is entered according to the selected reliability model.
- In section marked with 8, one of the units (m/s or km/h) is selected.
- In box 9, the state of the two modules relative to each other is selected as serial or parallel.
- By clicking the “Set” button in box 10, two modules are configured as serial or parallel.
- In box 11, the configuration name is displayed.
- In box 12, the entire configuration is displayed.

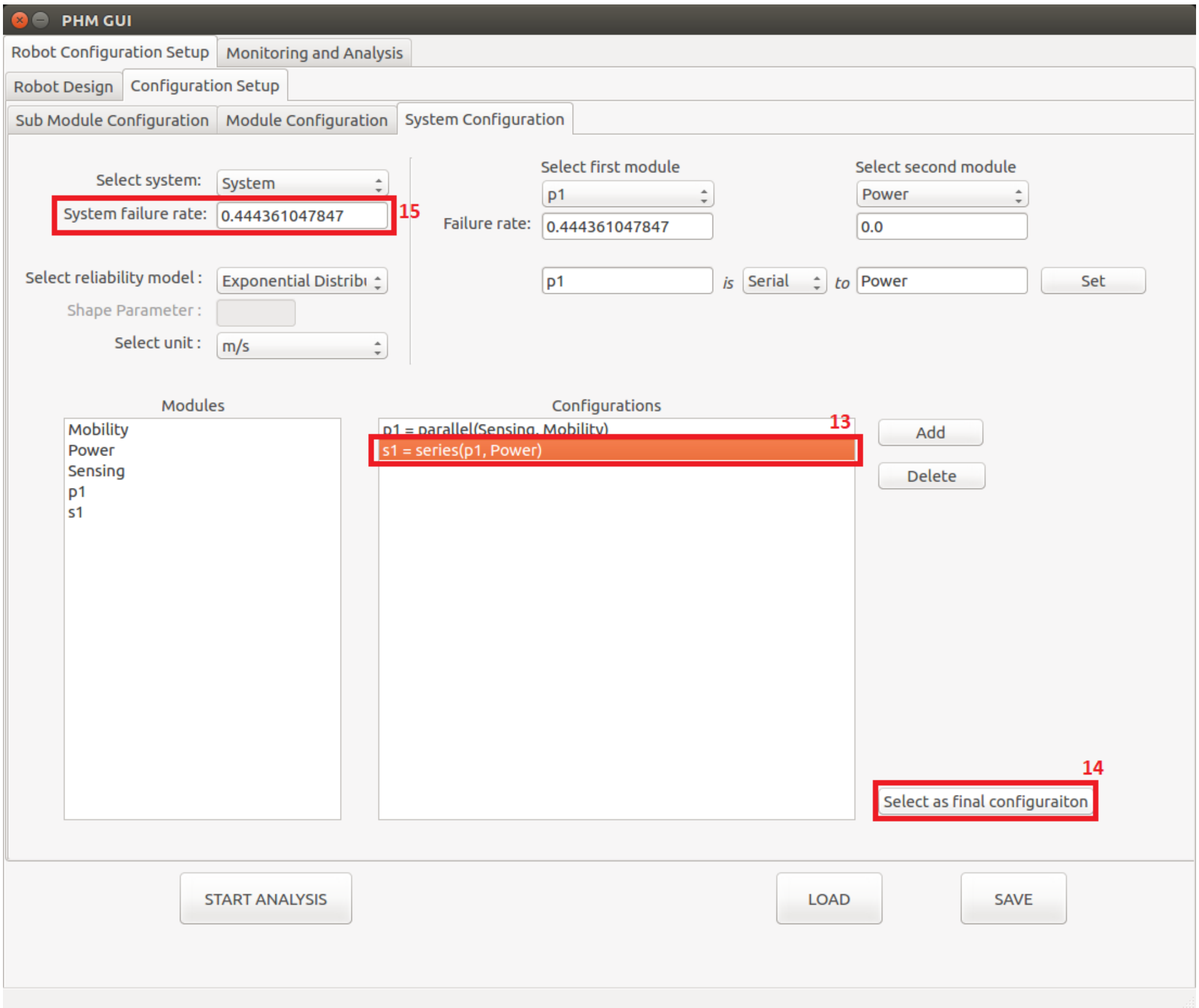


Figure 3.34 Setting the systems's failure rate after configuration

In order to assign the failure rate value of the system, it is necessary to decide which of the configuration is “Final Configuration”. The process of assigning the failure rate value of the system is shown in Figure 3.34.

- In box 13, the configuration of the system is selected.
- By clicking the "Select as final configuration" button in box 14, the failure rate value of the system is assigned.
- In box 15, the failure rate of the module is shown after selection.

3.3.3. Save & Load

3.3.3.1. How to save a system?

The user can save a system which is created in PHM Tool.

The created system in PHM Tool is saved in 2 different ways.

Firstly, if the program is closed by clicking the "X" button in the upper left corner, the last changes made in the interface are saved in the "last_configurations.yaml" file. This file is located in phm_tools / phm_start / params directory (See Figure 3.35).

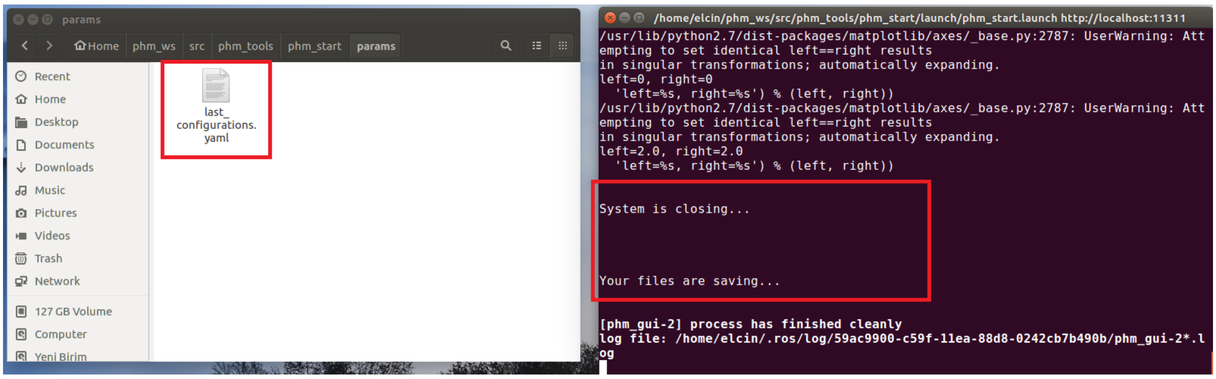


Figure 3.35 Saving the system after closing the PHM Tool using the "X" button

When the program is opened after the program is closed in this way, the last changes made in the program are uploaded to the PHM Tool again and work can be continued (See Figure 3.36). If this file is removed/deleted and the program is opened, no data will be seen in PHM Tool.

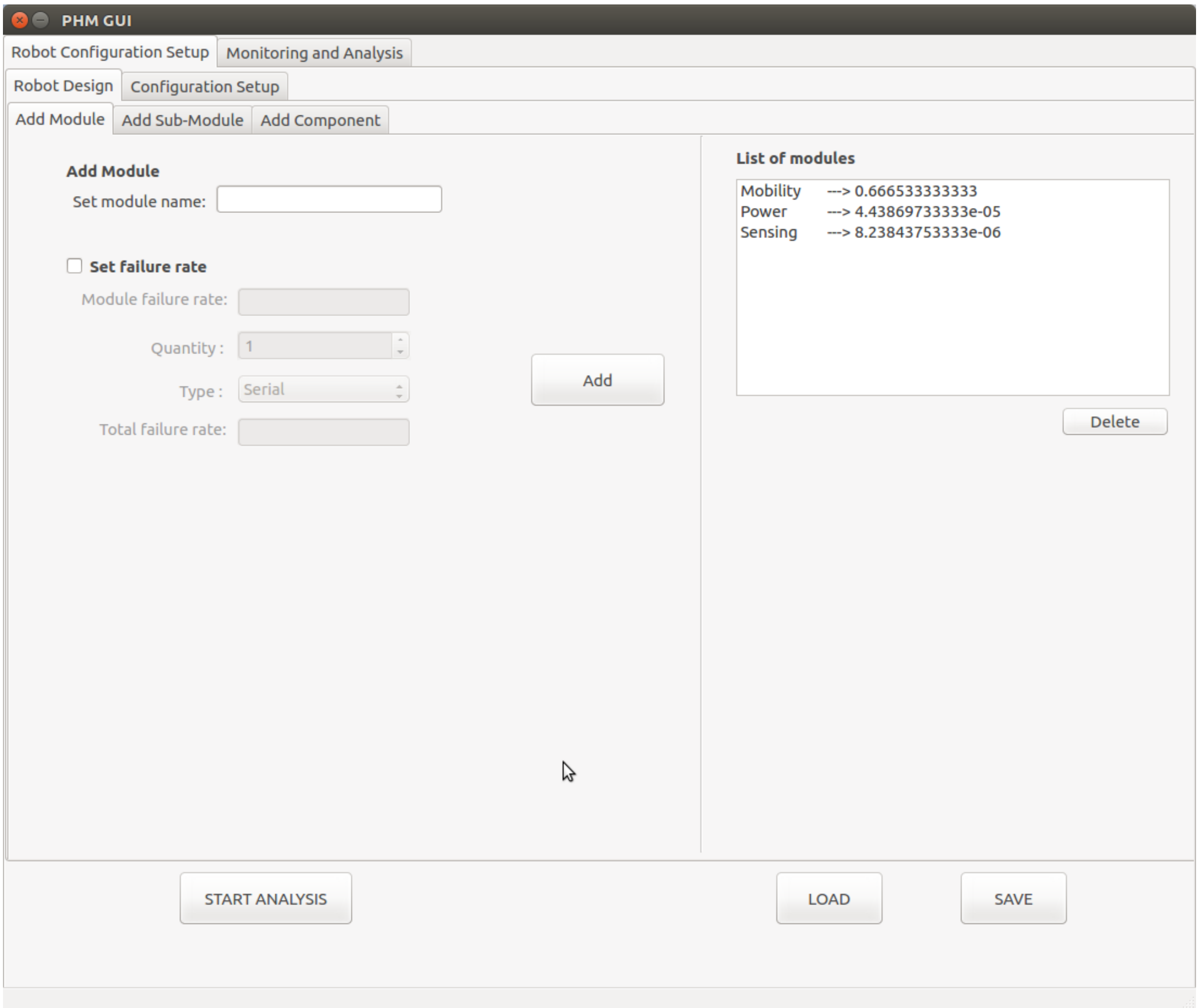


Figure 3.36 Loading the latest changes to the program

Secondly, the system can be saved by using the "Save" button in the interface. Figure 3.37 shows the process of saving the created system by clicking the "Save" button.

- Assume that a different module has been added to the system as in box 1.
- By clicking the "Save" button in box 2, the created system is saved.
- In box 3, the system is saved in phm_tools / phm_start / params directory with a date-time extension.

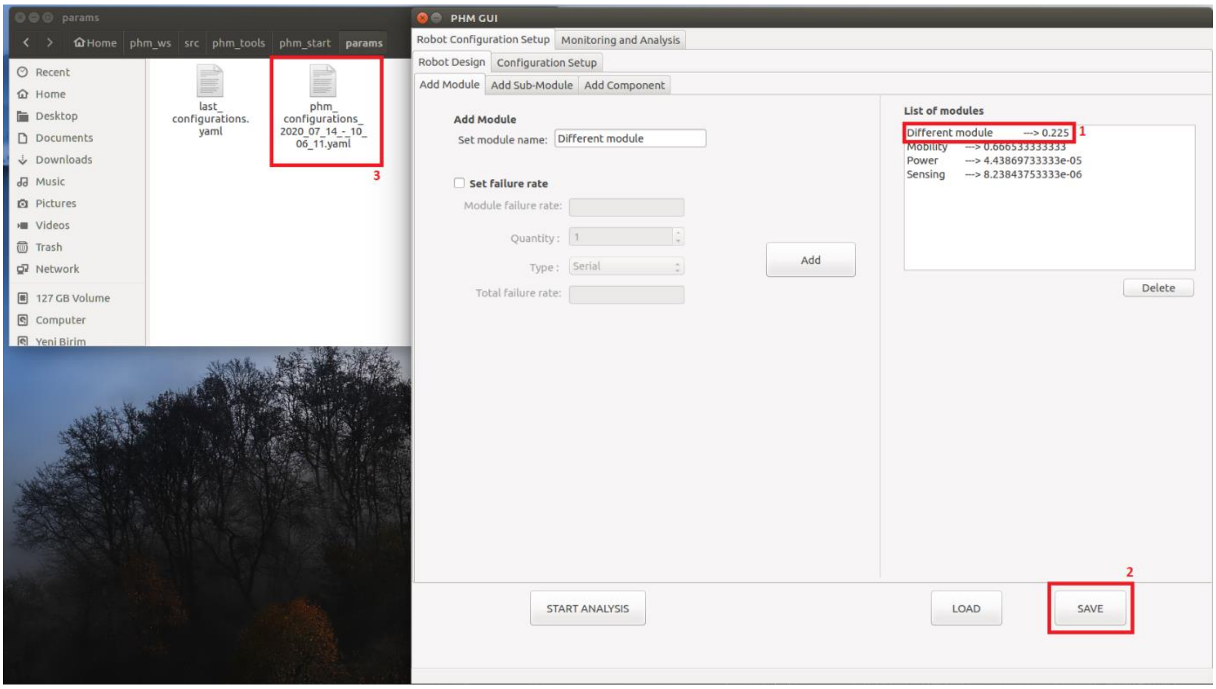


Figure 3.37 Saving the system using the "Save" button

3.3.3.2. How to load a system?

A saved system can be uploaded to PHM Tool when it is desired to be edited or analyzed later. The loading process is shown in Figure 3.38 and Figure 3.39.

- By clicking on the "Load" button in box 1, the file selection window (Box 2) is opened.
- In box 2, you go to the directory where the saved system is located.
- In box 3, the saved system is selected.
- By clicking the "Open" button in box 4, the system is loaded into the PHM Tool from selected directory.
- The loaded system can be seen in box 5 (Figure 3.39).

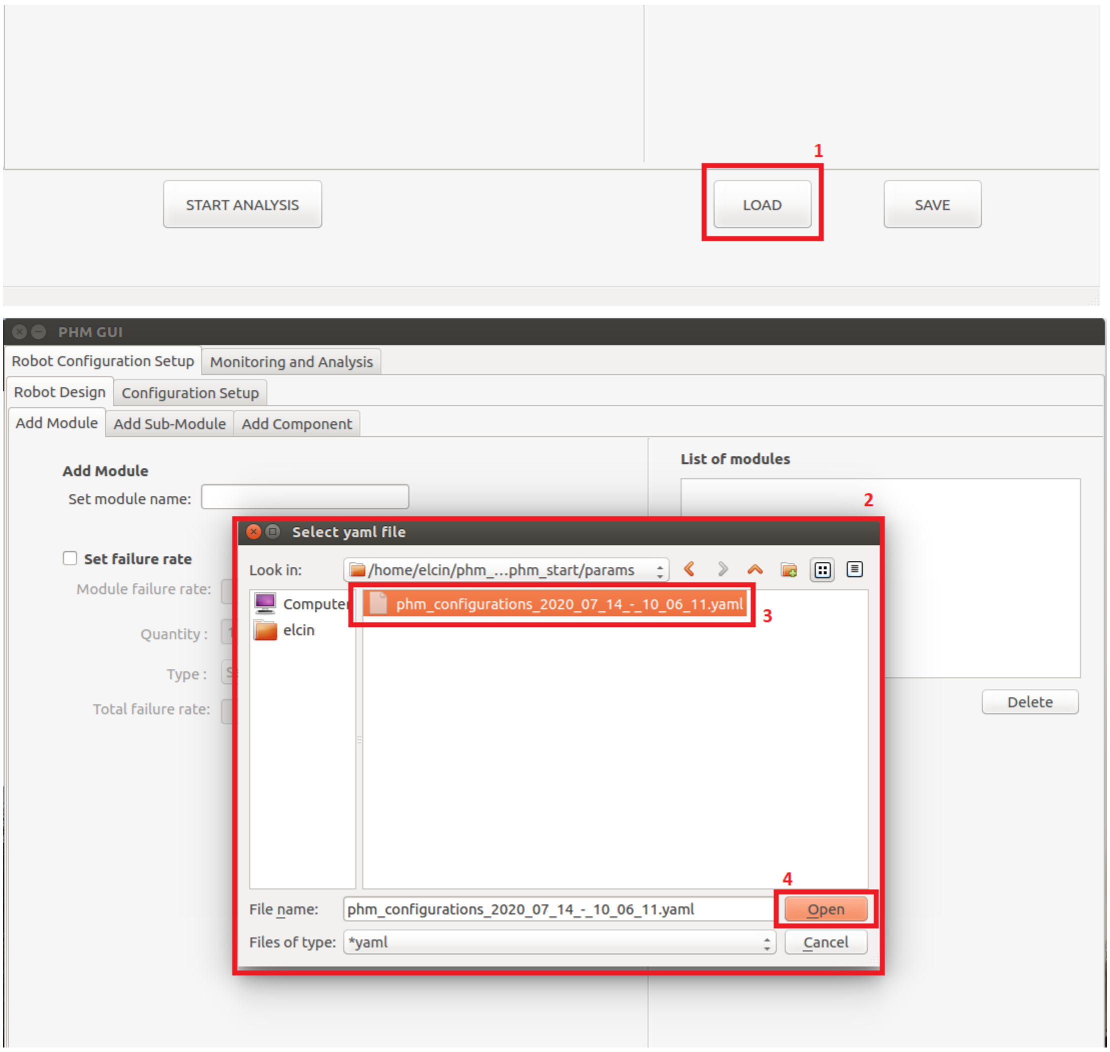


Figure 3.38 Loading the system from the selected directory

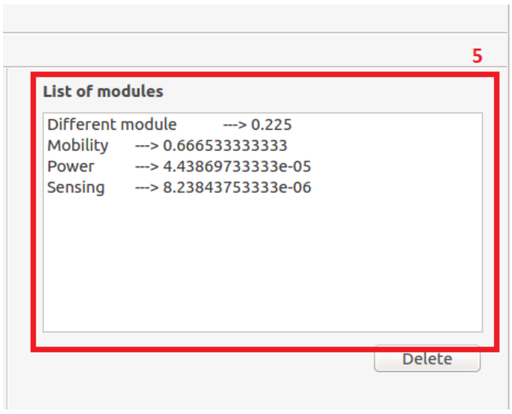


Figure 3.39 Modules in the loaded system

3.4. Monitoring and Analysis Tab

In the Monitoring and Analysis tab, the configured system in the “Robot Configuration Setup” tab is presented to the user in real time by calculating the hazard rate, reliability and POTC values according to the specified reliability model and unit. In addition, sensors can be added and the results are shown in real time.

3.4.1. Hazard Rate Analysis Tab

The system is configured in the “System Configuration” tab and when the "Start Analysis" button is clicked, the hazard rate values of the system and its subcomponents are calculated. The calculated hazard rate value of the system is shown in real time graph in the "Hazard Rate Analysis" tab according to the time. By adding module-based sensors, the user can calculate the hazard rate values as sensor based and see them as real time graphics.

The flowchart of the operations done in “Hazard Rate Analysis” tab is shown in Figure 3.40.

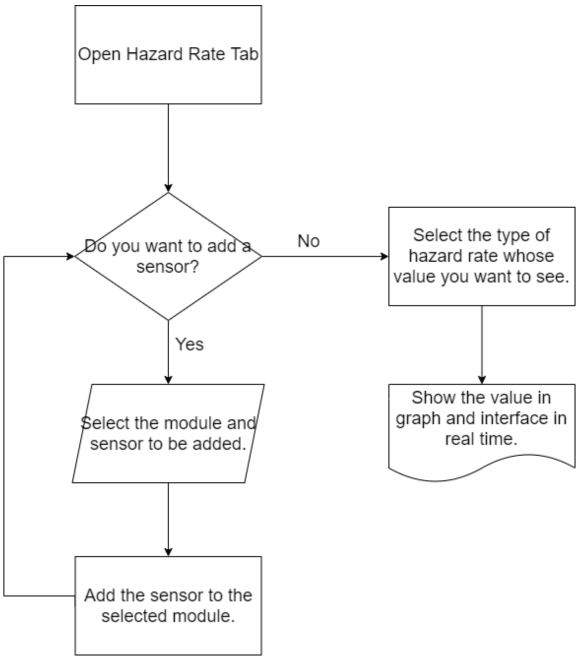


Figure 3.40 Flowchart of Hazard Rate Analysis tab

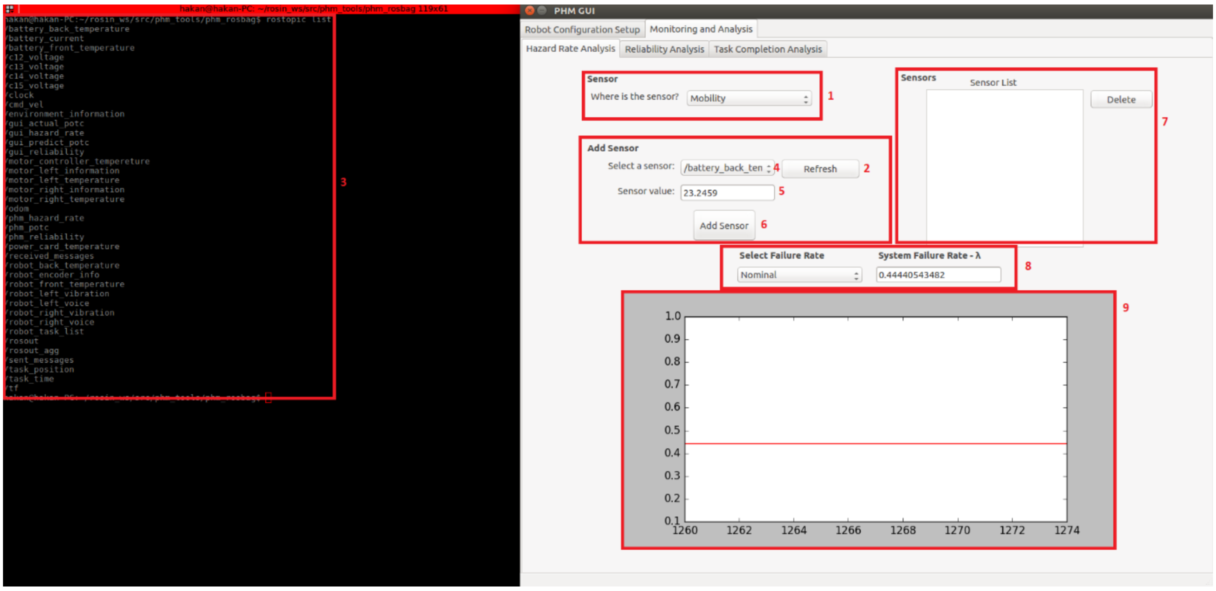


Figure 3.41 Hazard rate analysis and adding sensors to the selected module

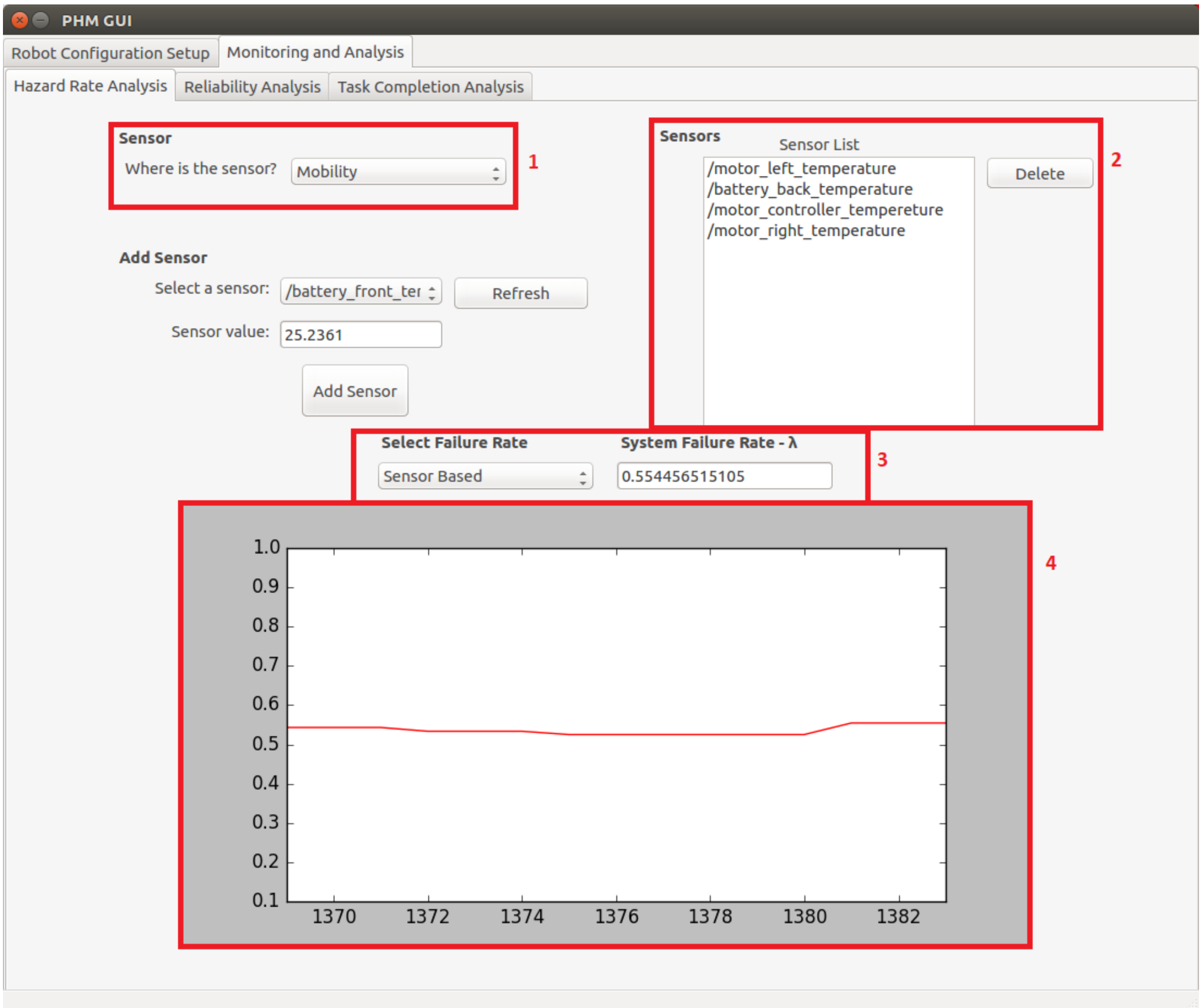


Figure 3.42 Sensor based analysis

The process of adding sensors and showing the hazard rate values are shown in Figure 3.41 and Figure 3.42.

- In box 1, the module to which the sensor will be added is selected.
- By clicking the "Refresh" button in section marked with 2, all the topics which are open in the ROS Master in box 3 are added as elements to the combo box in section marked with 4.
- In section marked with 5, the value of the topic selected in section marked with 4 is showed. This value is updated every second.
- By clicking the "Add Sensor" button in section marked with 6, the value of the sensor which is selected in section marked with 4 is added to the module selected in section 1. Thus, sensor-based values of the module and system are calculated.
- In box 7, the sensors added to the module which is selected in box 1 are shown. As shown in Figure 3.42, the sensors in the selected module in box 1 are listed as in box 2.
- In box 8, the failure rate value of the system is selected as nominal or sensor based and its value is displayed. As shown in box 3 in Figure 3.42, the sensor-based value is displayed.
- In box 9, the nominal or sensor-based values selected in box 8 show as real time graphs according to time. As shown in Figure 3.42, the sensor-based values selected in box 3 are shown as real time graph according to time in box 4.

3.4.2. Reliability Analysis Tab

In the "System Configuration" tab, the system is configured and the reliability model and its unit are selected. Then, “Start Analysis” button is clicked and the hazard rate value of the system is calculated. After the hazard rate value is calculated, the reliability values are calculated according to the selected reliability model and unit. The calculated system reliability value is shown in real time graph on the "Reliability Analysis" tab. In addition, this tab shows the reliability values of the modules in the system. If the user added sensors to the module, the sensor-based reliability value can also be seen on the interface. Reliability demonstrations are shown in Figure 3.44.

The flowchart of the operations done in “Reliability Analysis” tab is shown in Figure 3.43.

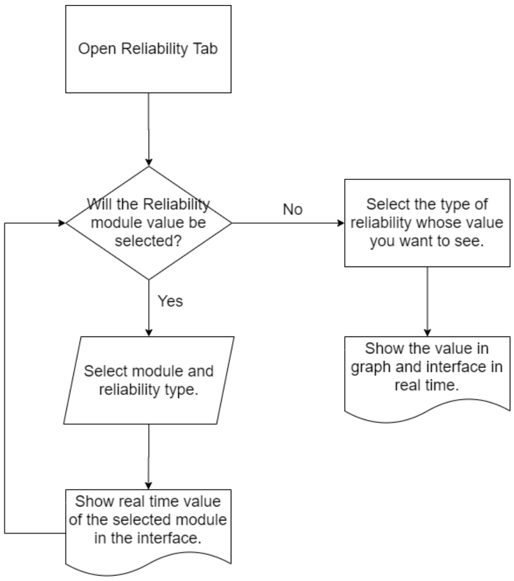


Figure 3.43 Flowchart of Reliability Analysis tab

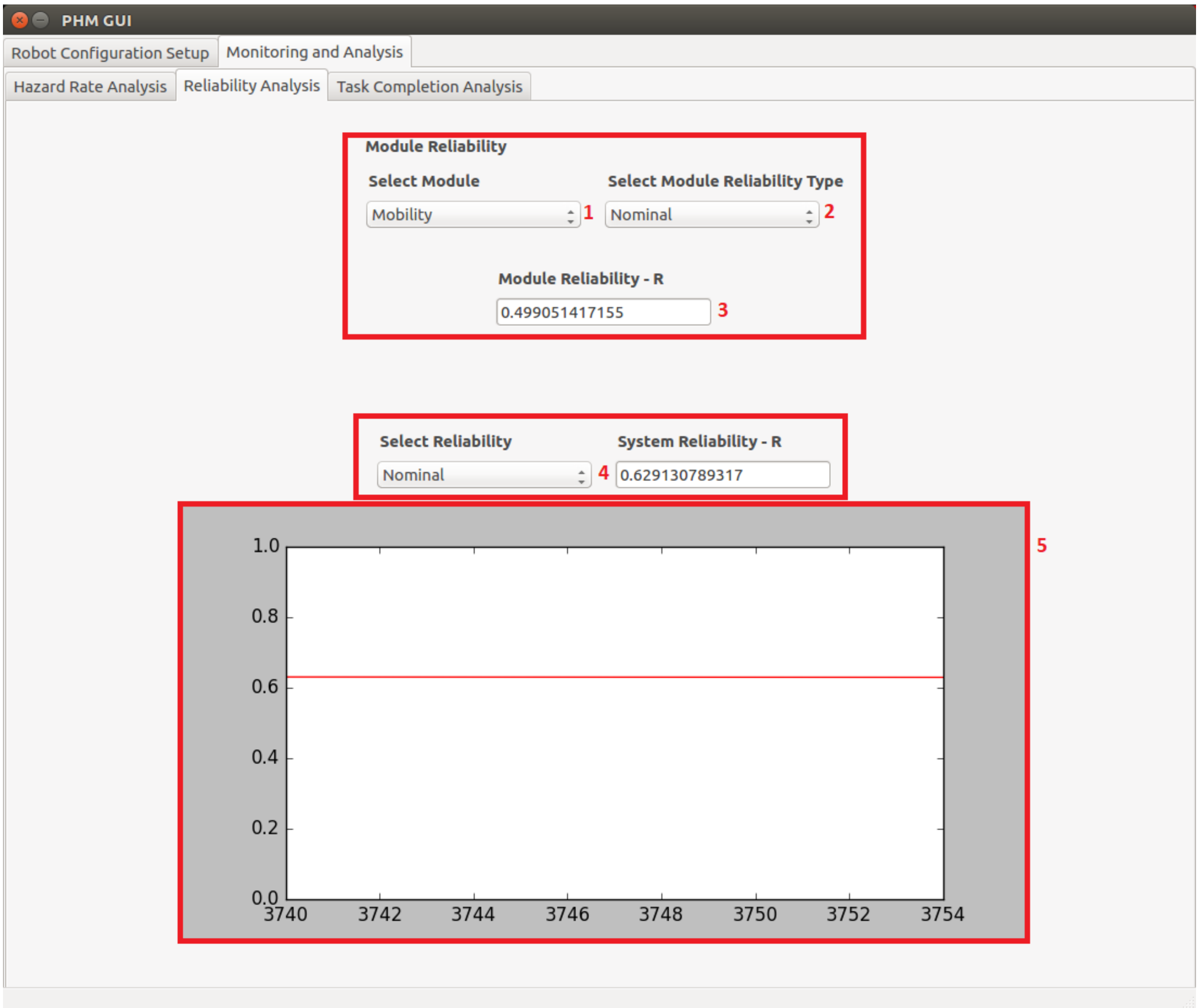


Figure 3.44 Reliability analysis

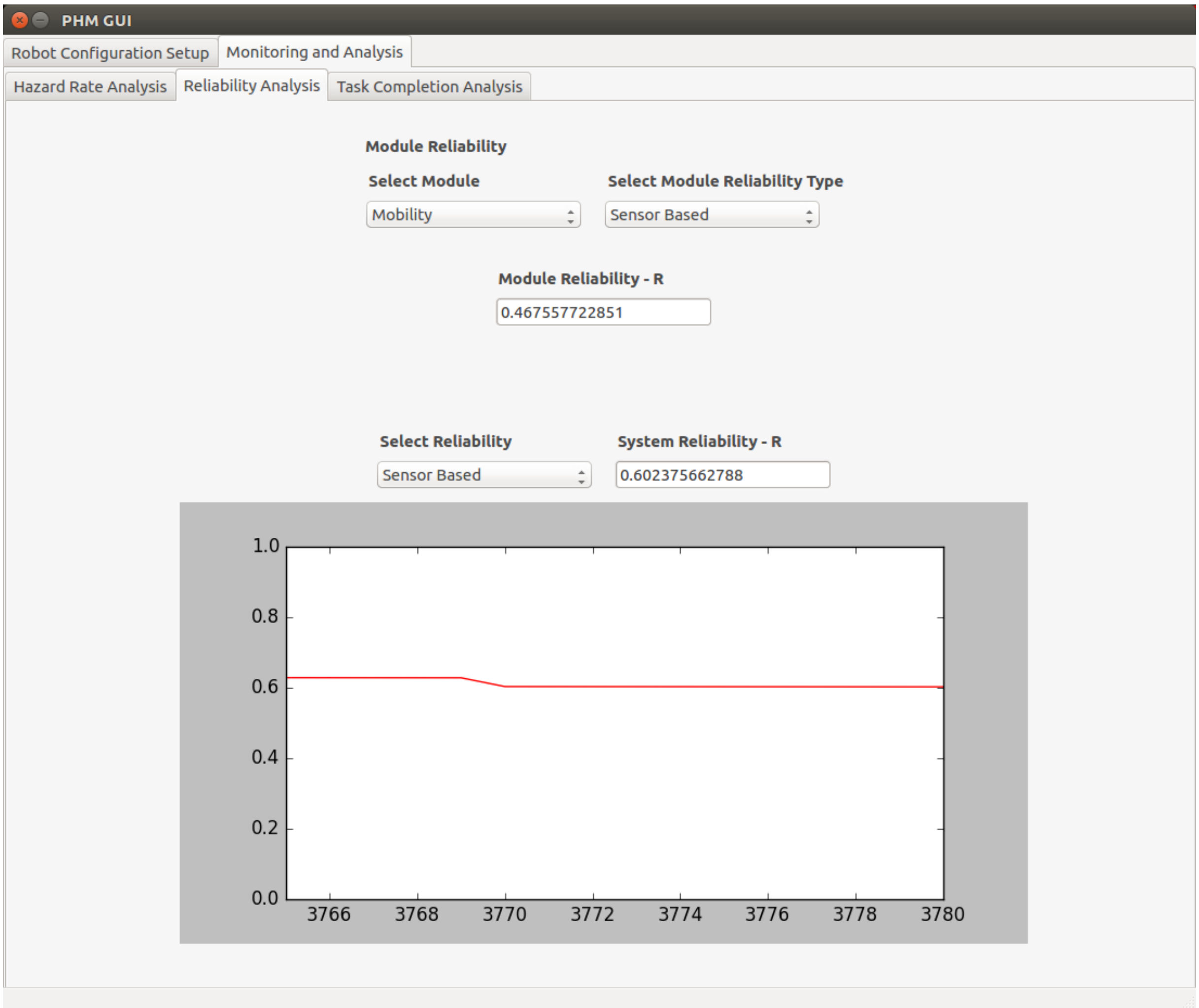


Figure 3.45 Sensor based reliability analysis

- In section marked with 1, the module whose value is to be displayed is selected.
- In section marked with 2, the reliability type of the module to be displayed is selected. These types are two as nominal and sensor based. If a sensor is added to the module in the Hazard Rate Analysis tab, when the added module is selected, its sensor-based value is displayed along with its nominal value.
- In section marked with 3, reliability value is shown according to the value selected in sections marked with 1 and 2.
- In section marked with 4, the reliability value of the system is selected as nominal or sensor based and its value is displayed. Figure 3.45 shows the sensor-based value.
- In box 5, the nominal or sensor-based values are shown as real time graphs by time. As shown in Figure 3.45, sensor-based values are shown as real time graph by time.

3.4.3. Task Completion Analysis Tab

The system is configured in the "System Configuration" tab and the "Start Analysis" button is clicked. Depending on the reliability model and unit chosen by the user, the reliability value is started to be calculated. There are two requirements to calculate the value of the Probability of Task Completion (POTC): First one is that the reliability value should be calculated and the second one is that the robot must have received a task to complete. There are also 2 methods to calculate the POTC value. These are "Real time analysis" and "Prognostic analysis".

3.4.3.1. Real Time Analysis Tab

There are 2 methods for calculating POTC in the "Real Time Analysis" tab: "Actual Analysis" and "Predict Analysis".

Actual analysis is the calculated POTC value after completing the task for the robot. This calculation is made according to the data realized by the robot in real time.

Predict analysis is the POTC value calculated when the task comes to the robot. When the task comes to the robot, it sends it to Phm tool. Phm tool estimates POTC for the incoming task based on the position and speed information in the task.

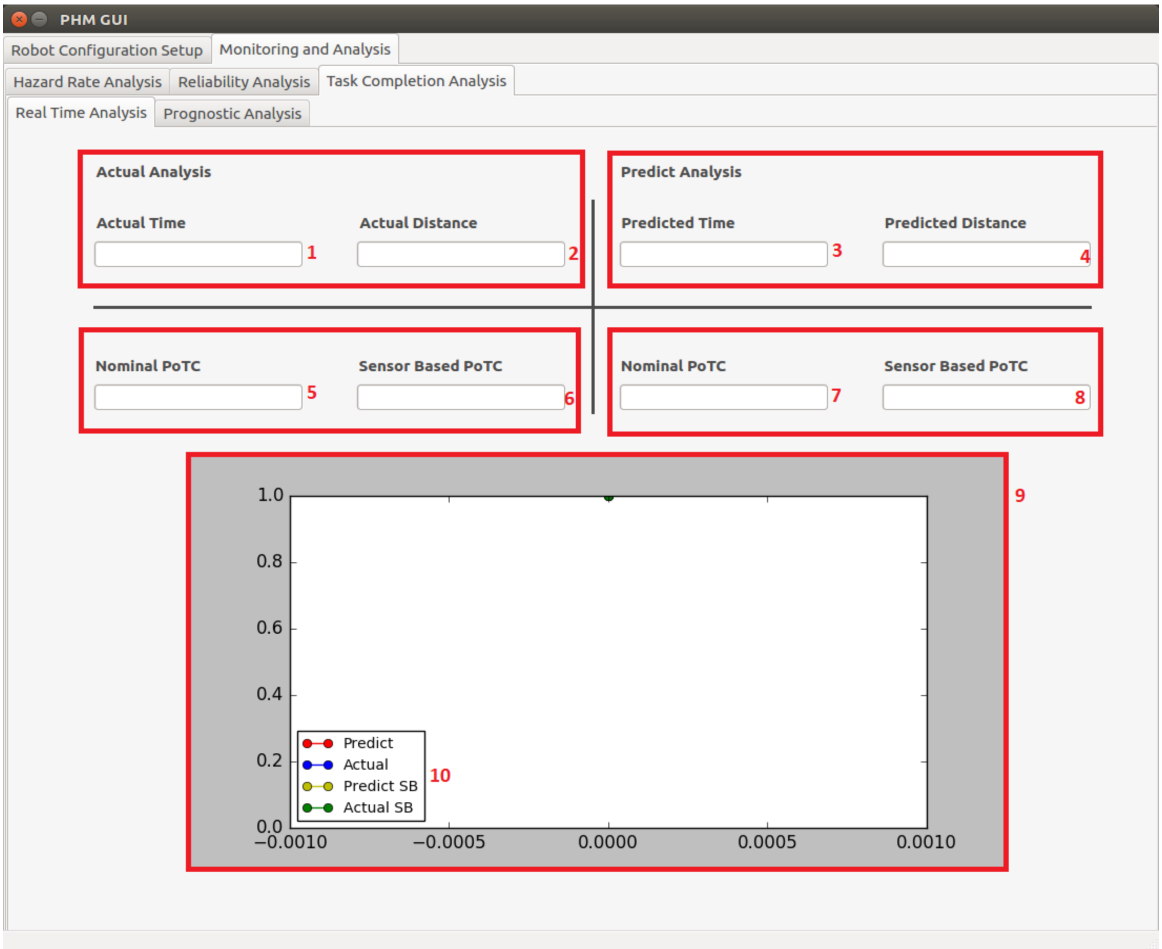


Figure 3.46 Real time task completion analysis

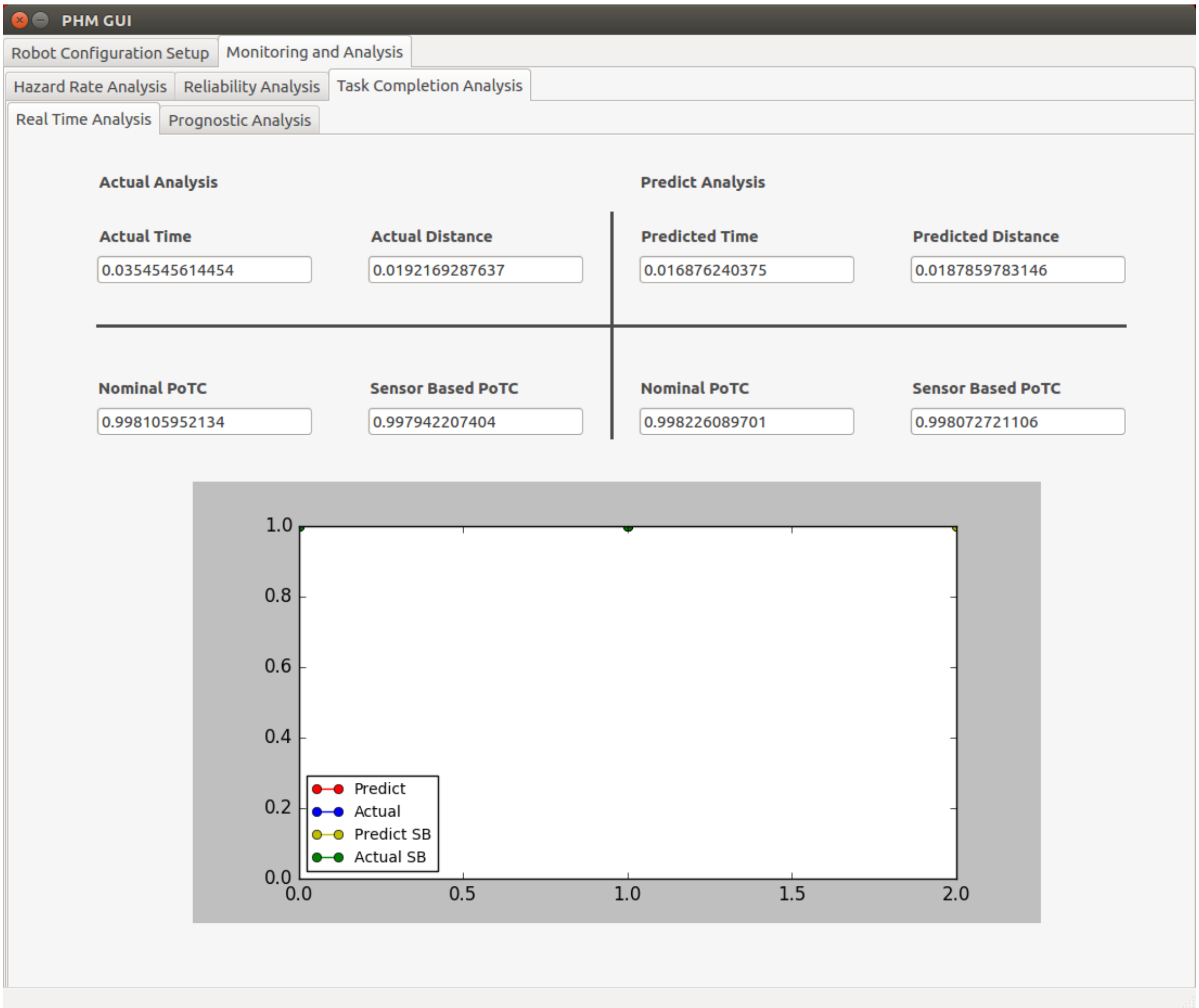


Figure 3.47 Real time task completion analysis with values

POTC operations are shown in Figure 3.46.

In Figure 3.47, it is shown that the robot has 2 missions and has completed 1 mission and also has not completed the last mission yet.

- The section marked with 1 indicates the time of completion of the robot's current finished task.
- In section marked with 2, the total distance traveled by the robot to complete its current task is shown.
- In section marked with 3, it estimates the how long it takes the robot to complete the task.
- In section marked with 4, the distance value that the robot estimates the total distance to go in the task that comes to the robot is shown.
- In section marked with 5, the POTC value is shown which is calculated by the robot according to the nominal reliability value after the task is completed.
- In section marked with 6, the POTC value calculated according to the sensor-based reliability value is shown after the robot has finished its task.
- In section marked with 7, when the task comes to the robot, the POTC value calculated according to the nominal reliability is shown by making a prediction to complete the task.

- In section marked with 8, when the task comes to the robot, the POTC value calculated according to the sensor-based reliability is displayed by making a prediction to complete the task.
- In section marked with 9, calculated POTC values are shown as real time graph.
- Section marked with 10 indicates the information in which the calculated POTC values are expressed on the graph.

3.4.3.2. Prognostic Analysis Tab

"Prognostic Analysis", saves the tasks coming to the robot. The user selects the task he wants to simulate and enters the amount of simulation. PHM Tool shows the time and POTC value in the interface after the amount entered by doing advanced simulation of the task. In addition, it shows the POTC values of the tasks in graph form. POTC display operations are shown in Figure 3.48

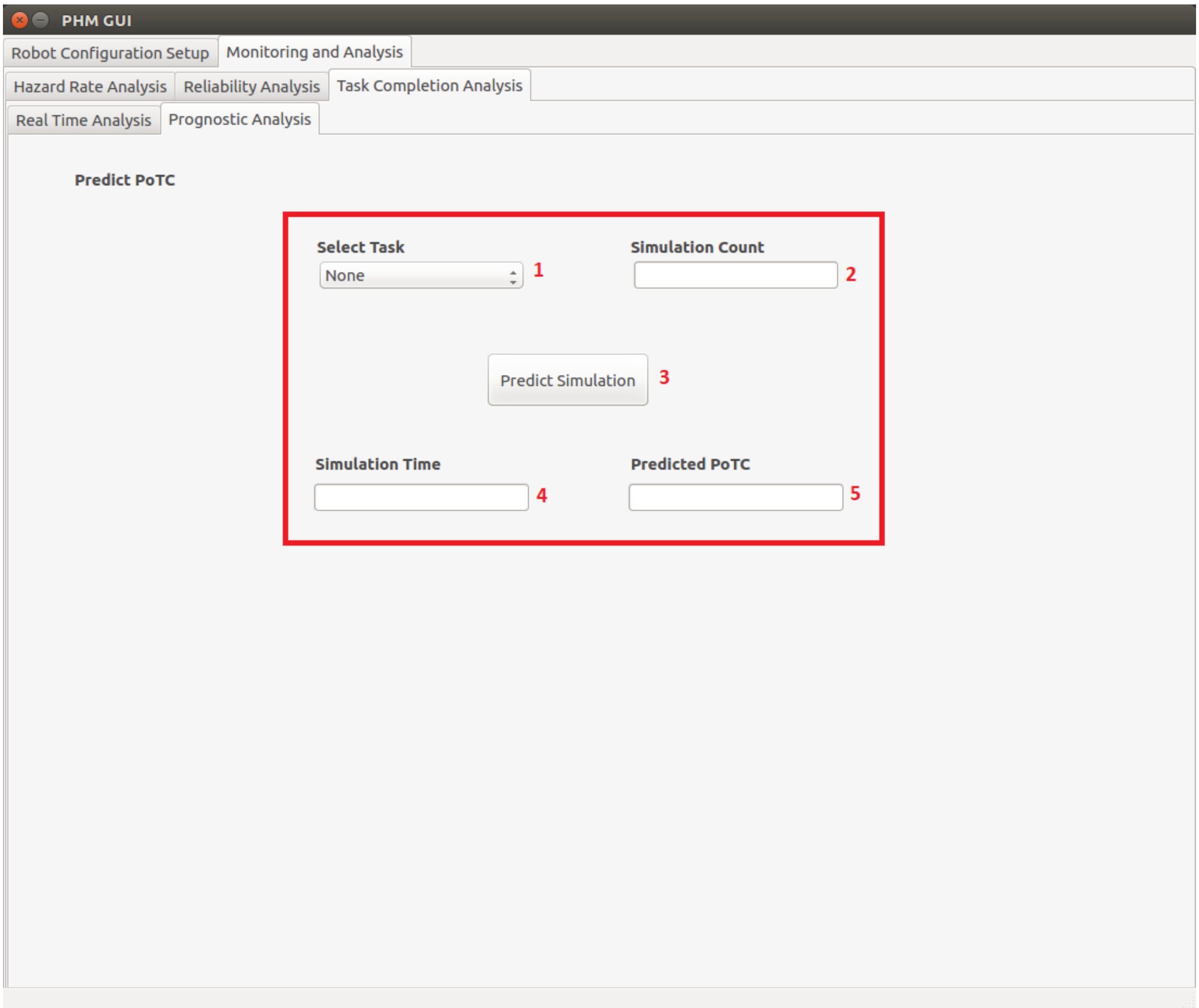


Figure 3.48 Prognostic analysis

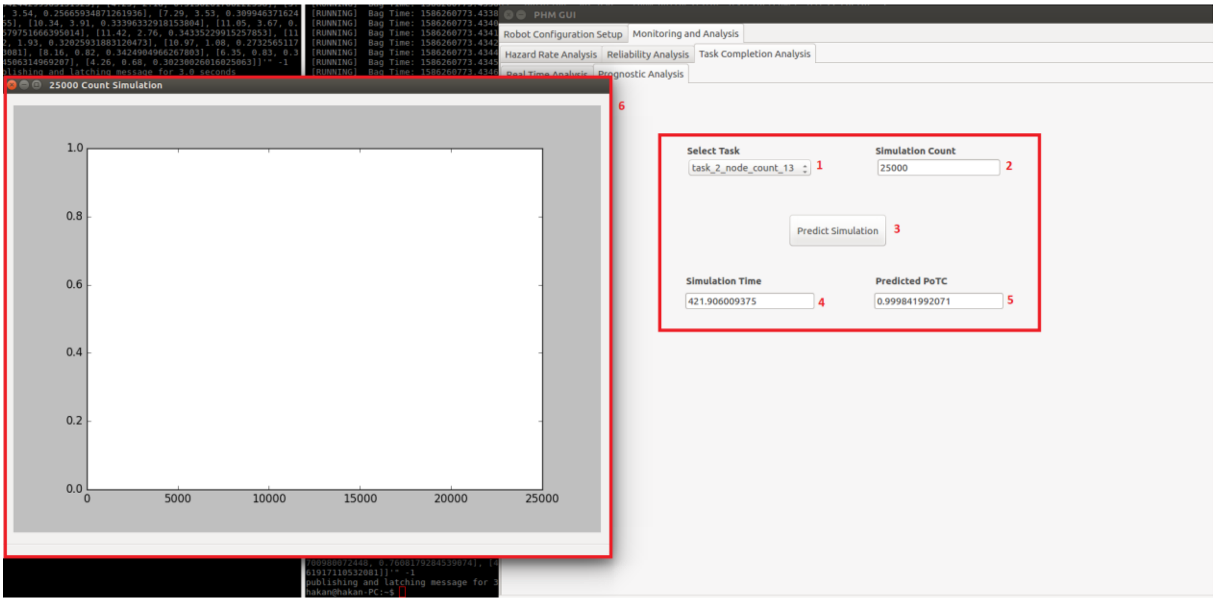


Figure 3.49 Prognostic analysis graph

- In section marked with 1, all tasks for the robot are shown. The user can choose the task he wants to simulate here.
- In section marked with 2, the number of times the selected task is desired to be simulated.
- In section marked with 3, at the end of each task, POTC values are calculated during the simulation count by simulating the task according to the values selected from sections marked with 1 and 2 and shown in Figure 3.49 in the form of a graph.
- In section marked with 4, the total time spent for the task is displayed in hours, as a result of the entered simulation count of the selected task.
- In section marked with 5, POTC value is shown as a result of the entered simulation count of the selected task.

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More information: rosin-project.eu

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5. References

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