FRAMalyse

User Guide

FRAMalyse 1.1.0 – January 2025

If you use FRAMalyse for your FRAM analysis, please give credit to our work citing our conference paper about the concept and design of FRAMalyse:

Grabbe, N., & Du, Y. (2025). FRAMalyse: an open tool to quantitatively analyze and evaluate the characteristics of models derived by the Functional Resonance Analysis Method. In Proceedings of the 35th European Safety and Reliability Conference (ESREL 2025), Stavanger, Norway.

Disclaimer

Matlab Runtime is required to run FRAMalyse which is included within the installation process. FRAMalyse is interfaced with FMV (Hill & Hollnagel, 2016), which is an open tool for visualization of FRAM models and can be downloaded for free at the functional resonance *website*, by importing the required FRAM model data in the form of Excel files. FRAMalyse is released freely but cannot be used in its original (or repacked form) before previous consent by the Licensor (see EULA, in Section 4). FRAMalyse mainly relies on Erik Hollnagel's book (2012), and on other scientific manuscripts cited throughout this user guide.

Contents

1 Introduction

The FRAMalyse software has been designed and developed by Yiran Du and Niklas Grabbe in the working group of Complex Socio-technical Systems Modeling – Technical University of Munich, Chair of Ergonomics. FRAMalyse is an open tool designed to solve practical problems that FRAM analysts encounter every day, such as facilitating the efficient and structured analysis and interpretation as well as communication of results to the management. It strengthens the computational capabilities of FRAM (Hollnagel, 2012), which makes the FRAM more actionable for real-world purposes, particularly when facing large-scale systems. Further information are available on the working group's *website*.

Section 2 details the installation steps to use FRAMalyse. Section 3 presents the functionalities, detailing each feature and the foundational user interface. Section 4 describes potential error messages in FRAMalyse, along with their causes and solutions. Section 5 outlines the license agreement.

2 Installing/Uninstalling

2.1 Installing steps

After opening the archive, open the file "FRAMalyse_setup", and double-click on "MyAppInstaller_mcr.exe" to start the installation process. This page displays the End-User License Agreement (EULA). Clicking "Next" signifies your acceptance of the agreement and proceeds with the subsequent steps.

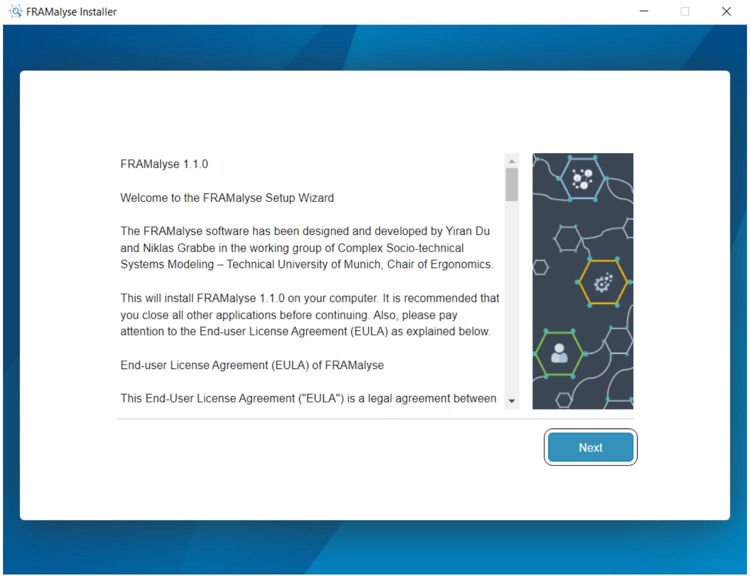

Figure 1: Start the installation process and accept the license agreement of FRAMalyse..

Select the installation folder and determine if you want to create a desktop shortcut.

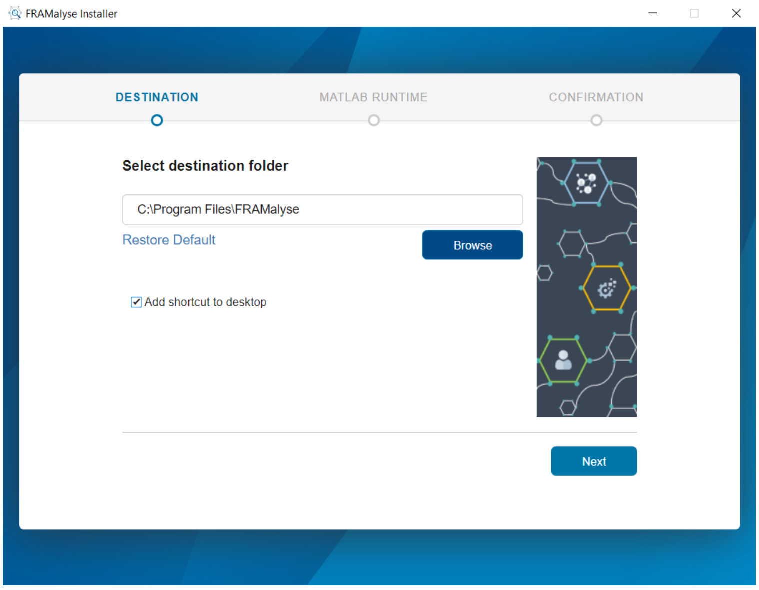

Figure 2: Select destination folder for FRAMalyse and add shortcut to desktop.

Install MATLAB Runtime to enable the execution of compiled MATLAB applications, such as FRAMalyse, without requiring a MATLAB installation.

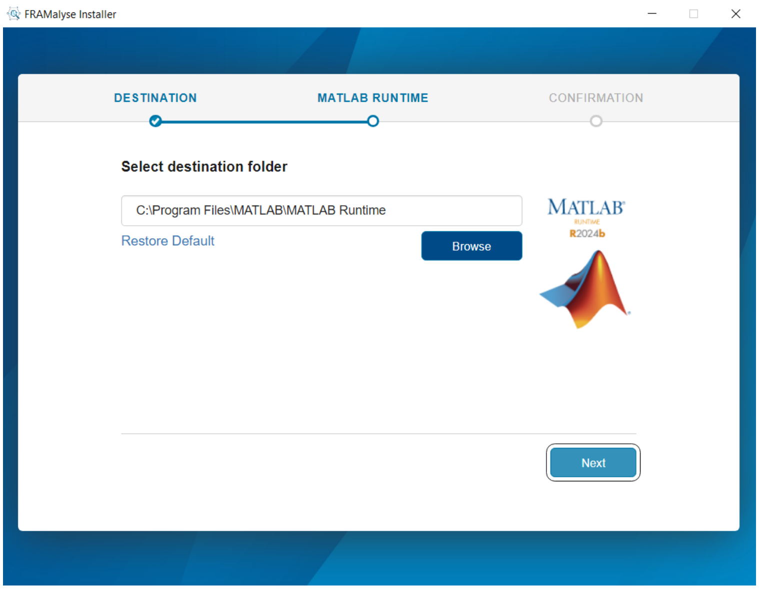

Figure 3: Select destination folder for MATLAB Runtime.

Also, make sure to accept the license agreement of MATLAB Runtime. If MATLAB Runtime is already installed on your computer, this process will be skipped.

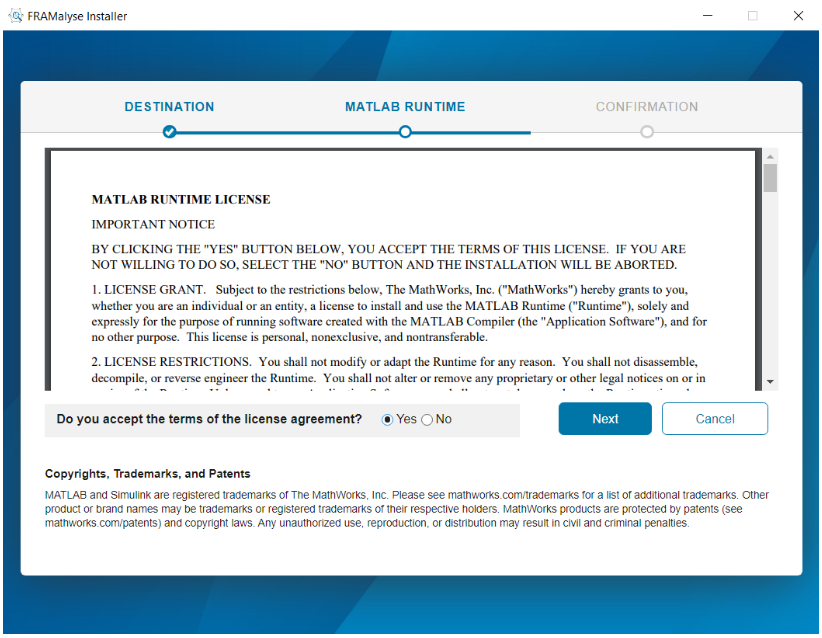

Figure 4: Accept the license agreement of MATLAB Runtime.

Please confirm the installation locations for FRAMalyse and MATLAB Runtime, then click "Begin Install" to proceed. Note that the required space for FRAMalyse and Matlab Runtime is approximately 2,4GB.

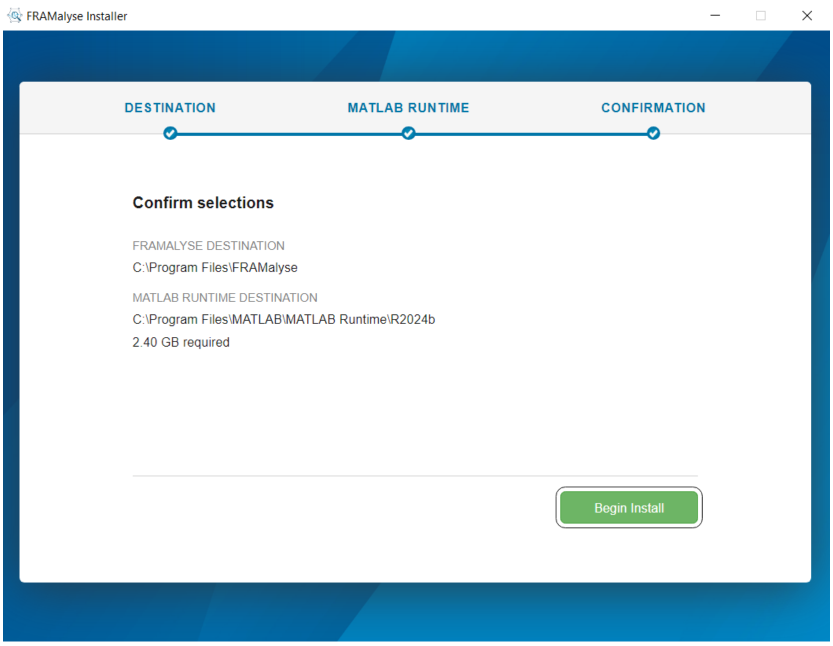

Figure 5: Begin installing.

A prompt will indicate that the installation is complete. Click "Close" to finalize the installation process.

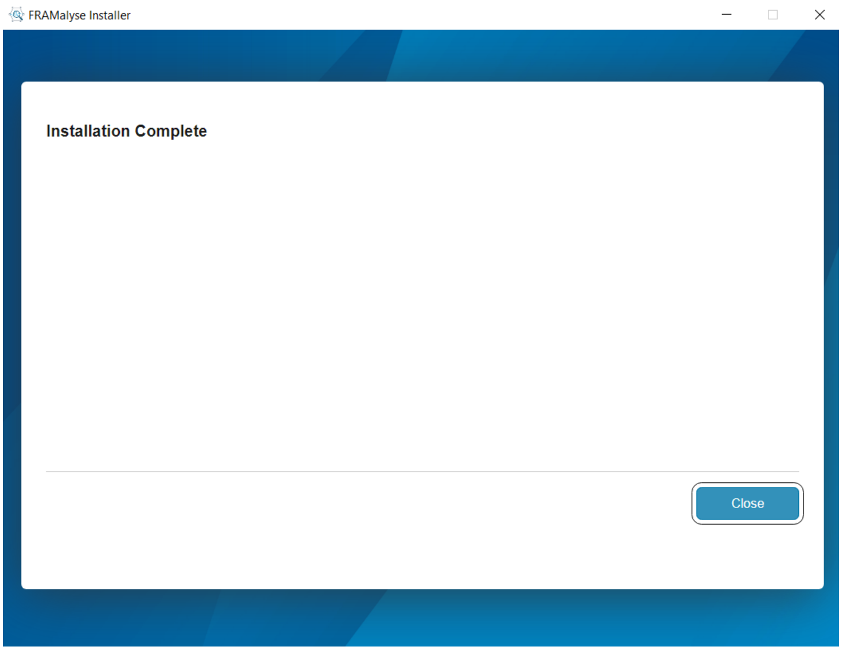

Figure 6: Installation complete.

2.2 Uninstalling steps

FRAMalyse can be uninstalled through the standard uninstallation procedure from Windows Control Panel. Open the "Control Panel." Select "Programs." Find FRAMalyse in the program list, right-click, and select "Uninstall."

3 Using FRAMalyse

The purpose of FRAMalyse consists of supporting the analysis of steps three and four in FRAM, i.e., aggregating variability to identify functional resonance and managing the variability to ensure the system's safety and performance. More specifically, FRAMalyse supports an efficient and systematic analysis, visualization, and interpretation of system variabilities in a FRAM model or instantiation in a quantitative and user-friendly way.

3.1 Overview – Basic functionalities

FRAMalyse is developed by Matlab App Designer as a free Standalone Desktop version for Windows environments. It is interfaced with FMV by importing the required FRAM model data in the form of Excel files. More specifically, FRAMalyse allows:

- Defining, editing, searching, and sorting functions in a tabular way with a detailed description of function type, agent, abstraction level/stage, and variability
- Calculating quantitative metrics representing variability, interaction, and complexity of functions and couplings
- Calculating Monte-Carlo simulation to identify critical paths of variable couplings

- Representing the FRAM model instantiation as a network in a grid assigned to agents and abstraction/space-time levels enriched by upstream and downstream functions information
- Assessing and visualizing model characteristics, interrelationships, and frequencies of network parameters
- Defining risk functions and visualizing the global system variability (GSV) and risk distribution over agent and abstraction levels and function types
- Assigning and visualizing risk functions along interaction and variability in a Functional Variability System Resonance Matrix (FVSRM)
- Importing model and instantiation data and exporting tables and images

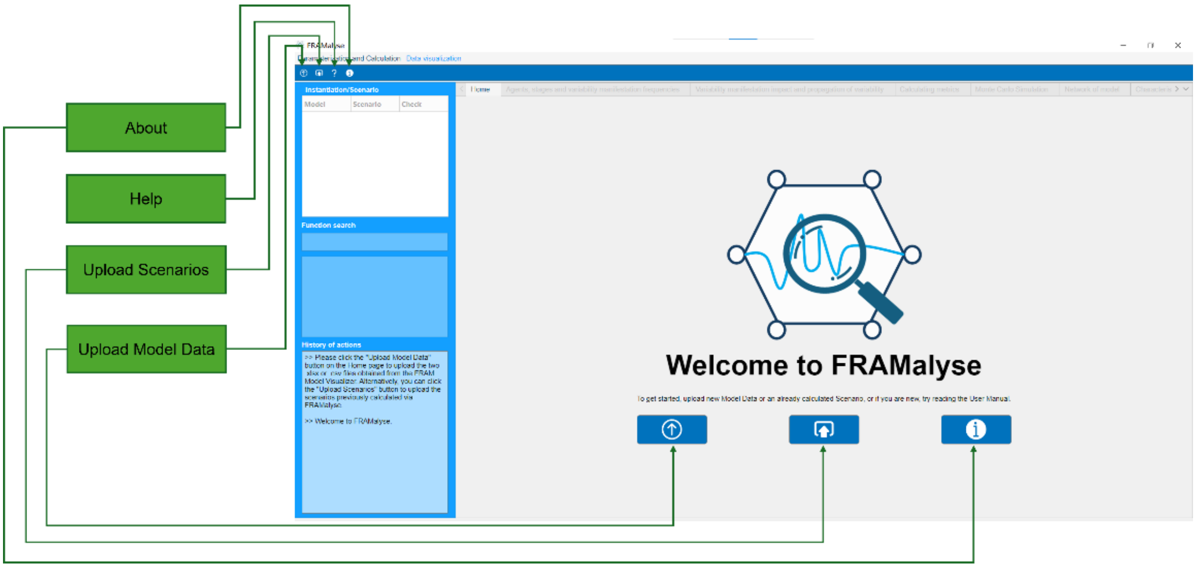

Figure 7: The initial interface of FRAMalyse.

3.1.1 Upload Model Data

If you are using FRAMalyse for the first time, you need to upload two files: FRAM_model-couplings (.csv or .xlsx) and FRAM_model-functions (.csv or .xlsx). To obtain these files, first create or upload your FRAM model (.xfmv) in the FRAM Model Visualiser (Hill & Hollnagel, 2016), then download the two files.

The former should contain the following couplings information:

Coupling Name	Output Function IDNr	Output Function IDName	Couplings	To Function IDNr	To Function IDName	To Function Aspect Type
1|adequate speed adjusted (	1	<adjust to adequate speed (OV)>	[adequate	0	<driving free (OV)>	I
1|adequate speed adjusted (	1	<adjust to adequate speed (OV)>	[adequate	212	<judge first OV's speed (F	I

Figure 8: The content of FRAM_model-couplings (.csv or .xlsx).

And the latter should contain the following functions information:

IDNr	IDName	FunctionType	Color	Has Orphans	Has Input
0	driving free (OV)	0	#FF7F00	0	true
1	adjust to adequate speed (OV)	0	#17BD01	0	true

Figure 9: The content of FRAM_model-functions (.csv or .xlsx).

Then, click "Upload Model Data", located in the "Home" tab or the toolbar at the top of the page, hold down the Ctrl key and select both files for upload.

Upon successful upload, FRAMalyse will display the file names, and the "History of actions" in the bottom-left corner will confirm the upload. Then, it will navigate to the tab “Agents, stages, and variability manifestation frequencies”.

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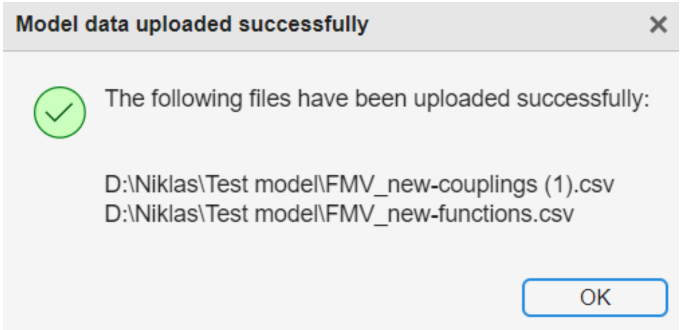


Figure 10: Dialog box: "Model data uploaded successfully".

3.1.2 Upload Scenarios

Users can also click the "Upload Scenarios" button, located in the "Home" tab or the toolbar at the top of the page, to upload one or more scenarios. These scenario files are obtained by clicking the "Download both tables" button in the "Calculating Metrics" tab of the FRAMalyse app. The names of the uploaded scenarios will be displayed in the "Scenario" column of the "Instantiation/Scenario" table on the upper-left side of the app. Each scenario will automatically be assigned a model name in sequential order, such as "Model_1", "Model_2," and ”Model_n”. After uploading, the app will automatically display the data from the recently uploaded scenario across the following tabs:

- Agents, Stages, and Variability Manifestation Frequencies
- Variability Manifestation Impact and Propagation of Variability
- Calculating Metrics
- Network of Model
- Characteristics, Frequencies, and Interrelationships
- Interdependencies – Chord Diagram
- Risk Functions

For example, as shown below, the user simultaneously uploaded the two scenario files "Scenario_1.xlsx" and "Scenario_2.xlsx". The names of these scenarios, along with their assigned model names—"Model_1" and "Model_2"—are displayed in the table "Instantiation/Scenario" in the upper-left corner of the page. Upon completion of the upload, the app automatically navigates to the "Agents, Stages, and Variability Manifestation Frequencies" tab, where the data for "Model_2/Scenario_2" is displayed. Additionally, "Model_2/Scenario_2" is shown in the "Current scenario" box in the upper-right corner.

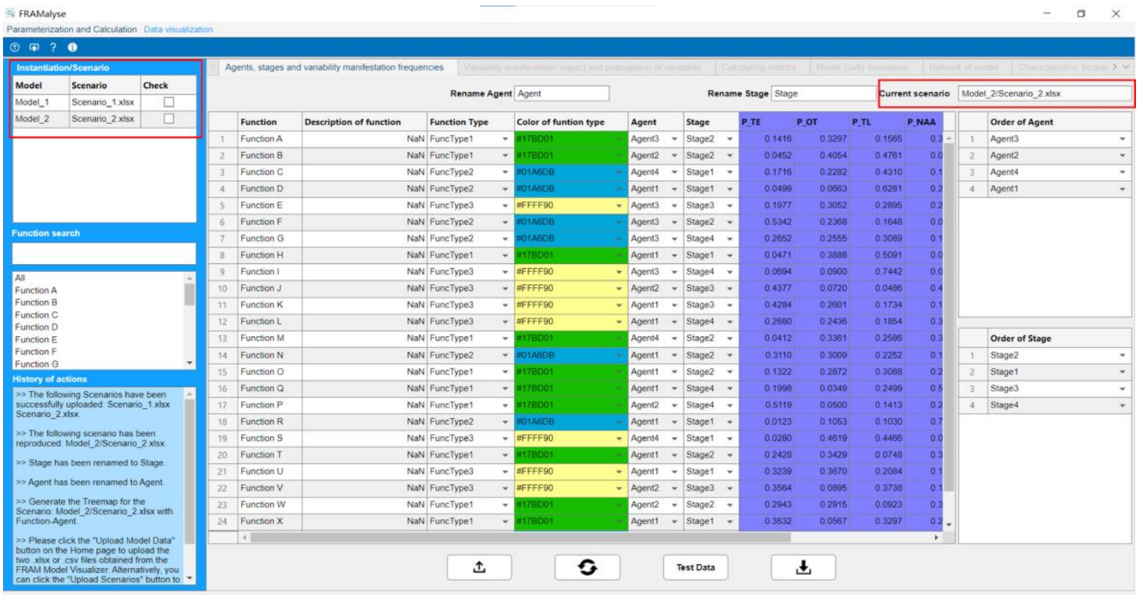
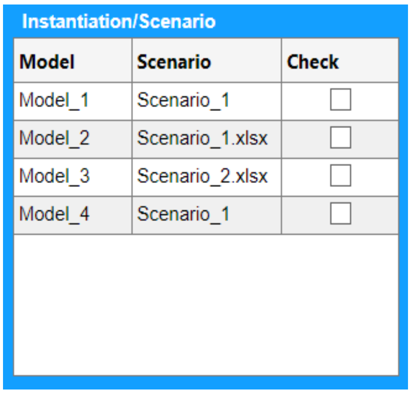


Figure 11: The result after the user uploaded two scenario files, "Scenarios_1.xlsx" and "Scenarios_2.xlsx", by clicking the "Upload Scenarios" button.

3.1.3 Instantiation/Scenario

The "Instantiation/Scenario" table, located at the top-left corner of the application, stores the names of either calculated or uploaded scenarios. Each row in the table represents a scenario and comprises three columns: "Model", "Scenario", and "Check".

- Model: The system automatically assigns a name to the scenario's model. By default, the model's name combines the word "Model" with the row number. For example, the model's name for the first row is "Model_1".
- Scenario: The scenario name varies based on how it was generated:
  1. If the scenario was computed by clicking the "Calculate Metrics" button in the "Calculating metrics" tab, its default name is "Scenario_1". As shown in the first and fourth rows in the figure below.
  2. If the scenario was uploaded using the "Upload Scenarios" button in the "Home" tab or from the toolbar at the top of the page, its name matches the filename of the uploaded scenario. As shown in the second and third rows in the figure below.
- Check: Users can select the corresponding Scenarios by checking the boxes in the "Check" column. Once selected, these Scenarios can be further processed in the "Monte Carlo Simulation" or "Risk functions" tabs.


Instantiation/Scenario

Model	Scenario	Check
Model_1	Scenario_1	☐
Model_2	Scenario_1.xlsx	☐
Model_3	Scenario_2.xlsx	☐
Model_4	Scenario_1	☐

Figure 12: The "Instantiation/Scenario" table containing four scenarios.

Rename “Model” and “Scenario”: The user can double-click any cell in the "Model" or "Scenario" columns and edit it to modify the name of the scenario.

Represent Scenario: Users can represent any scenario from the table "Instantiation/Scenario." To begin, the user should left-click on the desired scenario to represent, followed by a right-click to open the menu. By selecting the "Represent Scenario" option, the information associated with the chosen scenario will be displayed across the following tabs: "Agents, Stages, and Variability Manifestation Frequencies," "Variability Manifestation Impact and Propagation," "Calculating Metrics," "Network of Model," "Characteristics, Frequencies, and Interrelationships," "Interdependencies – Chord Diagram," and "Risk Functions."

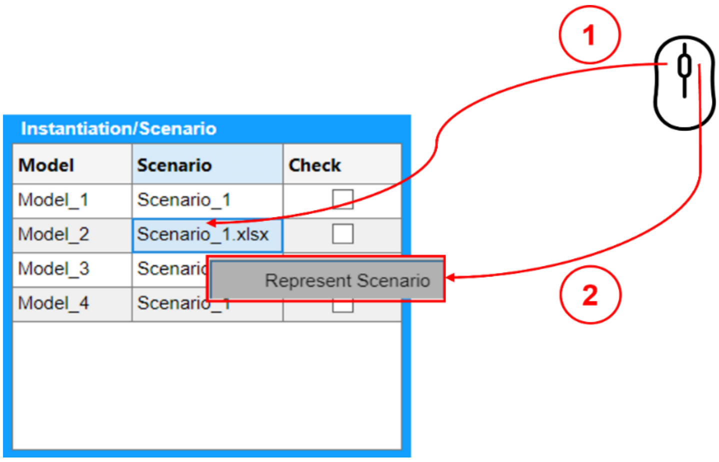


Figure 13: The "Represent Scenario" menu in the "Instantiation/Scenario" table.

When the user first opens the app, this table is not enabled. It only becomes enabled when scenarios have been calculated or directly uploaded. Once the scenarios are calculated or uploaded, the names of the calculated and uploaded scenarios will be displayed in the table.

3.1.4 Menu

Users can utilize the Menu Bar at the top of the App for quick navigation to the corresponding tabs.

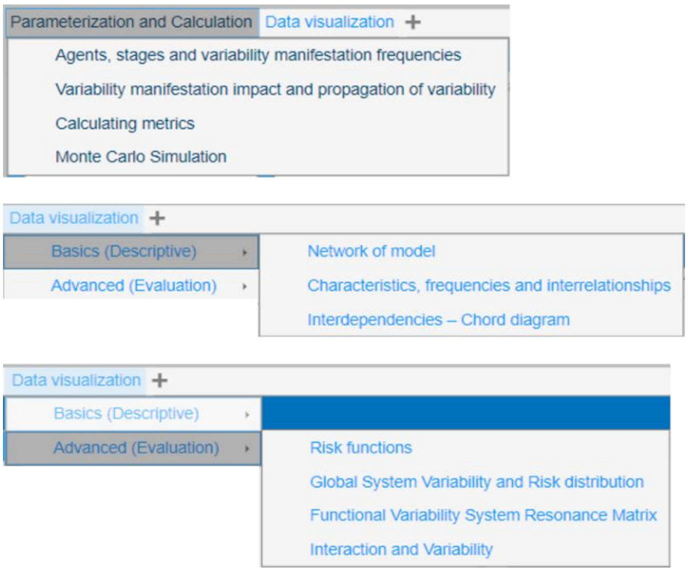


Figure 14: The menu bar at the top of FRAMalyse: "Parameterization and Calculation" and "Data Visualization".

3.1.5 Toolbar

At the top of the page, the Toolbar contains four buttons: "Upload Model Data", "Upload Scenarios", "Help", and "About". The functions of "Upload Model Data" and "Upload Scenarios" have been described previously. Clicking "Help" in different tabs opens a text window providing a brief overview of the features available in the current tab. Selecting "About" opens a text window introducing the App's authors and some background information of the app.

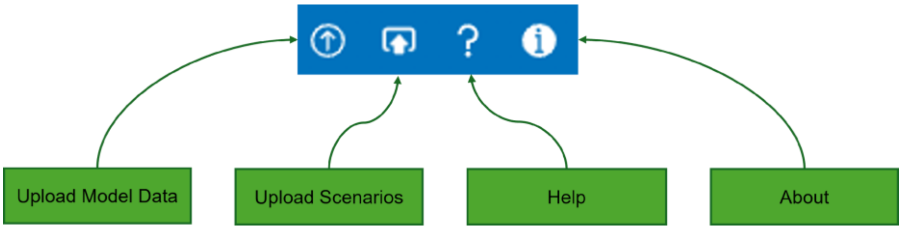


Figure 15: The toolbar at the top of FRAMalyse: "Upload Model Data", "Upload Scenarios", "Help", and "About".

3.1.6 Function search and Function list

Users can view a specific function from a scenario in the ["Network of model"]() and ["Characteristics, frequencies, and interrelationships"]() tabs using the "Function Search" and "Function List" on the left side.

Figure 16: The "Function search" and "Function list" before generating scenarios.

Similarly to the "Instantiation/Scenario" table, when the user first opens the app, the "Function Search" and "Function List" are disabled. They only become enabled once the scenarios have been calculated or directly uploaded. Upon calculation or upload, the functions of the calculated and uploaded scenarios will be displayed here.

3.1.7 History of actions

The "History of actions" box in the lower-left corner records every interaction that the user made with the app.

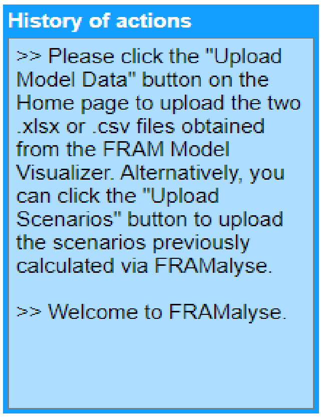


Figure 17: The "History of actions" upon opening the app.

3.2 Parameterization and Calculation

After successfully uploading the model data, you can define and calculate the relevant parameters of the model.

3.2.1 Agents, stages and variability manifestation frequencies

In the centered table, the function names from the Model Data are displayed along enriched information. By double-clicking a cell, users can edit the following information: function description, function type, color of function type, agent, stage, and the percentage distribution of variability values (P_TE, P_OT, P_TL, P_NAA, P_I, P_A, P_PR). By default, all functions have their type, agent, and stage set to "Unknown," with P_TE, P_OT, P_TL, P_NAA, P_I, P_A, and P_PR all set to zero. Only the color of the function type is filled based on the colors used in FMV.

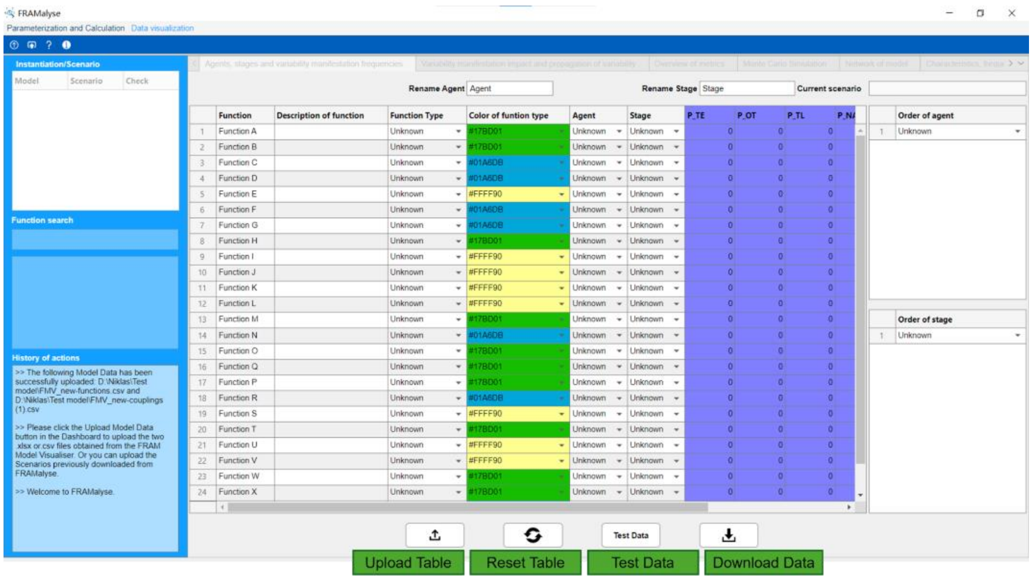


Figure 18: The "Agents, stages, and variability manifestation frequencies" tab after the user uploaded the model data via the "Upload Model Data" button.

Edit Function Type: When the user edits a function type, a dialog window will appear. Clicking "Yes" will update the function type for all functions with the same color. The function type can be edited either by manually typing after double-clicking or by selecting from a Dropdown list. If manually typed, the newly entered value will be added to the Dropdown options for future use.

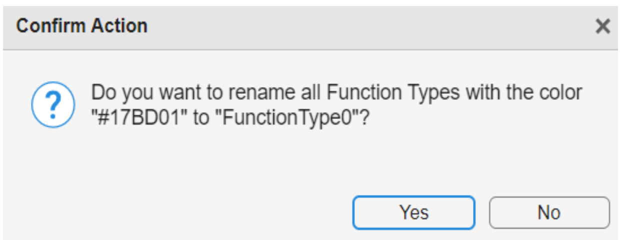


Figure 19: The dialog box displayed when the user edits the Function Type.

Edit Color of Function Type: Users can double-click a cell to manually input a hexadecimal color code or double-click to open a Dropdown menu to select from existing color codes (i.e. seven recommended colors).

Edit Agent and Stage: Users can double-click a cell to manually input an Agent Name or Stage Name. If manually entered, the new input value will be added to the Dropdown options for future use.

Edit P_TE, P_OT, P_TL, P_NAA, P_I, P_A, P_NAA: These values represent the variability manifestation in terms of the phenotypes timing and precision. For each function, the sum of P_TE, P_OT, P_TL, and P_NAA equals one, and the sum of P_I, P_A, and P_NAA equals one. Each value is a real number between zero and one. When the user has edited all but one empty cell exist, the system will automatically fill in that cell to ensure the sum of the probabilities equals one.

On the right side of the page are two small tables, each displaying the elements from the Agent and Stage columns, arranged in the order of their appearance. Users can click on the cells of these tables and select elements from the Dropdown menu to reorder the Order of Agent and Order of Stage. The Order of Agent determines the sequence of the x-axis in the subsequent network, while the Order of Stage determines the sequence of the y-axis.

Above the tables, users can rename the Agent and Stage in the app using the "Rename Agent" and "Rename Stage" text boxes. The "Current scenario" text box will display the computed scenario after the metrics are calculated.

Below the Tables section, four buttons are arranged sequentially: “Upload Table”, “Reset Table”, “Test Data”, and “Download Data”:

Click the "Upload Table" button: Users can upload previously downloaded tables via the button, which corresponds to the "Download Data" function.

Click the "Reset Table" button: Clicking the button triggers a dialog box prompting confirmation for resetting the table. Selecting "Yes" clears the contents of the three tables, while selecting "No" cancels the action.

Click the "Test Data" button: Clicking the button generates random test data for the centered table:

- The Function Type column is randomly filled with "FuncType1," "FuncType2," and "FuncType3."
- The Agent column is randomly filled with "Agent1," "Agent2," "Agent3," and "Agent4."
- The Stage column is randomly filled with "Stage1," "Stage2," "Stage3," and "Stage4."
- The P_TE, P_OT, P_TL, P_NAA columns are filled with random real numbers between zero and one, ensuring that the sum of these four values equals one for each function.
- The P_I, P_A, P_NAA columns are filled with random real numbers between zero and one, ensuring that the sum of these three values equals one for each function.
- The "Order of agent" and "Order of stage" tables on the right display unique elements from the Agent and Stage columns, respectively, in the order of their first occurrence in the original columns.

Click the "Download Data" button: Clicking this button allows users to save the three tables as a single .xlsx file, with the default file name "Agents, stages and variability manifestation frequencies." The file includes three sheets: the centered table is saved in the sheet "Parameters," the "Order of agent" table on the right is saved in the sheet "OrderOfAgents," and the "Order of stage" table on the right is saved in the sheet "OrderOfStages."

3.2.2 Variability manifestation impact and propagation of variability

After defining Agents, Stages, and Variability Manifestation Frequencies, users can specify the Variability Manifestation Impact and its propagation for the uploaded Model Data in this tab. This tab consists of three tables and four buttons.

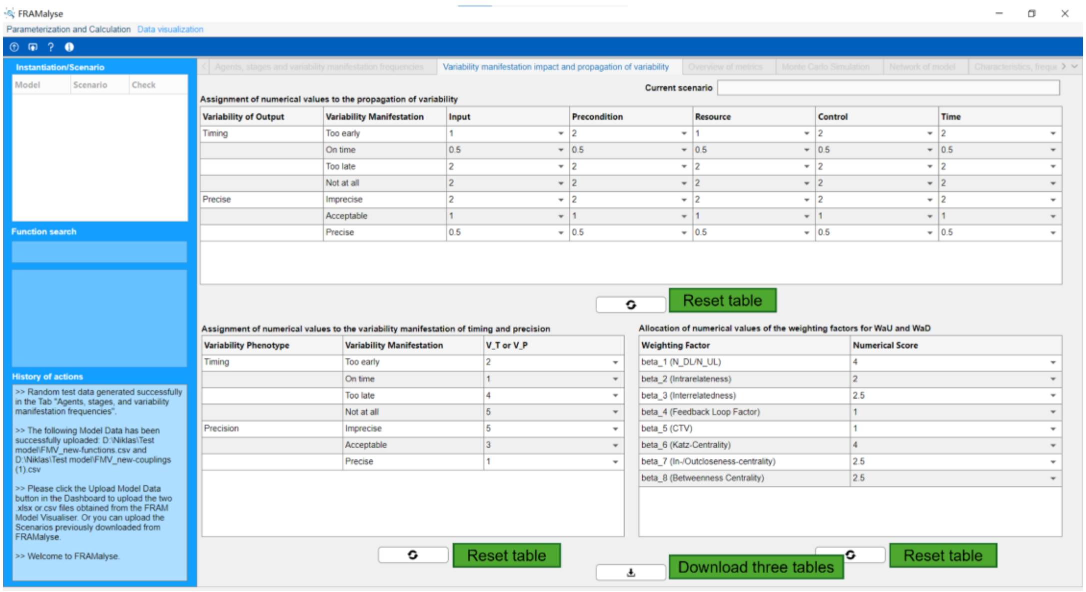


Figure 20: The "Variability manifestation impact and propagation of variability" tab with default values.

Edit the tables: The tables display default data, and users can double-click on a cell to select alternative default values or manually input custom values.

Click the three "Reset table" buttons: allow users to reset the corresponding tables to their default values.

Click the "Download three tables" button: By clicking this button, users can save the three tables in this Tab as a single .xlsx file, with the default filename "Variability manifestation impact and propagation of variability." This file includes three sheets: Sheet "Propagation" contains the contents of the table "Assignment of numerical values to the propagation of variability"; Sheet "V" contains the table "Assignment of numerical values to the variability manifestation of timing and precision"; and Sheet "Beta" contains the table "Allocation of numerical values of the weighting factors for WaU and WaD."

3.2.3 Calculating metrics

After defining Agents, Stages, Variability Manifestation Frequencies, and Variability Manifestation Impact and Propagation, users can calculate metrics for a new scenario based on the Model Data and parameters defined in the previous two tabs. The definitions and calculation formulas of the metrics follow the approach by Grabbe et al. (2022). For further details, please refer to the Appendix.

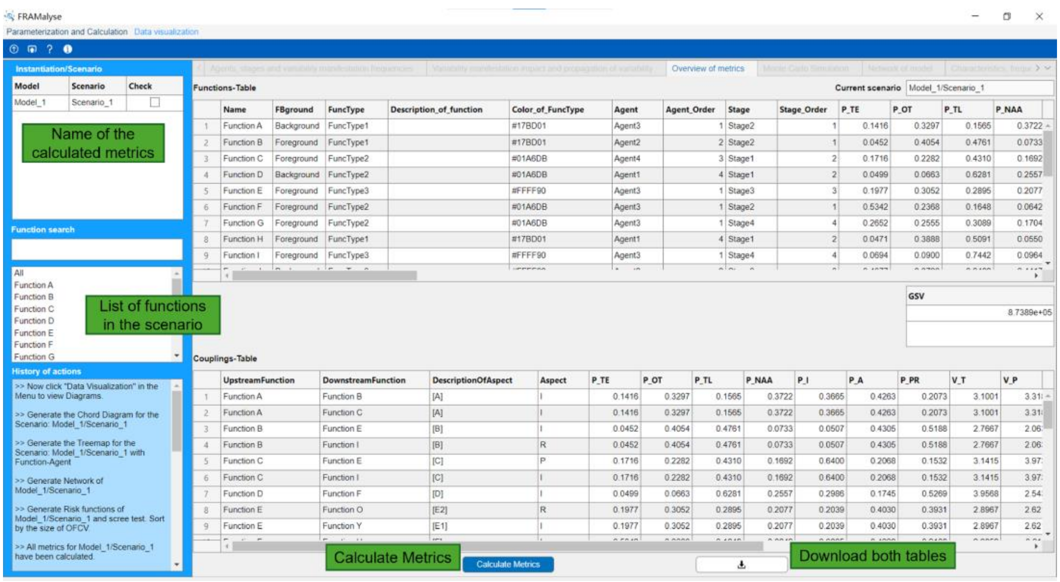


Figure 21: The "Calculating metrics" tab after the user clicked the "Calculate metrics" button.

Click the "Calculate Metrics" button: Before clicking this button, the three tables in the tab are empty. Upon clicking,

- the system will automatically calculate the various metrics of the scenario and fill them into the tables. Please note that the calculation time depends on the complexity of the Model Data. The "Functions-Table" at the top contains the 68 metrics as listed in the Appendix. The "Couplings-Table" at the bottom contains the following 23 metrics:
  - DescriptionOfAspect, and Aspect,
  - P_TE, P_OT, P_TL, P_NAA, P_I, P_A, and P_NAA,
  - V_T, V_P, and OV,
  - a_TE, a_OT, a_TL, a_NAA, a_I, a_A, and a_PR,
  - a_T, a_P, and CV.

  In addition, there is another metric, GSV, which is displayed in the middle table. For detailed explanations and calculation formulas of these metrics, please refer to Appendix A.
- the "Instantiation/Scenario" table on the left displays the name of the newly calculated Scenario, which consists of the Model Name and Scenario Name. The names can be modified by double-clicking. Below the table is the list of functions included in the Scenario.
- in addition, the relevant metrics of the scenario will be visualized, with diagrams generated and displayed in the following Tabs: "Network of model," "Characteristics, frequencies and interrelationships," "Interdependencies – Chord diagram," and "Risk functions." Detailed information can be found in the subsequent sections.

Click the "Download both tables" button: Clicking this button will generate an .xlsx file containing two sheets. The Functions-Table is stored in the "Nodes" sheet, and the Couplings-Table is stored in the "Edges" sheet.

3.2.4 Monte Carlo Simulation

In this tab, users can perform Monte Carlo Simulations on scenarios to identify critical paths, adapted by Patriarca et al. (2017b). The top left section contains four input fields for the following parameters:

- **Threshold Criticality of CV** (default: 12): A coupling is deemed critical if its CV exceeds this threshold. A path comprising multiple couplings is considered critical if the CV of every coupling within the path exceeds this value.
- **Number of Runs** (default: 100): The total number of iterations for the Monte Carlo Simulation.
- **Error Probability** (default: 0.05): The ratio of critical outcomes for a path to the total number of simulation runs. Combinations that exceed the set error probability are marked red; the rest are green.
- **Longest Paths** (default: 11): Specifies the maximum number of functions a path can contain in the "Critical Longest Paths of Couplings" table when the user clicks the "All Paths" button. If the user clicks the "Shortest Paths" button, the Longest Paths parameter does not affect the Monte Carlo Simulation.

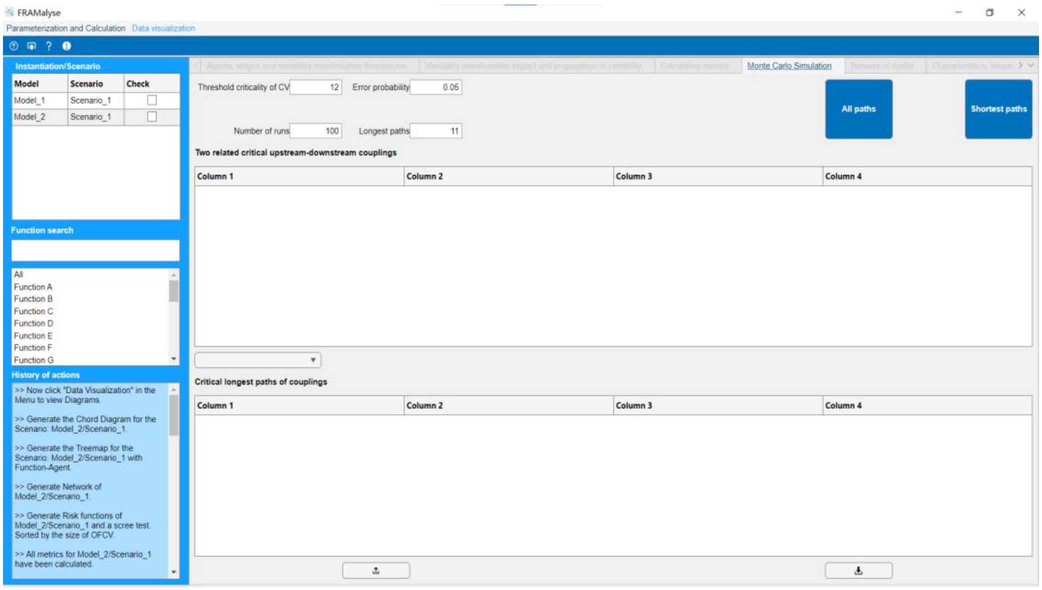


Figure 22: The initial interface and default values of the "Monte Carlo Simulation" tab.

In the top-right corner of the tab, there are two buttons: "**All paths**" and "**Shortest paths**", representing two types of simulations. Clicking "**All paths**" triggers Monte Carlo simulations for the selected scenarios, displaying critical path data in two tables below.

The first table, **"Two Related Critical Upstream-Downstream Couplings"**, lists paths including three functions. Each row represents a path with columns structured as follows:

- First Four Columns: Simulation parameters entered above the table, including **"Type of Simulation", "Threshold Criticality of CV", "Number of Runs"**, and **"Error Probability"**.

- Columns Five to Twelve: Path details such as **"Upstream Function", "Description of Aspect", "Intermediate Function", "Aspect", "Intermediate Function", "Description of Aspect", "Downstream Function", "Aspect".**
- From Column Thirteen Onwards: The ratio of critical occurrences in specific scenarios. Cells are color-coded based on this ratio: red if it exceeds the Error Probability, and green otherwise. Columns are ordered left-to-right by their sums, while rows are arranged top-to-bottom by cumulative values.

Two related critical upstream-downstream couplings

	Type of simulation	Threshold criticality of CV	Number of runs	Error probability	Upstream function	Description of aspect	Intermediate function	Aspect	Intermediate function	Description of aspect	Downstream function	Aspect	Model_2/Scenario_1	Model_1/Scenario_1
1	All paths	12	100	0.0500	Function I	[I]	Function C	I	Function C	[C]	Function E	P	1.0000	1.0000
2	All paths	12	100	0.0500	Function D	[D]	Function F	I	Function F	[F]	Function H	I	1.0000	1.0000
3	All paths	12	100	0.0500	Function F	[F]	Function H	I	Function H	[H]	Function M	C	1.0000	1.0000
4	All paths	12	100	0.0500	Function B	[B]	Function I	R	Function I	[I]	Function C	I	1.0000	1.0000
5	All paths	12	100	0.0500	Function B	[B]	Function I	R	Function I	[I]	Function O	T	1.0000	1.0000
6	All paths	12	100	0.0500	Function I	[I]	Function O	T	Function O	[O]	Function E	I	1.0000	1.0000
7	All paths	12	100	0.0500	Function I	[I]	Function O	T	Function O	[O]	Function Q	C	1.0000	1.0000
8	All paths	12	100	0.0500	Function I	[I]	Function O	T	Function O	[O]	Function P	I	1.0000	1.0000
9	All paths	12	100	0.0500	Function G	[G]	Function F	I	Function F	[F]	Function H	I	1.0000	0.9800

Figure 23: The "Two related critical upstream-downstream couplings" table after the user clicked the "All paths" or "Shortest paths" button.

Additionally, users can interact with the "**Two Related Critical Upstream-Downstream Couplings**" table by selecting any cell in a row and right-clicking to access a menu. The menu offers a primary option, **"Represent Path in a Network"**, and secondary options corresponding to scenario names. Clicking on a specific scenario displays the selected path within the **"Network of Model"** tab, and the system automatically navigates to this tab. For instance, the figure below demonstrates the outcome of selecting the path in the first row for representation within the "**Network of Model"** tab. Here, the "**Upstream Function"** is "**Function I"**, the "**Intermediate Function"** is "**Function C"**, and the "**Downstream Function"** is "**Function E"**.

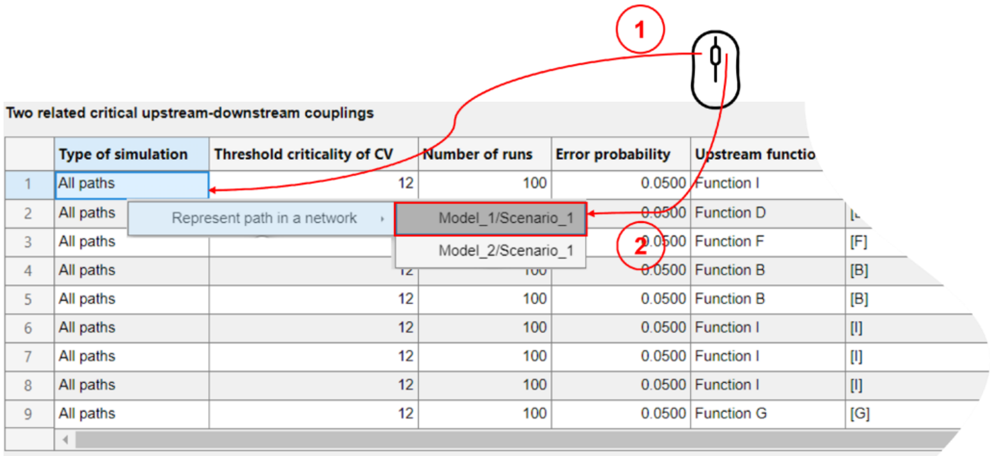


Figure 24: Open the "Represent path in a network" menu and select a scenario.

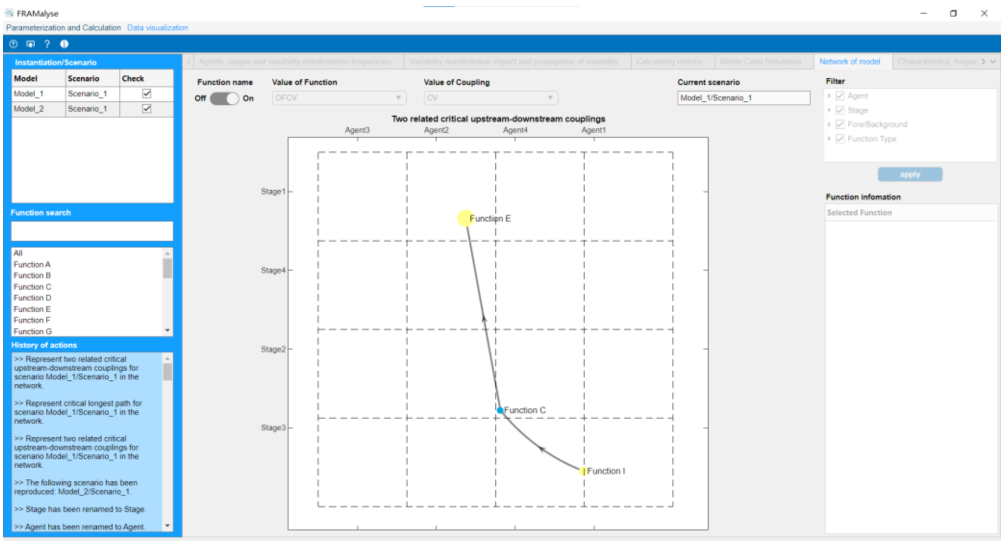


Figure 25:The selected path is displayed in the network of the selected scenario.

The **"Critical Longest Paths of Couplings"** table organizes and presents paths from scenarios with lengths between four and the user-defined **"Longest Paths"** limit. Each row details a unique path, with columns grouped into the following sections:

- **User Input Values**: Columns 1–6 provide the user-specified parameters, including **"Type of Simulation", "Threshold Criticality of CV", "Number of Runs", "Error Probability", "Longest Paths",** and **"Scenario"**.
- **Simulation Results:** Columns 7–8 summarize outcomes from the Monte Carlo simulation. **"Length"** indicates the number of functions within the path, and **"Critical Percentage"** denotes the fraction of critical occurrences relative to the total **"Number of runs"**. Paths are ranked first by **"Length"** in descending order, then by **"Critical Percentage"** within each length group.
- **Path Details:** Starting from column 9, subsequent columns describe the sequence of functions within the path and the corresponding couplings, specifying their **"Aspect"** and **"Description of Aspect"**.

Critical longest paths of couplings

	Type of simulation	Threshold criticality of CV	Number of runs	Error probability	Longest paths	Scenario	Length	Critical percentage	Function 1	Description of aspect
1	All paths	12	100	0.0500	11	Model_1/Scenario_1	7	1.0000	Function B	[B]
2	All paths	12	100	0.0500	11	Model_1/Scenario_1	6	1.0000	Function B	[B]
3	All paths	12	100	0.0500	11	Model_1/Scenario_1	6	1.0000	Function B	[B]
4	All paths	12	100	0.0500	11	Model_1/Scenario_1	6	1.0000	Function I	[I]
5	All paths	12	100	0.0500	11	Model_1/Scenario_1	6	1.0000	Function J	[J]
6	All paths	12	100	0.0500	11	Model_1/Scenario_1	6	0.9800	Function J	[J]
7	All paths	12	100	0.0500	11	Model_1/Scenario_1	5	1.0000	Function B	[B]
8	All paths	12	100	0.0500	11	Model_1/Scenario_1	5	1.0000	Function B	[B]

Aspect	Function 2	Description of aspect	Aspect	Function 3	Description of aspect	Aspect	Function 4		Aspect	Function 5	Description of aspect
R	Function I	[I]	I	Function C	[C]	P	Function E	[E2]	R	Function O	[O]
R	Function I	[I]	I	Function C	[C]	P	Function E	[E2]	R	Function O	[O]
R	Function I	[I]	I	Function C	[C]	P	Function E	[E2]	R	Function O	[O]
I	Function C	[C]	P	Function E	[E2]	R	Function O	[O]	C	Function Q	[Q]
I	Function G	[G]	C	Function E	[E2]	R	Function O	[O]	C	Function Q	[Q]
I	Function G	[G]	I	Function F	[F]	I	Function H	[H]	C	Function M	[M]
R	Function I	[I]	I	Function C	[C]	P	Function E	[E2]	R	Function O	
R	Function I	[I]	I	Function C	[C]	P	Function E	[E1]	I	Function Y	

Aspect	Function 6	Description of aspect	Aspect	Function 7
C	Function Q	[Q]	I	Function K
C	Function Q			
I	Function P			
I	Function K			
I	Function K			
I	Function S			

Figure 26: The "Critical longest paths of couplings" table after the user clicked the "All paths" button.

Furthermore, users can left-click on any cell within a row and then right-click the selected cell to open a menu. By selecting the option **"Represent Critical Longest Path in a Network,"** the corresponding path for that row will be displayed in the **"Network of model"** tab, and the interface will automatically navigate to the **"Network of model"** tab. For example, in the illustration below, the operation is performed on the first row of the table. As a result, the path corresponding to the first row is displayed within the network. This path consists of seven functions: **"Function B," "Function I," "Function C," "Function E," "Function O," "Function Q,"** and **"Function K."**

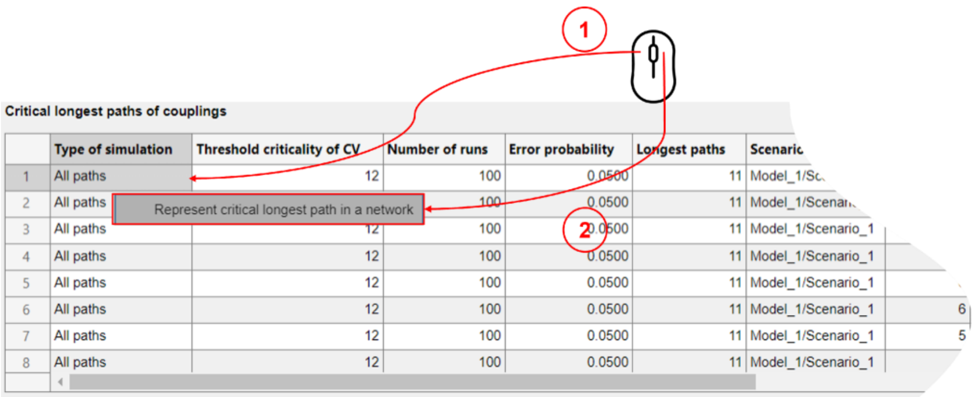


Figure 27: Open the "Represent critical longest path in a network" menu.

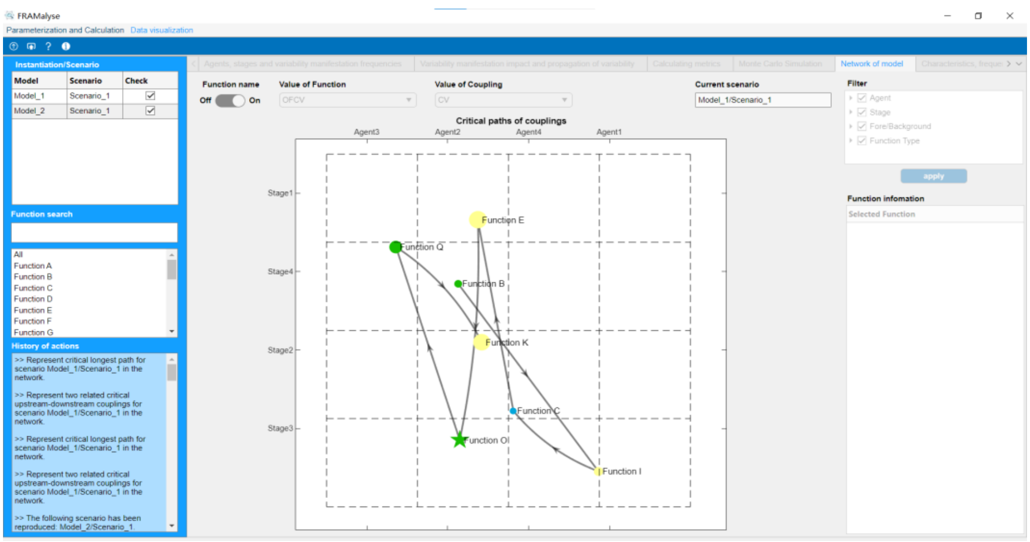


Figure 28: The selected path displayed in the network of the selected scenario.

Using the Dropdown menu located above the **"Critical Longest Paths of Couplings"** table, users can view the critical longest paths of couplings for different scenarios.

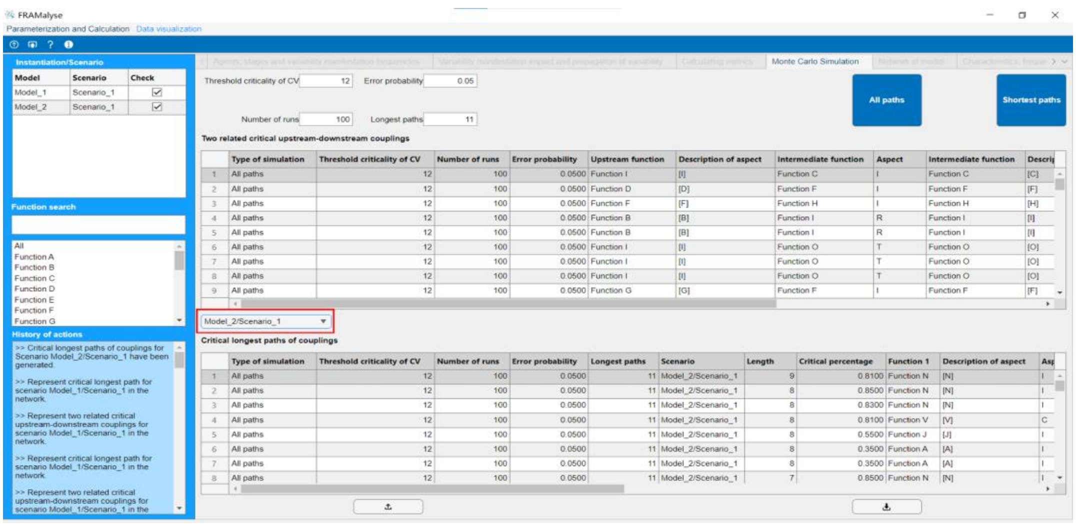


Figure 29: Change the value in the Dropdown to select the scenarios displayed in the "Critical longest paths of couplings" table.

In the upper-right corner of the tab, users can also click the **"Shortest paths"** button, which initiates Monte Carlo Simulations for the scenarios, similar to the **"All paths"** button. The results are displayed in the same two tables. While the outcomes in the **"Two Related Critical Upstream-Downstream Couplings"** table remain identical to those generated by the **"All paths"** button, the results in the **"Critical Longest Paths of Couplings"** table differ. The **"All paths"** button identifies all paths between each pair of functions within a scenario, with lengths ranging from four to the value specified in the **"Longest paths"** input. In contrast, the **"Shortest paths"** button focuses only on the shortest path between each pair of functions, provided the path length is at least four.

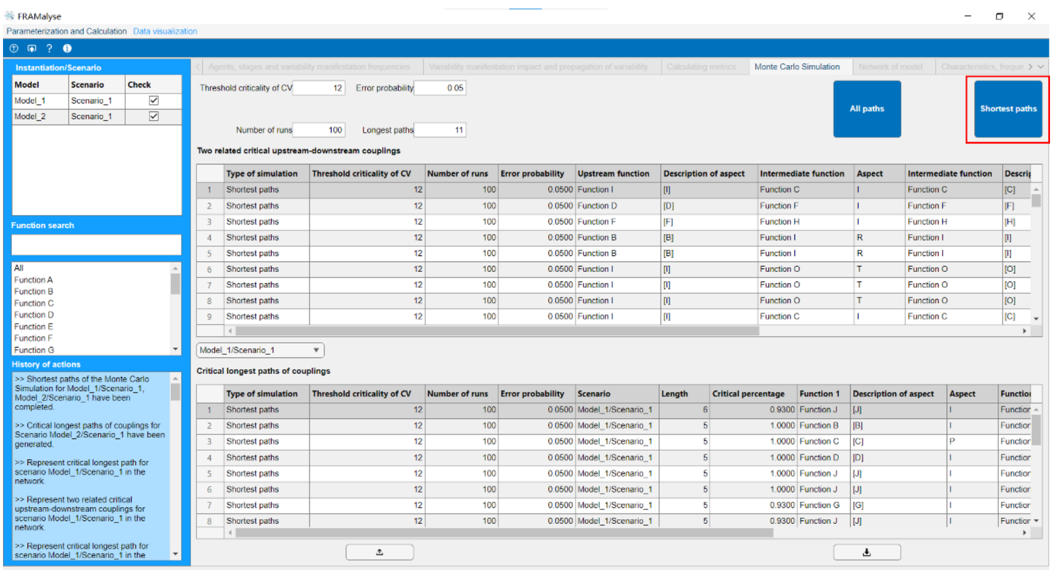


Figure 30: The result after the user clicked the "Shortest paths" button.

At the bottom of the tab, there are **"Download"** and **"Upload"** buttons. Users can click the **"Download"** button to save the tables from this tab as multiple sheets within a single .xlsx file. The default file name is **"Monte_Carlo_Data".** Specifically, the **"Two Related Critical Upstream-Downstream Couplings"** table is stored in a sheet named **"Two Critical Couplings".** For each scenario, the corresponding **"Critical Longest Paths of Couplings"** table is saved as a separate sheet, named **"Critical Longest Paths_1",** with subsequent scenarios numbered sequentially (e.g., _2, _3, etc.). For example, if the Monte Carlo Simulation results for two scenarios, "Model_1/Scenario_1" and "Model_2/Scenario_1," are downloaded, the resulting file named **"Monte_Carlo_Data"** will contain three sheets:

- **"Two Critical Couplings"** for the **"Two Related Critical Upstream-Downstream Couplings"** table.
- **"Critical Longest Paths_1"** for the **"Critical Longest Paths of Couplings"** table from "Model_1/Scenario_1".
- **"Critical Longest Paths_2"** for the **"Critical Longest Paths of Couplings" table from** "Model_2/Scenario_1".

Clicking the **"Upload"** button allows users to re-upload a previously downloaded **"Monte_Carlo_Data"** file. Upon upload, the four numerical input fields in the top-left corner of the **"Monte Carlo Simulation"** tab, as well as the two tables, will automatically update based on the data contained in the uploaded **"Monte_Carlo_Data"** file.

3.3 Data visualization

Once Scenarios are generated or uploaded, users can perform data visualization of the relevant metrics. The visualization is divided into two sections: Basics-Descriptive information and Advanced evaluation. The descriptive information includes three tabs: "Network of model," "Characteristics, frequencies and interrelationships," and "Interdependencies – Chord diagram." The advanced evaluation includes four tabs: "Risk functions," "Global System Variability and Risk distribution," "Functional Variability System Resonance Matrix," and "Interaction and Variability." Users can select a specific tab from the Menu at the top.

3.3.1 Basics - Descriptive information

3.3.1.1 Network of model

The center of this tab displays the network of the current scenario. The network represents the FRAM model instantiation in a grid assigned to agents and abstraction levels, which aligns with the Abstraction/Agency framework by Patriarca et al. (2017a). Nodes represent functions, with their color corresponding to the color of the function type. The node size is determined by OFCV by default, where a higher OFCV results in a larger node. The node with the highest OFCV is highlighted by a star. Edges between nodes represent couplings, with their color and thickness determined through CV by default. A higher CV results in thicker and darker edges, and the edge with the highest CV is highlighted in red. The horizontal axis of the network represents agents, and the vertical axis represents stages. Their order is determined by the "Order of agent" table and the "Order of stage" table in the Tab "Agents, stages and variability manifestation frequencies." This page includes six components for interacting with the network: Toggle function name, Dropdown of function values, Dropdown of coupling values, Filter, Table of function information, and Box for function search.

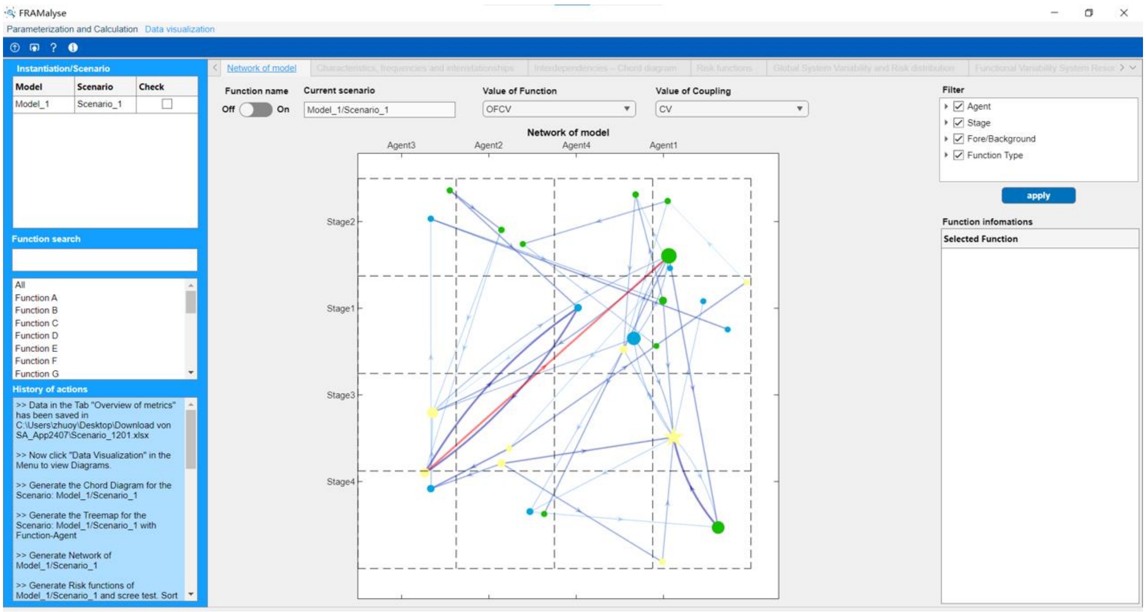


Figure 31: The "Network of model" tab after the user clicked the "Calculate metrics" button.

Click the "Toggle function name" button: By default, the switch is off, and the function name is not displayed. When the switch is turned on, the function name appears next to the corresponding node.

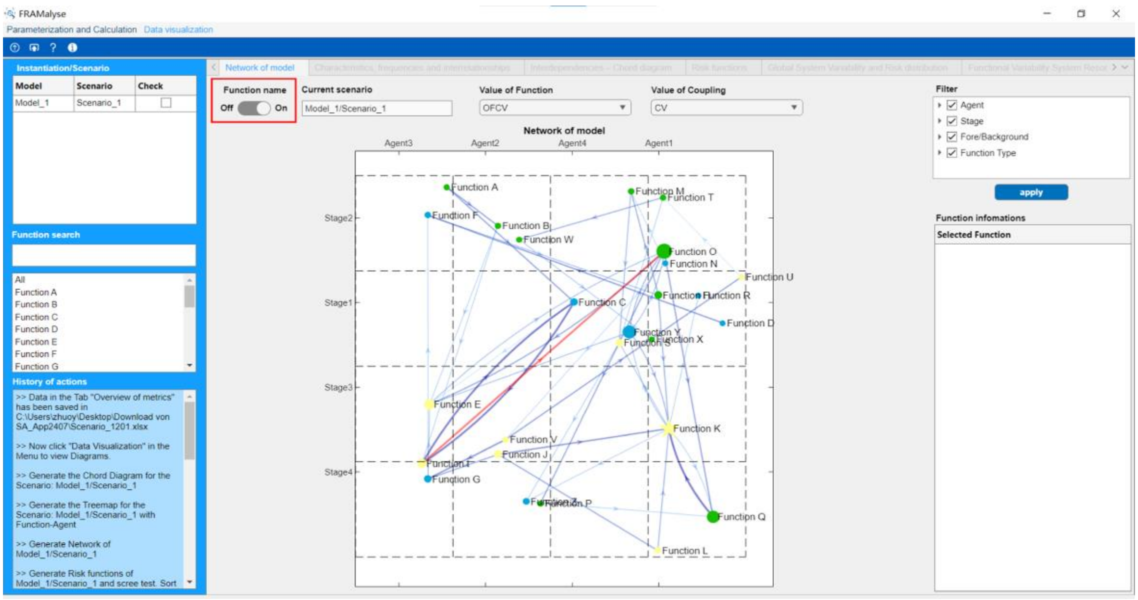


Figure 32: The network after switching the "Function name" to "on".

Click the "Dropdown of value of function" button: By default, the value of a function is OFCV. At this point, OFCV determines the size of the nodes, with the node having the highest OFCV highlighted as a star. In addition to OFCV, the Dropdown includes the following options:

- P_TE, P_OT, P_TL, P_NAA, P_I, P_A, P_PR,
- V_T, V_P, OV,
- DLFCV, ULFCV,
- N_DL, N_UL, Intra_stage, Intra_agent, Intrarelatedness,
- Inter_agent, Different_agent_count, Interrelatedness, Direct_feedback_loops, Indirect_loops_count, Indirect_loops_length, mean_loop, feedback_loop_factor,
- CTV, Katz, Incloseness, Outcloseness, Betweenness,
- N_DL_relativ, N_UL_relativ, Intrarelatedness_relativ, Interrelatedness_relativ, feedback_loop_factor_relativ, CTV_relativ, Katz_relativ, Incloseness_relativ, Outcloseness_relativ, Betweenness_relativ,
- WaU, WaD,
- DLFCV_relativ, ULFCV_relativ.

In the figure below, the Value of function has been changed to P_TE.

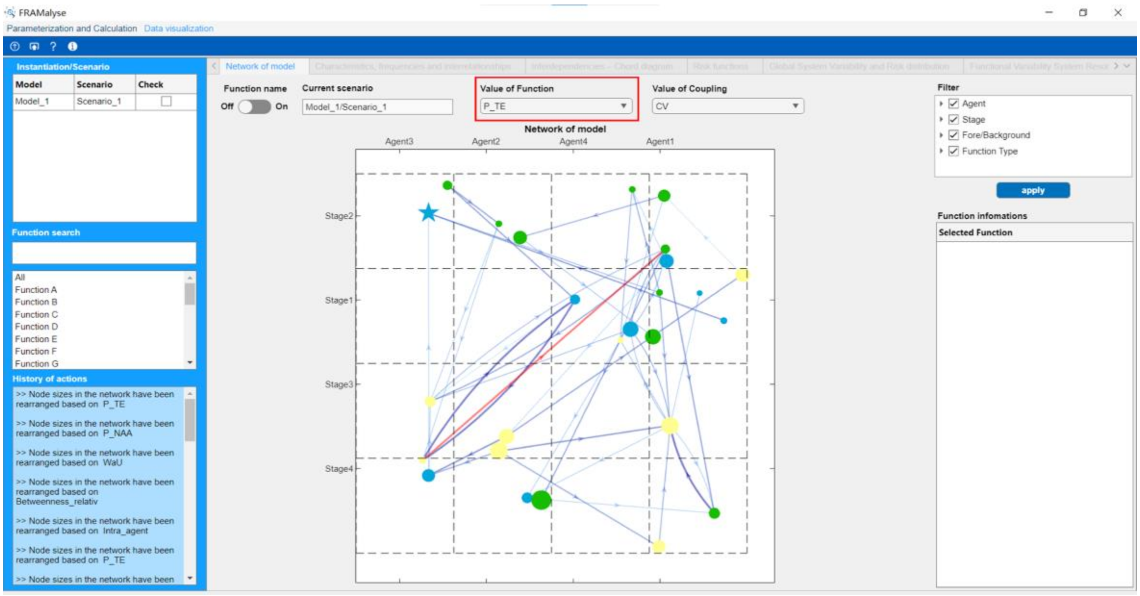


Figure 33: The network after changing the "Value of Function" Dropdown to "P_TE".

Click the "Dropdown of value of coupling" button: By default, the value of a function is CV. At this point, CV determines the color intensity and thickness of the edges. A higher CV results in thicker and darker edges, with the edge having the highest CV highlighted in red. In addition to CV, users can select other options via the "Dropdown of value of couplings," including: V_T, V_P, a_T, and a_P. In the figure below, the Value of couplings is set to V_T.

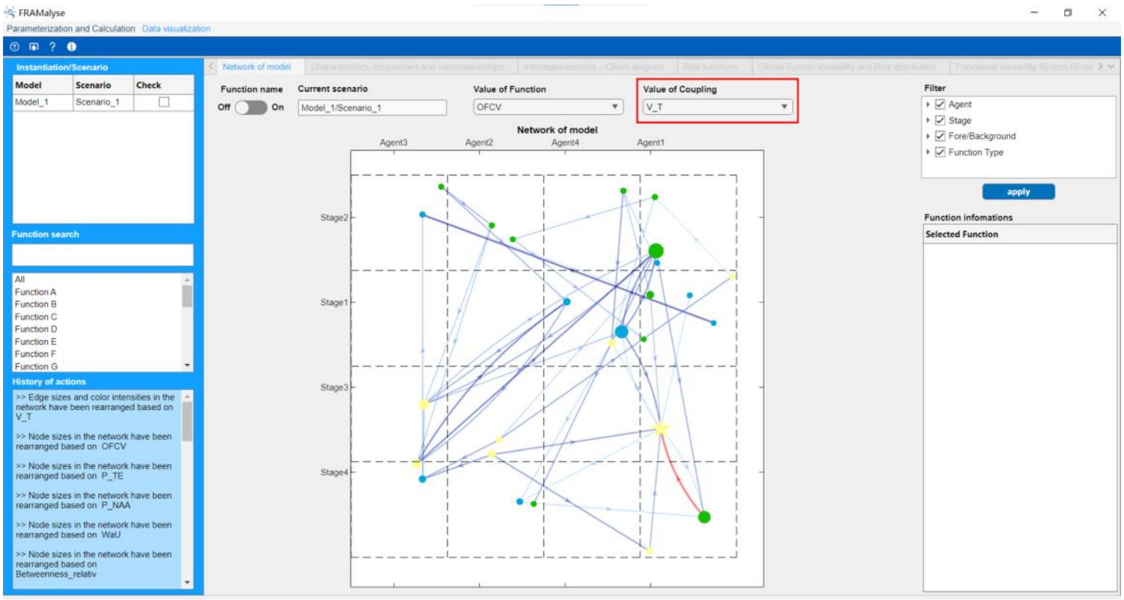


Figure 34: The network after changing the "Value of Coupling" Dropdown to "V_T".

Click the "Filter" and "apply" buttons: The Filter contains four primary filters: "Agent," "Stage," "Fore/Background," and "Function Type," each with several secondary filters. By default, all filter options are selected, displaying the entire network. Users can select specific filters and click the "apply" button to display functions and couplings that match the selected criteria. For example, in the figure below, Agent4 is excluded by the Filter. After clicking the "apply" button, all nodes belonging to Agent4 and their corresponding edges are hidden in the network.

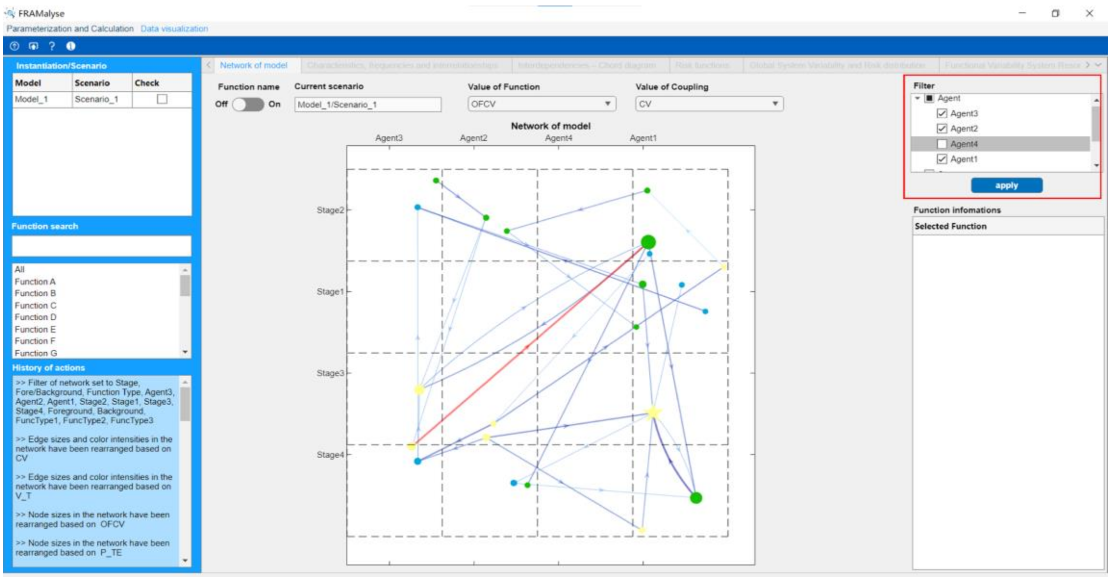


Figure 35: The network after filtering out all functions in Agent4.

Edit “Function search”: Users can view a specific function by clicking its name in the list. Alternatively, they can manually enter the function name in the "Function search" box, which brings the selected function to the top of the list. Additionally, the function can be selected directly by clicking near its node in the network.

When a user selects a specific function, the network displays only the selected function along with its upstream functions, downstream functions, uplinks, and downlinks. Uplinks are shown in orange, and downlinks in blue. If the "Toggle function name" is activated, the selected Function's name is highlighted in green. Meanwhile, the "Function information" table on the right displays details of the selected function, including:

- "Function Name",
- "Number of Uplinks",
- "Number of Downlinks",
- "Fore-Background",
- "Function Type",
- "Stage", "Agent",
- "Upstream functions | Aspect", and
- "Downstream functions | Aspect".

Users can continue interacting with the network via the "Dropdown of value of functions", "Dropdown of value of couplings", and "Filter". Additionally, the tab "Characteristics, frequencies and interrelationships" presents bar charts and a Sankey diagram of the selected function. Detailed information is provided in the "Characteristics, frequencies and interrelationships" Section. The figure below illustrates the changes after selecting "Function K" from the Function List.

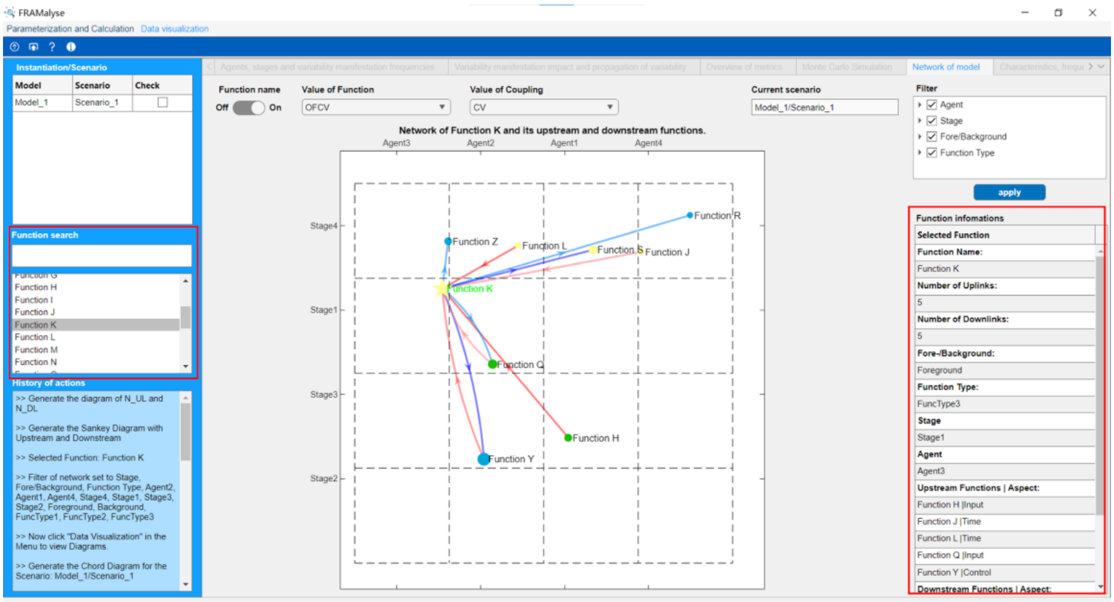


Figure 36: The network and the "Function information" table after the user clicked "Function K" in the "Function list".

3.3.1.2 Characteristics, frequencies and interrelationships

This tab displays the characteristics, frequencies, and interrelationships of functions in the scenario. The content is divided into four sections: at the top, from left to right, are the **Bar charts**, **Treemap**, and **Overall number of functions/couplings**, while the bottom section shows the **Sankey diagram**. The bar charts and Sankey diagram focus on a specific function within the scenario, while the treemap and overall number of functions/couplings pertain to the entire scenario. The figure below shows the result after calculating the metrics and clicking "Function K" in the function list.

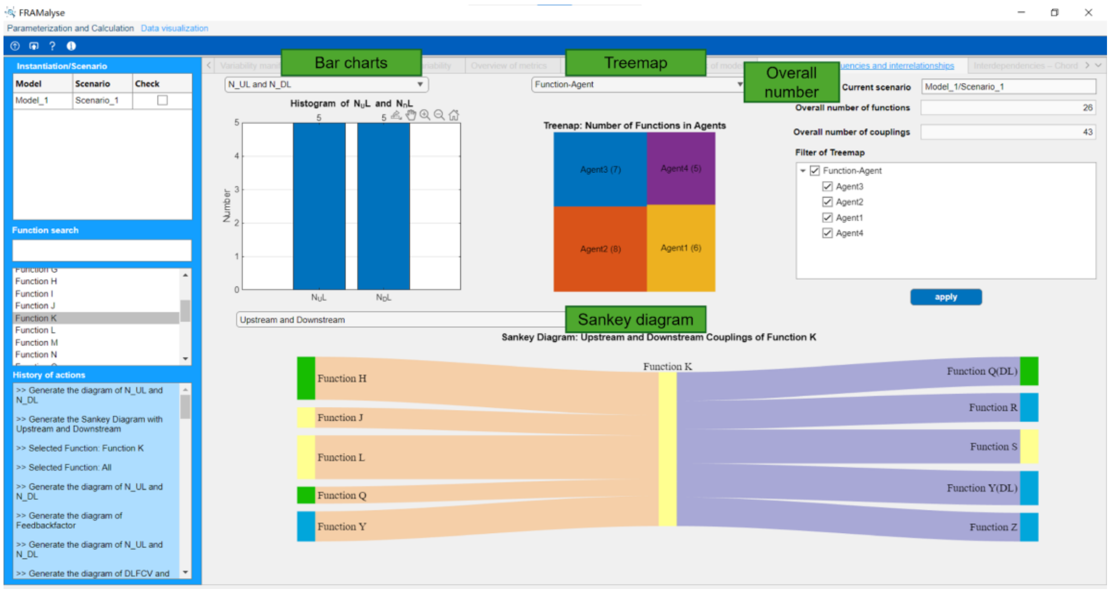


Figure 37: The "Characteristics, frequencies and interrelationships" tab after the user clicked "Function K" in the "Function list".

Bar charts: By clicking the Dropdown above the bar chart, a specific bar chart can be generated for the selected function. The Dropdown contains the following eleven options:

- N_UL and N_DL,
- DLFCV and ULFCV,
- OFCV,
- WaU and WaD,
- Intra- and Interrelatedness,
- Feedbackfactor,
- CTV and Katz,
- Betweenness, Incloseness, and Outcloseness,
- Phenotype Timing: Frequencies,
- Phenotype Precision: Frequencies, and
- Average of coupling variability.

The figure below shows the eleven bar charts for the selected "Function K."

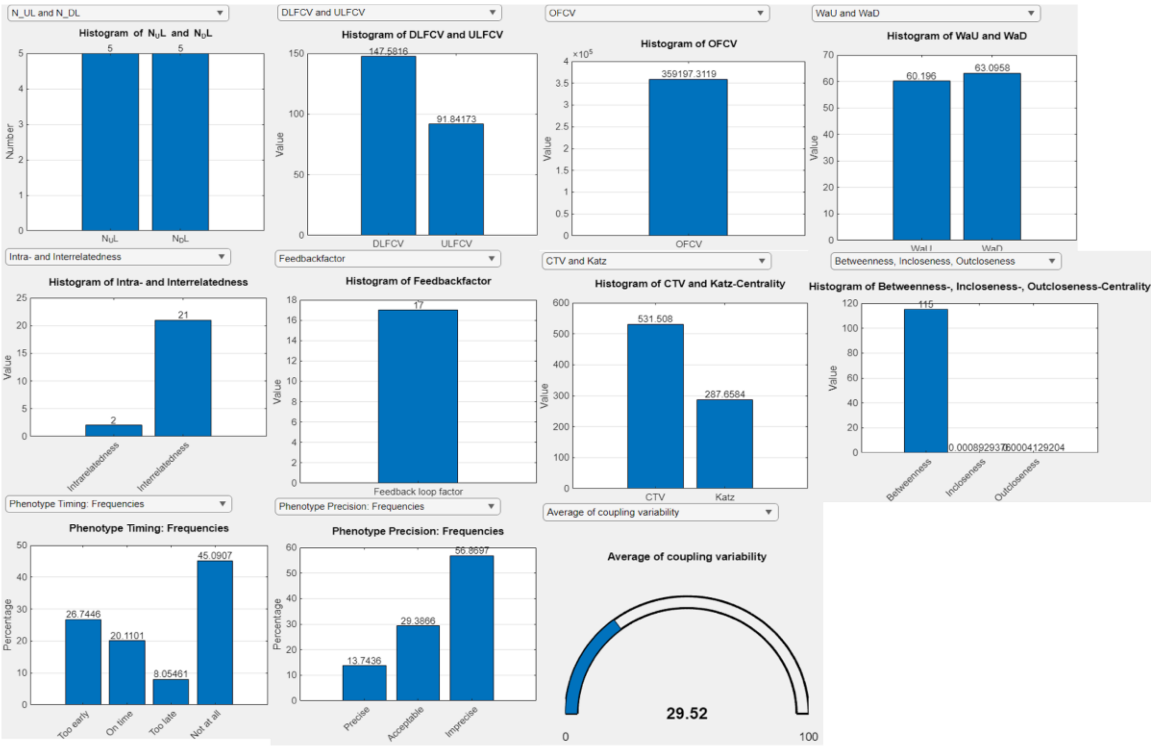


Figure 38: The eleven options in the Dropdown of the bar chart and their corresponding results.

Treemap: The Treemap visualizes the distribution of the number of functions or couplings based on different criteria. By selecting from the Dropdown menu above the Treemap, users can choose from the following 13 options:

- Function-Agent, Function-Stage, Function-Fore/Background, Function-Function Type,
- Coupling-Within Agent, Coupling-Within Stage, Coupling-Within Fore/Background, Coupling-Within Function Type, Coupling-Within Aspect,
- Coupling-Between Agents, Coupling-Between Stages, Coupling-Between Fore/Background, Coupling-Between Function Types.

The figure below presents the 13 treemaps for this scenario. For example, the Function-Agent Treemap illustrates the number of functions associated with each agent.

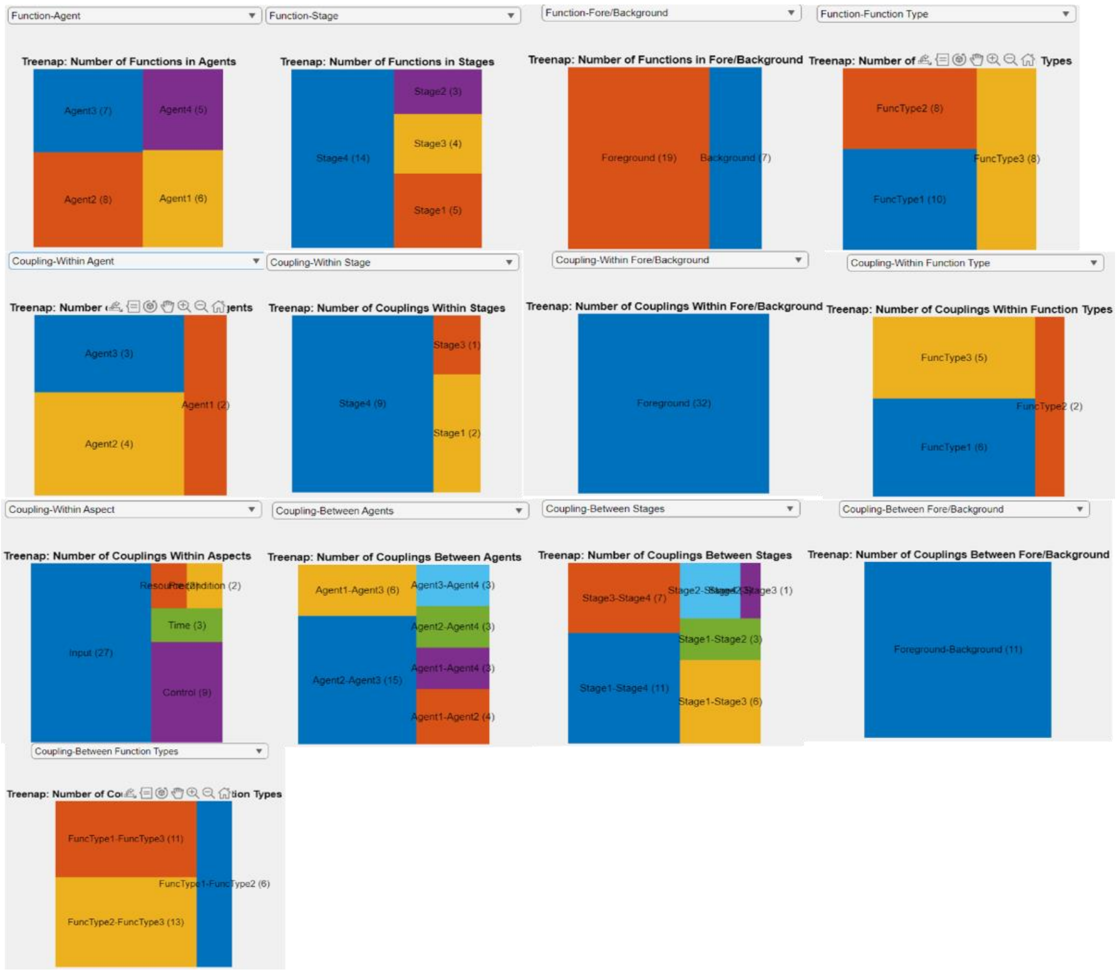


Figure 39: The thirteen options in the Dropdown of the Treemap and their corresponding results.

Users can also interact with the Treemap using the "Filter of Treemap" and the "apply" button. For example, by deselecting Agent4 in the "Filter of Treemap" and clicking "apply," the resulting Treemap appears as shown below.

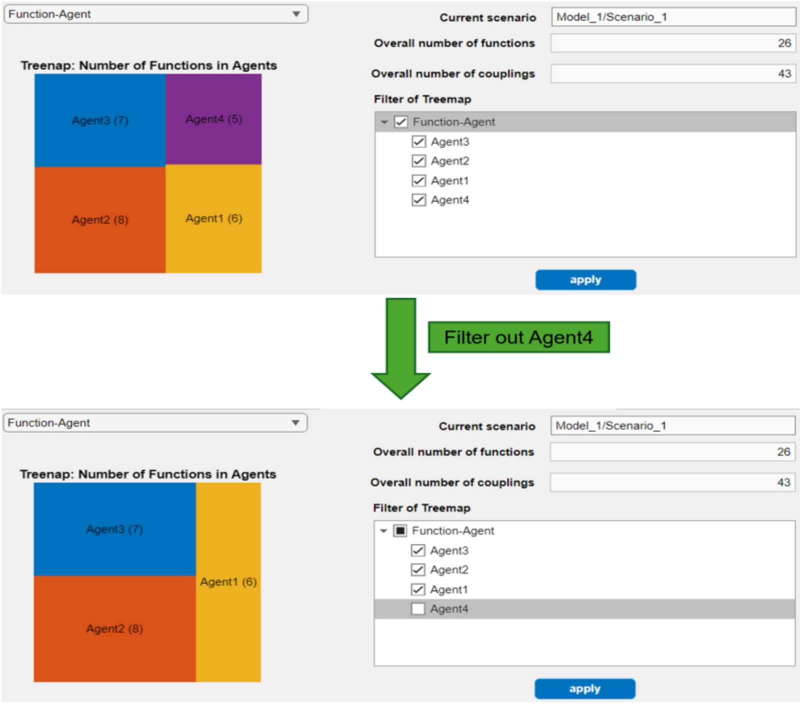


Figure 40: The Treemap after the user filtered out Agent4.

Overall number of functions/couplings: The top right corner of this tab displays the number of functions and couplings in the current scenario. For example, the figure below shows that the current scenario contains 26 functions and 43 couplings.

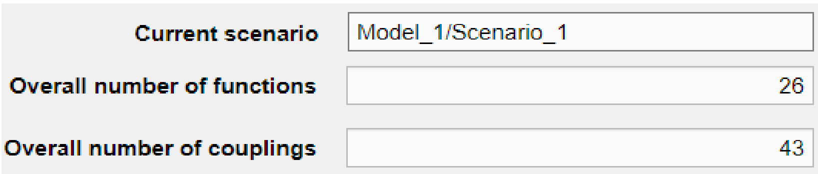


Figure 41: The overall number of functions/couplings in the current scenario.

Sankey diagram: At the bottom of the tab "Characteristics, frequencies and interrelationships", a Sankey diagram is displayed. When a user clicks on a function in the "Function list," the Sankey diagram for that function will appear here. The diagram consists of blocks representing functions and quantity flows representing couplings. The selected function is positioned in the center, with its upstream functions on the left and downstream functions on the right. The color of the blocks corresponds to the "Color of Function Type" defined in the "Agents, stages and variability manifestation frequencies" tab. Couplings between the selected function and its upstream functions are colored orange, while those between the selected function and its downstream functions are colored blue. The width of the quantity flows increases with the coupling's CV. When a user clicks on any point along a coupling, the relevant information about the coupling is displayed near the clicked spot. This information includes Upstream Function, Upstream Agent, Upstream Stage, Upstream Function Type, Downstream Function, Downstream Agent, Downstream Stage, Downstream Function Type, Aspect, CV, and Count. The figure below illustrates the Sankey diagram displayed when the user clicks on "Function K" in the "Function List," as well as the relevant information shown when clicking on the coupling between "Function H" and "Function K." To close the information window, the user must click the same spot again.

Note: When a function is both an upstream and downstream function of the selected function, the Sankey diagram will add "(DL)" after the downstream function node to distinguish it. "DL" stands for Downlink. See the red box in the figure below.

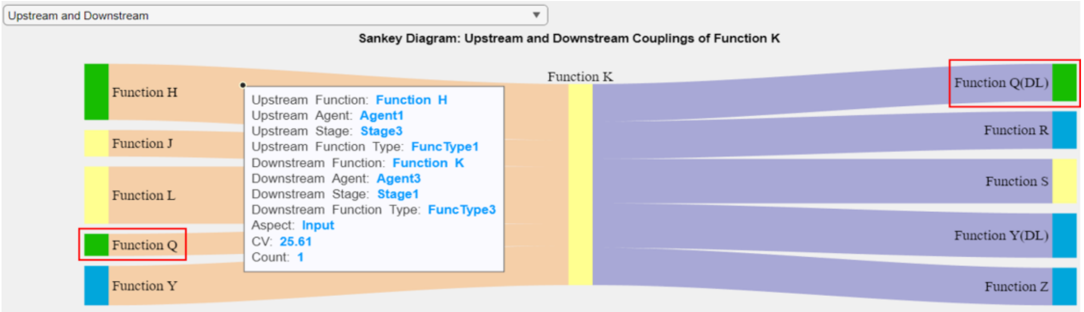


Figure 42: The Sankey diagram of Function K and its upstream and downstream functions.

Users can also interact with the Sankey diagram using the Dropdown menu above it. When "Upstream" is selected from the Dropdown, the Sankey diagram will display only the selected function and its upstream functions. When "Downstream" is selected, the diagram will show the selected function and its downstream functions only.

The Sankey diagrams in this section are generated using the MATLAB toolbox "Sankey plot" developed by Liu (2025). The treemaps are created using the MATLAB toolbox "Treemap" developed by Hicklin (2025).

3.3.1.3 Interdependencies – Chord diagram

This tab consists of three parts: Chord diagram, Filter, and Information table.

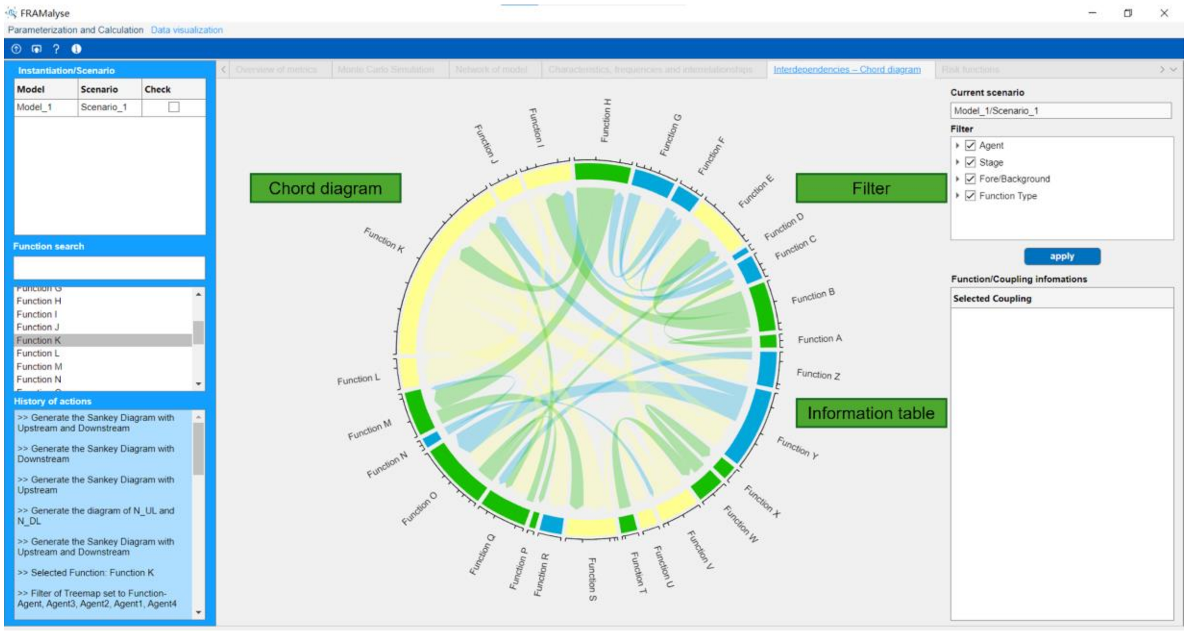


Figure 43: The "Interdependencies – Chord diagram" tab after the user clicked the "Calculate Metrics" button.

The Chord diagram radially illustrates the relationships between various functions in the current scenario. This figure enhances the network representation by an improved visualization of the connectedness between functions. It is composed of nodes and edges. nodes represent functions, with colors defined by the "Color of function type" in the "Agents, stages and variability manifestation frequencies" tab. Edges represent couplings, with arrows at the ends to indicate the direction of the coupling. The color of the edges is determined by the upstream function.

When a user clicks on a node or edge in the Chord diagram, it is highlighted with a red box, and related information is displayed in the Information table.

- Clicking on a node shows details such as: "Function Name", "Number of Uplinks", "Number of Downlinks", "ULFCV", "DLFCV", "Fore-Background", "Function Type", "Stage", "Agent", "Upstream functions | Aspect", and "Downstream functions | Aspect" (See the figure below).
- Clicking on an edge displays details including: "Upstream Function", "Downstream Function", "Description of Aspect", "Aspect", "CV", and "Count" (See the figure below).

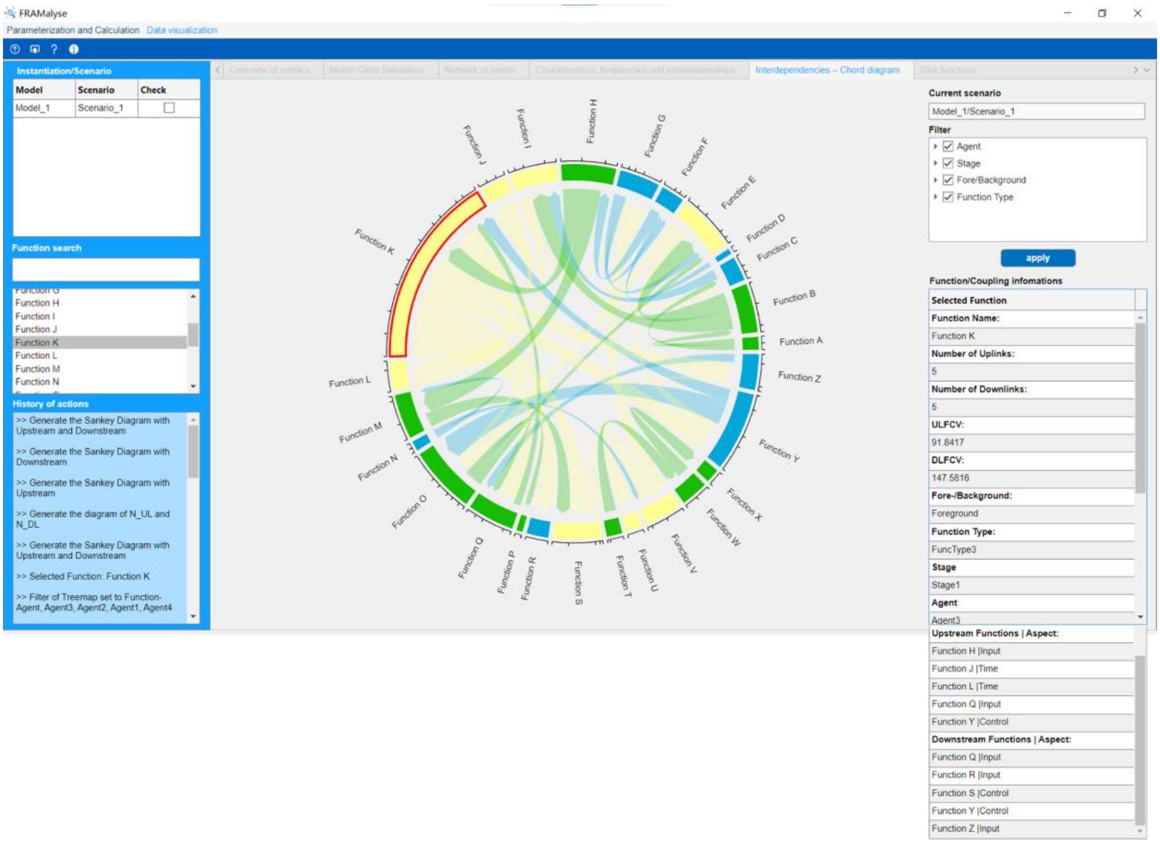


Figure 44: The "Chord Diagram" and "Information Table" after the user clicked "Function K" in the Chord Diagram.

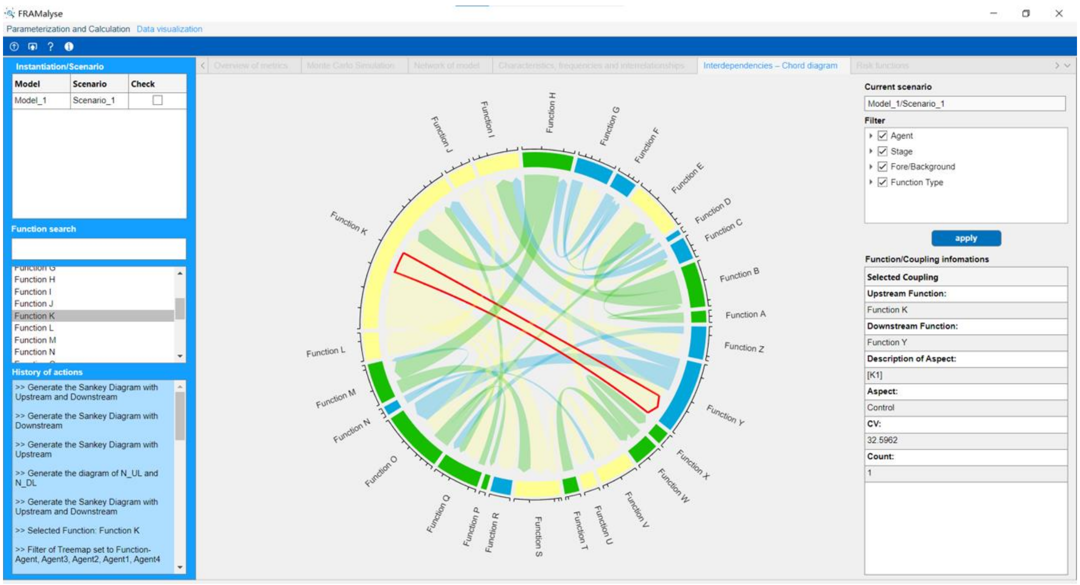


Figure 45: The "Chord Diagram" and "Information Table" after the user clicked a coupling in the Chord Diagram.

Additionally, users can interact with the Chord diagram through the Filter. The filter consists of four primary filters: "Agent," "Stage," "Fore/Background," and "Function Type," each divided into several secondary filters. For example, in the figure below, "Agent3" is excluded using the filter, and after clicking the "apply" button, the resulting Chord diagram is shown.

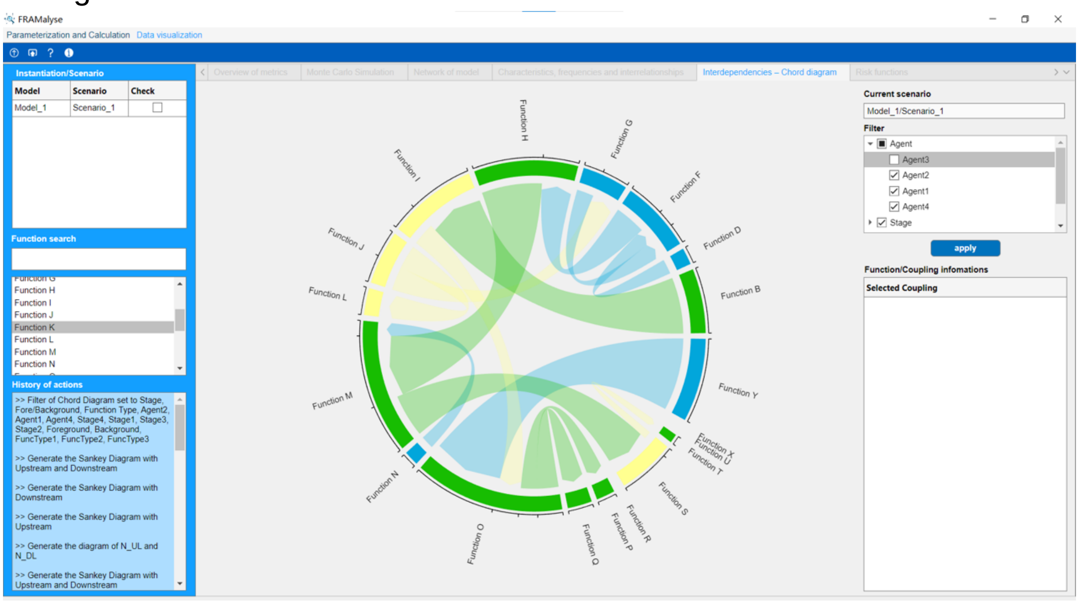


Figure 46: The "Interdependencies – Chord Diagram" tab after the user filtered out all functions of Agent3.

The Chord diagrams are generated using the MATLAB toolbox "Sankey plot" developed by Liu (2025).

3.3.2 Advanced Evaluation

In this section, users can define the risk functions of scenarios and conduct analysis and comparison.

3.3.2.1 Risk functions

This tab consists of the following components: a central coordinate area, a Dropdown menu at the top, the "Current scenario" box, the table "List of risk functions," and the "Analyse" button.

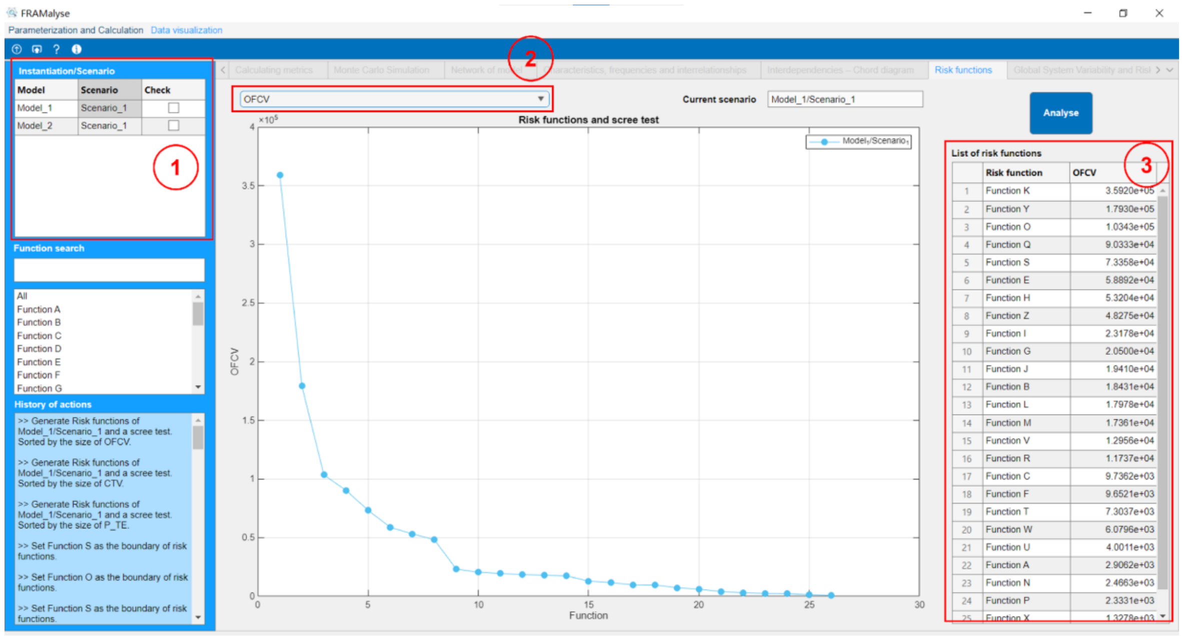


Figure 47: The "Risk Functions" tab after generating scenarios.

In this tab, users can define risk functions for scenarios to facilitate subsequent analysis. The process of defining risk functions consists of three steps:

1. **Click Scenario:** Clicking on a scenario in "Instantiation/Scenario" on the left generates a line chart in the central coordinate area. The horizontal axis represents functions, while the vertical axis defaults to OFCV. The chart arranges the functions of the selected scenario in descending order of OFCV. The "Current scenario" box in the upper-right corner displays the scenario name, and the table on the right lists the functions and their OFCV values in descending order.
2. **Click Dropdown:** Users can select alternative metrics from the Dropdown menu. The system will reorder the functions based on the selected metric and update both the line chart and the table "List of risk functions".
3. **Click the Table "List of risk functions":**
   a) In the Table "List of risk functions," first select a Function (e.g., Function K in the figure) by left-clicking it with the mouse. Then, right-click on the selected Function and choose the menu item "Set as the boundary of risk functions." The selected function will be highlighted in red in the table. Next, repeat the same steps for another function (e.g., Function S in the figure). The system will highlight both functions and all the functions between them in red. These highlighted functions are defined as the risk functions for the current scenario. Simultaneously, a red dashed box encompassing these functions will appear in the line chart of the

coordinate area, completing the definition of the risk functions for the current scenario. (As shown in the figure below)

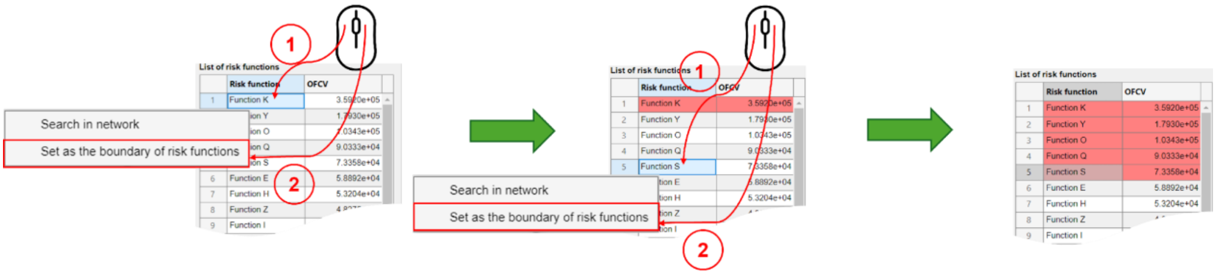


Figure 48: The process of defining risk functions.

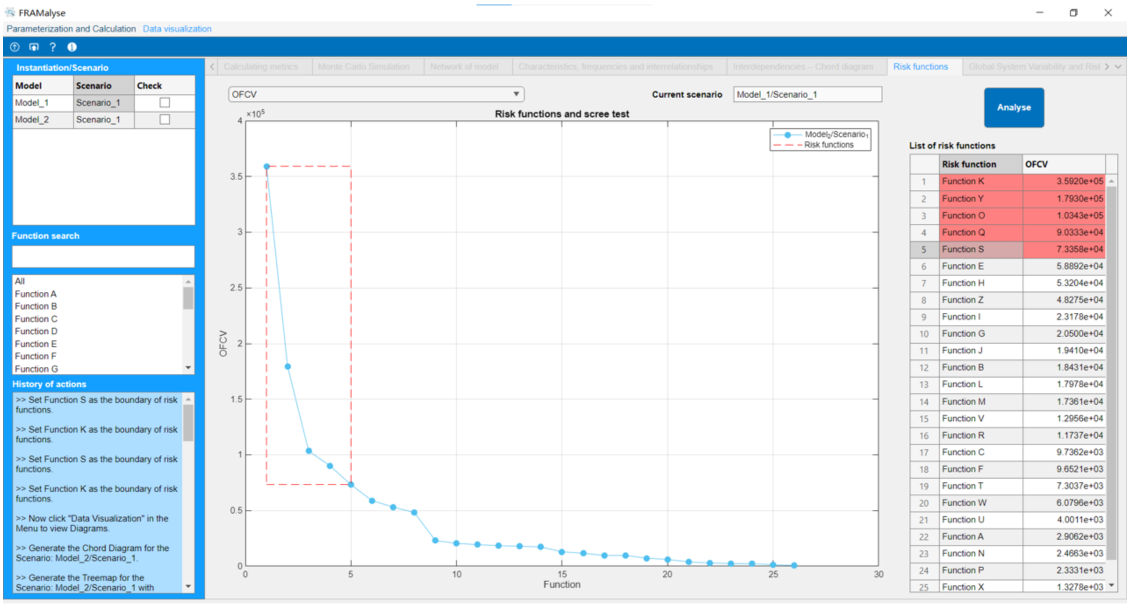


Figure 49: The "Risk functions" tab after defining the risk functions.

b) After defining the risk functions, if other functions need to be redefined as boundaries, the same two steps can be applied to the other functions. (e.g., Function O and Function S in the figure)

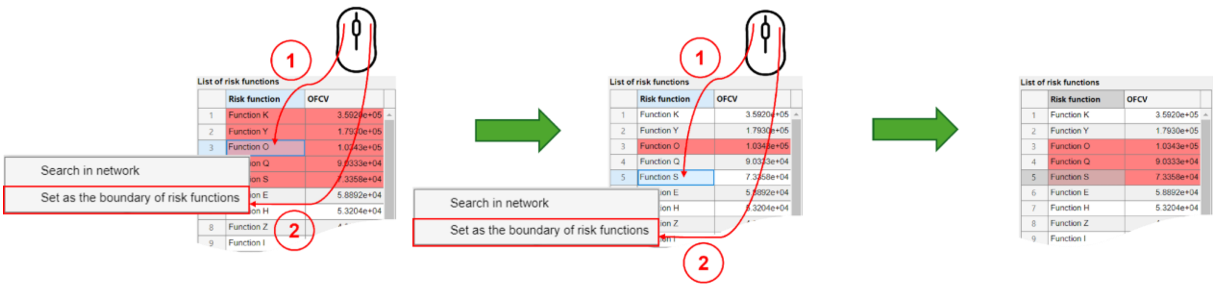


Figure 50: The process of redefining the risk functions after they have been initially defined.

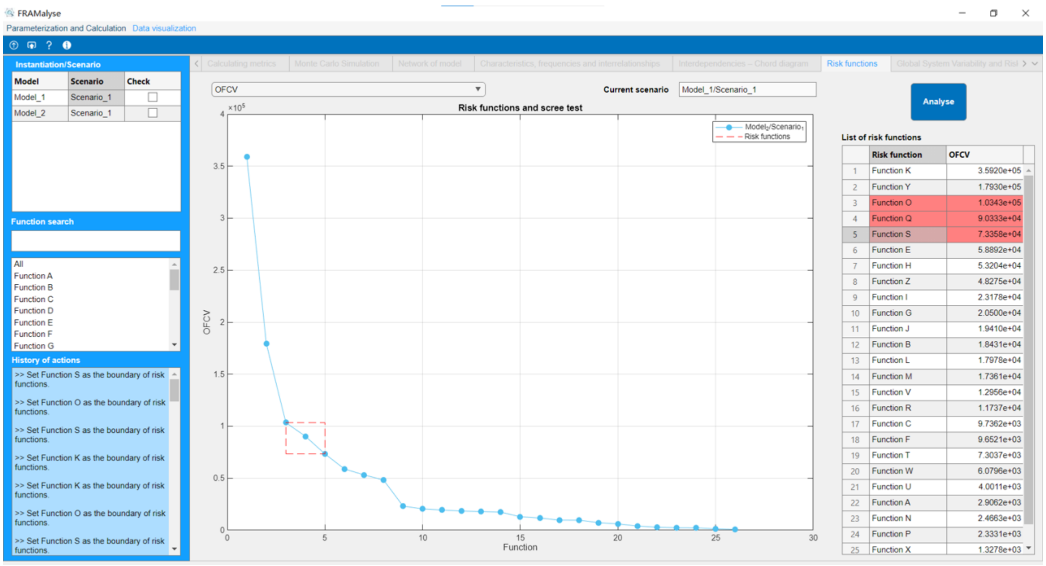


Figure 51: The "Risk functions" tab after redefined the risk functions.

c) After defining the risk functions, if the metric in the Dropdown menu is changed, the red highlights in the table and the red dashed box in the coordinate area will be cleared, requiring the risk functions for the current scenario to be redefined. For example, changing the metric in the Dropdown menu from OFCV to CTV results in the outcome shown in the figure below.

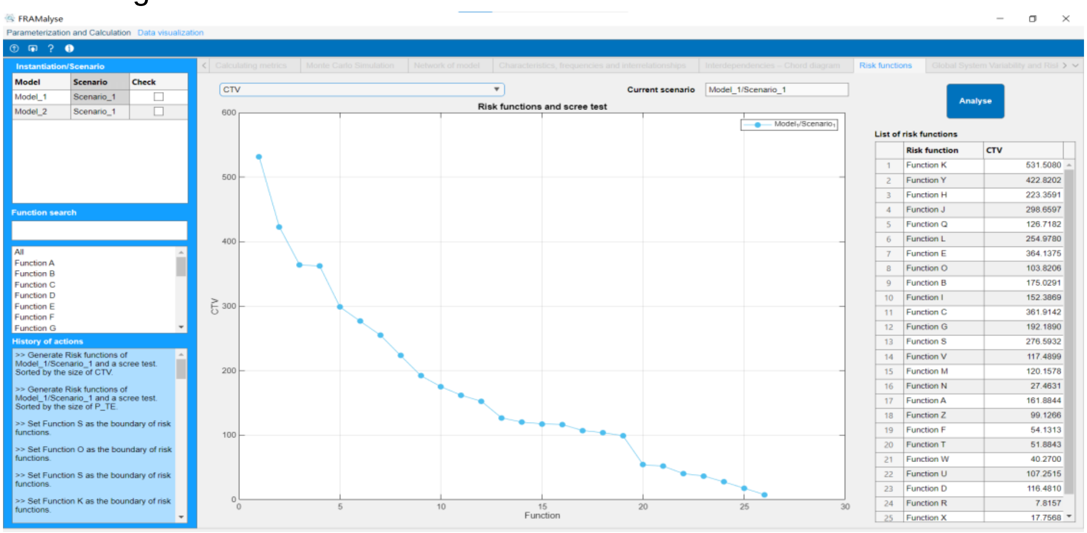


Figure 52: Changing the value in the DropDown after defined the risk functions.

d) If the user selects the “Search in network” option from the menu of a function, it is equivalent to selecting that function in the left-hand Function list (see “Network of model” and “Characteristics, frequencies and interrelationships”). As a result, the relevant information for the function will be displayed in the "Network of model" tab, and the bar charts and Sankey diagram for the Function will be generated in the "Characteristics, frequencies and interrelationships" tab. The page will navigate to the "Network of model" tab.

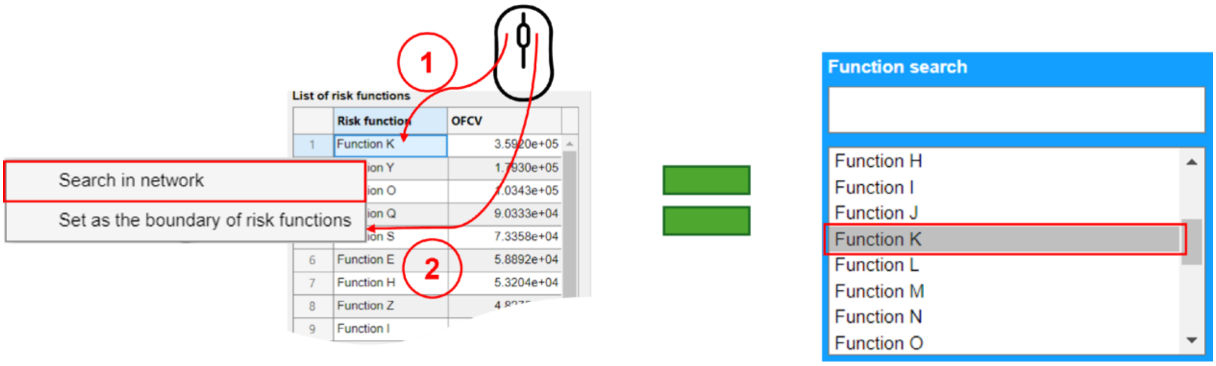


Figure 53: Clicking the "Search in network" menu is equivalent to selecting the corresponding function in the "Function list".

The user can repeat the above three steps to define risk functions for multiple scenarios. Then, the user can check the scenarios to be analyzed in the "Check" column of the left-hand table "Instantiation/Scenario" and click the "Analyse" button at the top-right of the tab. After the analysis is complete, the page will automatically navigate to the tab "Risk distribution and Global System Variability."

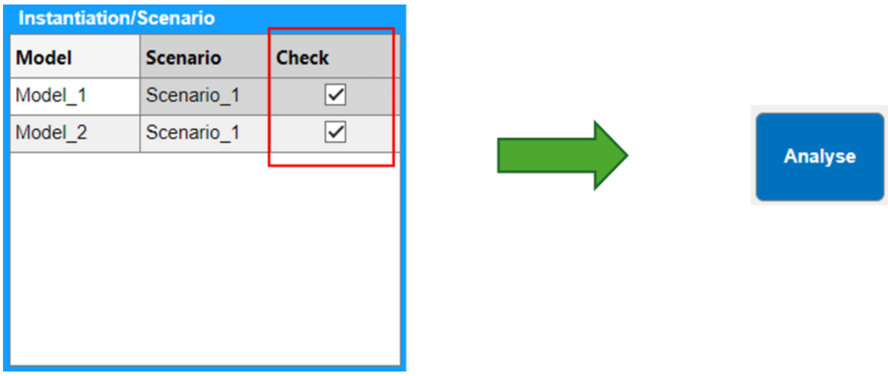


Figure 54: Select the scenarios to analyze by checking the boxes in the "Check" column of the "Instantiation/Scenario" table, then click the "Analyse" button.

3.3.2.2 Global System Variability and Risk distribution

In this tab, the Global System Variability and Risk distribution of the scenarios are analyzed and compared. These scenarios and their risk functions are selected by the user in the "Risk function" tab. This tab consists of two horizontal bar charts, each with its own Dropdown menu and filter options.

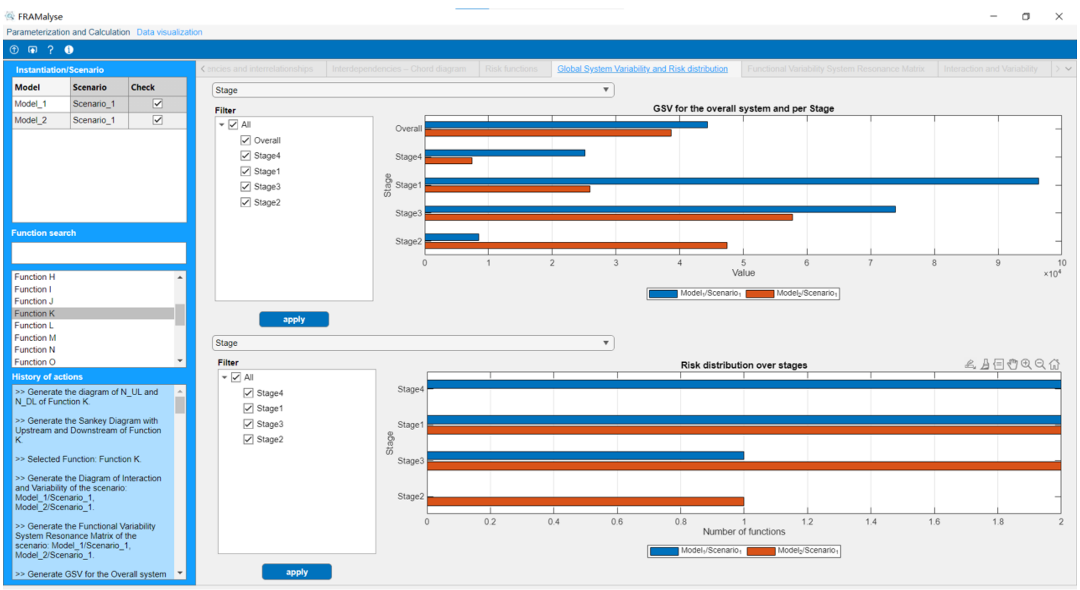


Figure 55: The "Global System Variability and Risk Distribution" tab after the user clicked the "Analyse" button.

The upper horizontal bar chart, by default, displays the Global System Variability (GSV) for the overall system and per stage for each scenario. The x-axis represents the GSV values, and the y-axis lists the “Overall” and all the stage types in the scenarios. Different scenarios are distinguished by different colors. Interaction with the horizontal bar chart can be achieved by configuring the filter and Dropdown menu on the left side of the chart.

Set the Filter: The user can select the options to be compared in the filter and click the "apply" button below to generate a horizontal bar chart containing only those selected options. For example, in the figure below, "Stage1," "Stage3," and "Stage2" are selected.

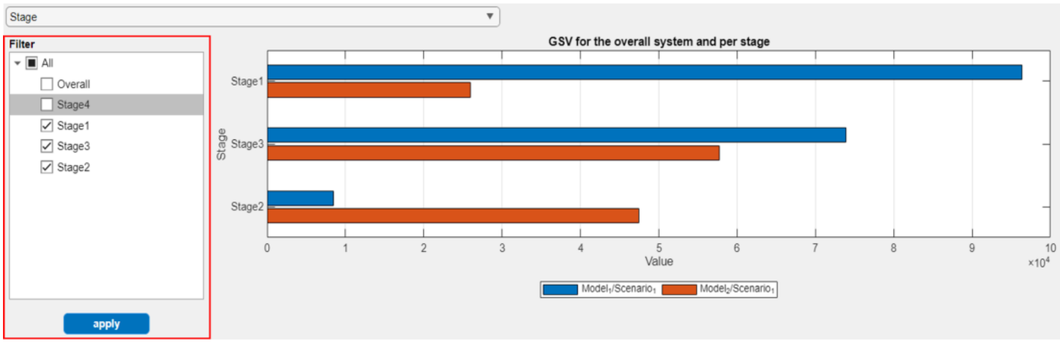


Figure 56: The "GSV for the overall system and per stage" horizontal bar chart after filtered out the "Overall" and "Stage4" options.

Set the Dropdown Menu: The default option in the Dropdown menu is "Stage". The user can also click the Dropdown and select "Agent" or "Type of Function" to generate the corresponding horizontal bar chart.

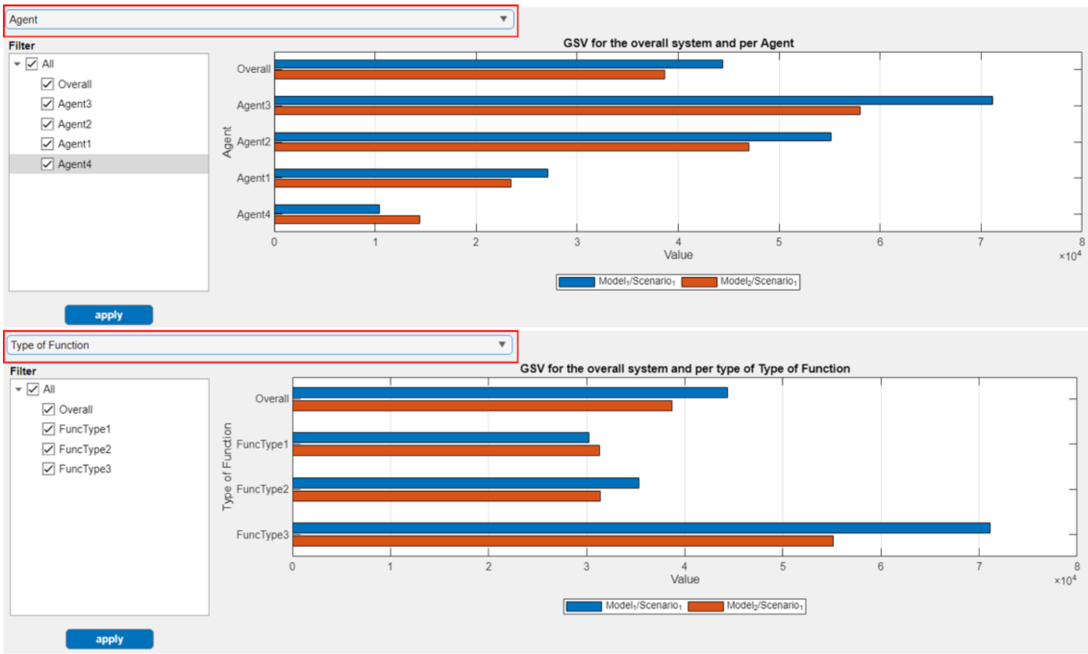


Figure 57: The "GSV for the overall system and per stage" horizontal bar chart when the dropdown values are set to "Agent" and "Type of Function".

The lower horizontal bar chart, by default, displays the distribution of risk functions across different stages for each scenario. The x-axis represents the number of functions, and the y-axis, by default, lists all stages in the scenarios. The user can interact with the chart through the filter and Dropdown menu on the left. In the following example: In Scenario "Model_1/Scenario_1," the risk functions are defined as “Function K,” “Function Y,” “Function O,” “Function Q,” and “Function S.” In Scenario "Model_2/Scenario_1," the Risk functions are defined as “Function O,” “Function Q,” “Function S,” “Function E,” and “Function Z.”

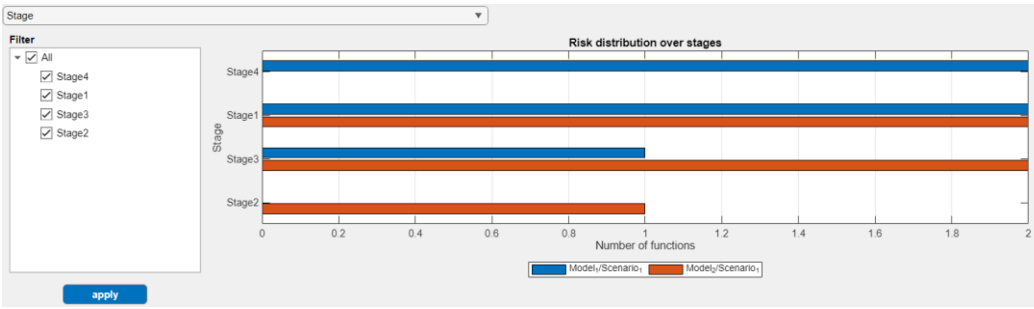


Figure 58: The "Risk distribution over stages" horizontal bar chart after the user clicked the "Analyse" button.

Set the Filter: The user can select options in the filter and click the "apply" button to generate a horizontal bar chart that meets the filter criteria. For instance, in the figure below, "Stage3" and "Stage2" are selected, and after clicking the "apply" button, the generated horizontal bar chart only displays the number of risk functions in Stage3 and Stage2.

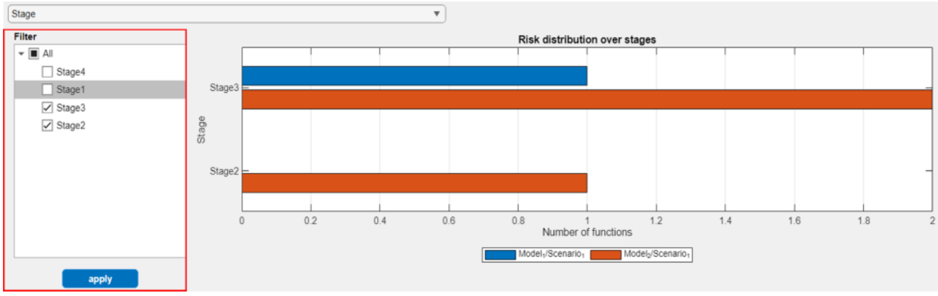


Figure 59: The "Risk distribution over stages" horizontal bar chart after filtered out the " Stage4" and "Stage1" options.

Set the Dropdown Menu: The Dropdown menu defaults to "Stage," but the user can also select "Agent" or "Type of Function" from the Dropdown to generate the respective horizontal bar chart.

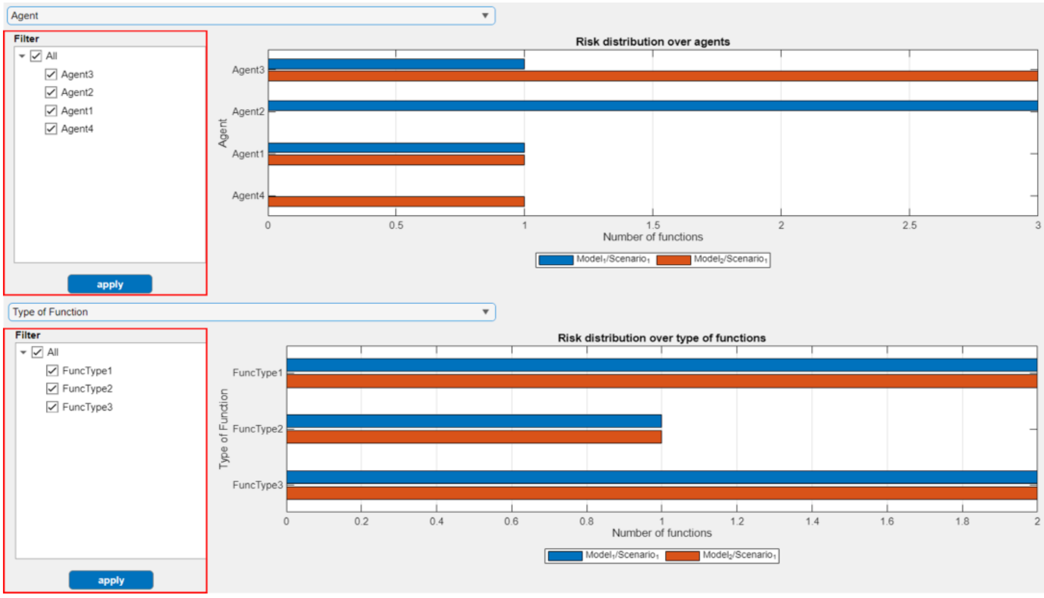


Figure 60: The " Risk distribution over stages " horizontal bar chart when the dropdown values are set to "Agent" and "Type of Function".

3.3.2.3 Functional Variability System Resonance Matrix

The middle section of this tab generates a Functional Variability-System Resonance Matrix (FVSRM), according to Grabbe et al. (2022), for each scenario. This matrix represents the criticality of functions and their potential for functional resonance across two dimensions: functional variability (DLFCV + ULFCV) and system resonance (WaU + WaD). The horizontal axis of the matrix represents functional variability (DLFCV + ULFCV), and the vertical axis represents system resonance (WaU + WaD). Each axis is divided into three intervals by two boundaries, resulting in nine regions in the matrix. By default, the lower boundary is set at 5%, and the upper boundary at 30%. The FVSRM displays the following areas: green (C-C, C-B, B-C) for uncritical functions, blue (A-C) for highly variable functions with low system resonance, yellow (B-B) for medium variability and medium system resonance (functions between uncritical and critical), orange (C-A) for low variability but high system resonance, and red (B-A, A-A, A-B) for critical functions. The number within each rectangular region indicates the number of functions located in that area.

Figure 61: The "Functional Variability System Resonance Matrix" tab after the user clicked the "Analyse" button.

Users can interact with the matrices in three ways: setting the boundaries, clicking areas on the matrices, or clicking the table.

Set the boundaries: Users can modify the lower and upper boundaries in the top-right corner of the tab and click the "Set" button. The system will then update the matrices and the images on the "Interaction and Variability" tab according to the new boundaries. For example, in the figure below, the lower boundary is changed from 5% to 10%, and the upper boundary from 30% to 40%, with the updated result shown below.

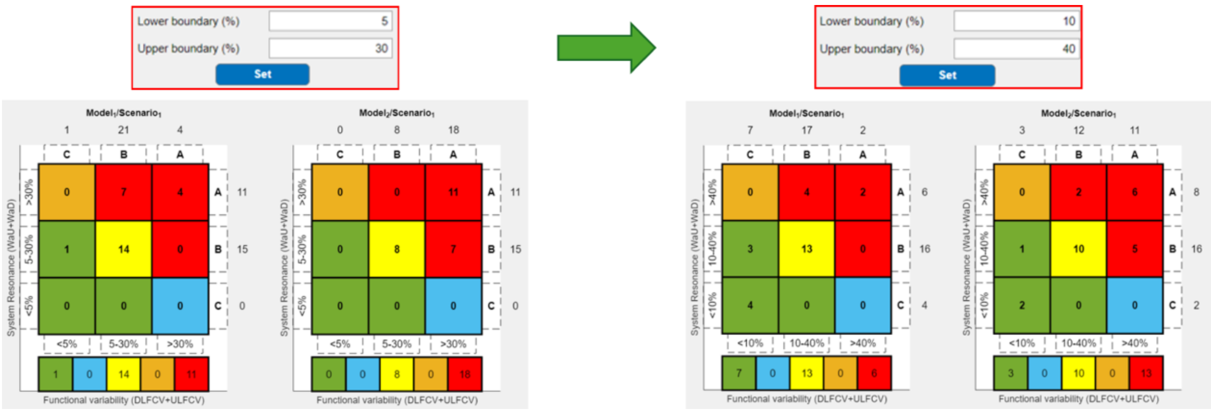


Figure 62: The change in the Functional Variability System Resonance Matrix after modifying the values of the "Lower Boundary" and "Upper Boundary".

Click areas on the matrices: When the user clicks on a colored area or the letters "A," "B," or "C" in the matrices, the corresponding region in the matrix will be highlighted in blue, and the names of the functions in that area will be displayed in the table on the right. For instance, in the figure below, the user clicked on the yellow area of Scenario "Model_1/Scenario_1," with the resulting output shown.

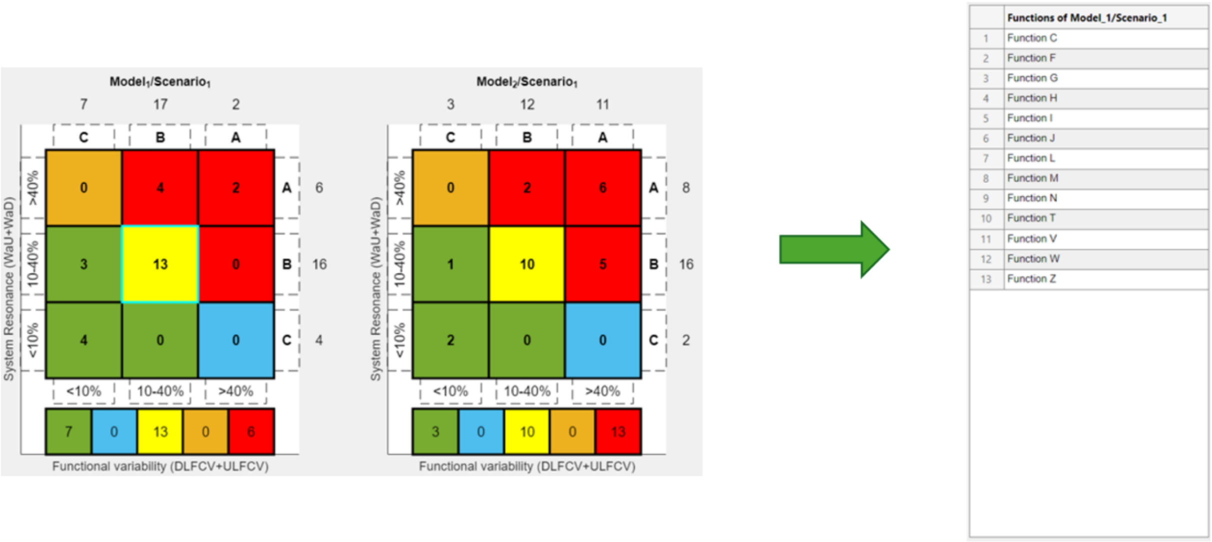


Figure 63: After clicking the yellow area of the "Model_1/Scenario_1" matrix, the functions within that area are displayed in the table on the right.

Click the table: The user can left-click on a function name in the table, then right-click the function to open the menu and select the "Search in network" option. This action is equivalent to selecting the function from the left-hand function list (see "Network of model" and "Characteristics, frequencies and interrelationships"). Consequently, the function's relevant information will be displayed in the "Network of model" tab, and its bar charts and Sankey diagram will be generated in the "Characteristics, frequencies and interrelationships" tab. The page will automatically navigate to the "Network of model" tab.

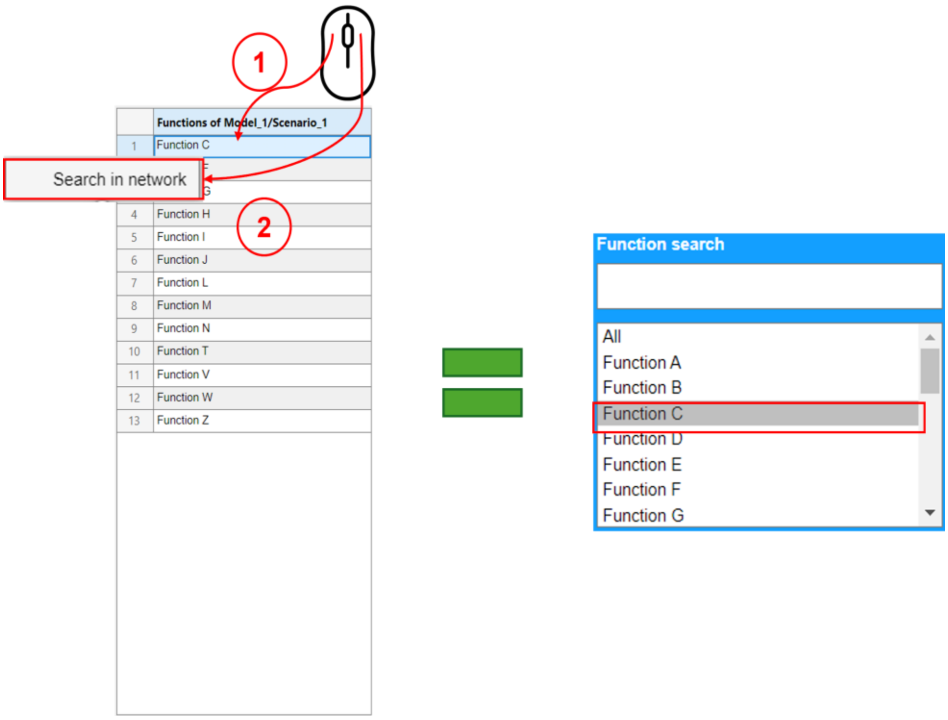


Figure 64: Clicking the "Search in network" menu is equivalent to selecting the corresponding function in the "Function list".

3.3.2.4 Interaction and Variability

Users can conduct a detailed analysis of risk functions across different scenarios from the two dimensions of functional variability and system resonance, as shown in the figure below. The figure illustrates the risk functions of two scenarios, depicting functional variability (DLFCV and ULFCV as stacked bar charts on the left y-axis) and system resonance (WaU and WaD as stacked line markers on the right y-axis). The red dashed line indicates high functional variability, while the blue dashed line represents high system resonance. Their thresholds are defined by the "Upper boundary" in the "Functional Variability System Resonance Matrix" tab. The background color of the risk functions corresponds to the color of their respective regions in the matrix within the "Functional Variability System Resonance Matrix" tab. Note that for a single scenario, one image is generated showing its risk functions. For two or more scenarios, an image for each scenario is created, each containing a compilation of risk functions from all scenarios.

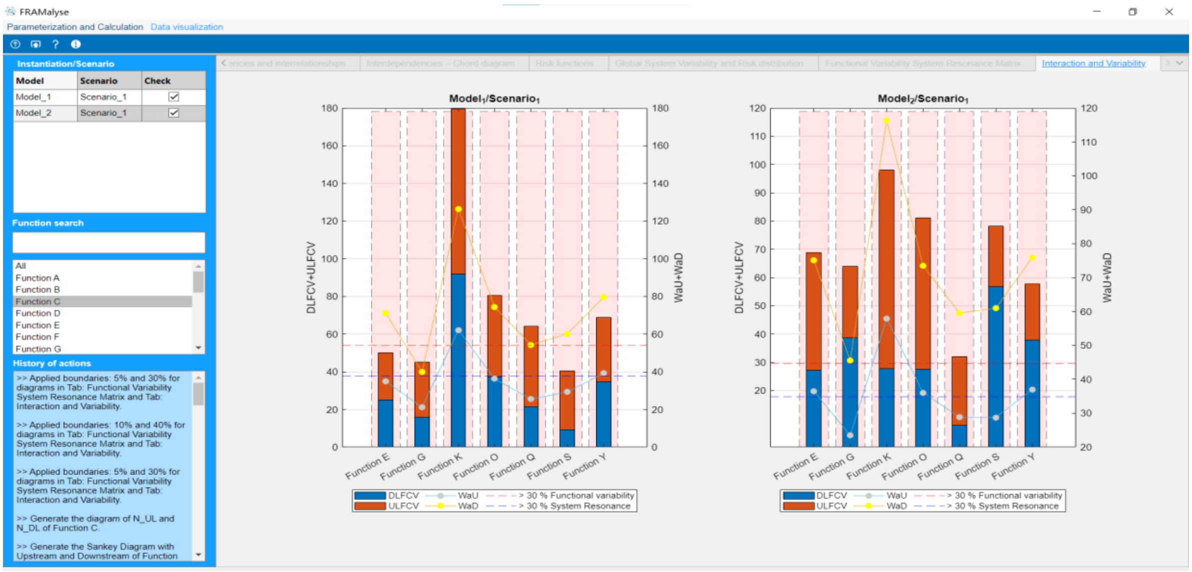


Figure 65: The “Interaction and Variability” tab after the user clicked the "Analyse" button.

3.4 Other

Users can further interact with diagrams displayed in the app by moving the mouse to the top-right corner of the corresponding diagram. Seven buttons will appear, listed from left to right as follows:

- Export: Displays a menu of export options.
- Brush: Toggles data brushing mode.
- Data Cursor: Toggles data cursor mode.
- Pan: Toggles pan mode.
- Zoom In: Toggles zoom-in mode.
- Zoom Out: Toggles zoom-out mode.
- Restore View: Restores the original view of axes or the tiled chart layout.

When users click on "Export," a Dropdown menu will open, offering three download options, listed from top to bottom as follows:

- Save the content as a tightly cropped image or PDF.
- Copy the content as an image.
- Copy the content as a vector graphic.

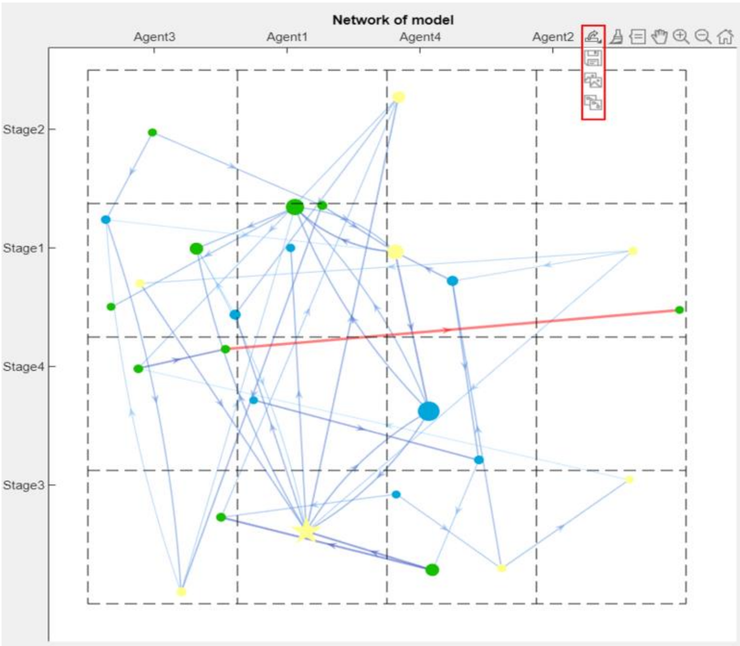
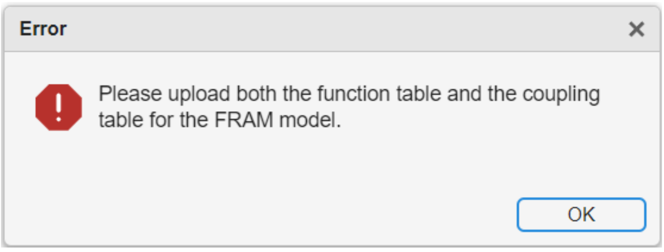


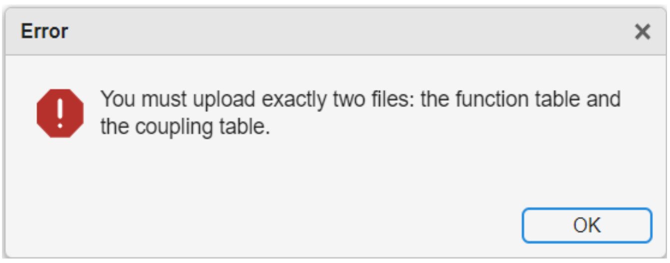
Figure 66: Interaction options for the "Network of model" diagram.

4 Troubleshooting

This section helps to resolve problems or errors you may encounter while using FRAMalyse. For all the issues listed below, follow the solutions provided. If these don't fix the issue, then there might be a problem in the source code and contact the developer.

Problem with Uploading Model Data:

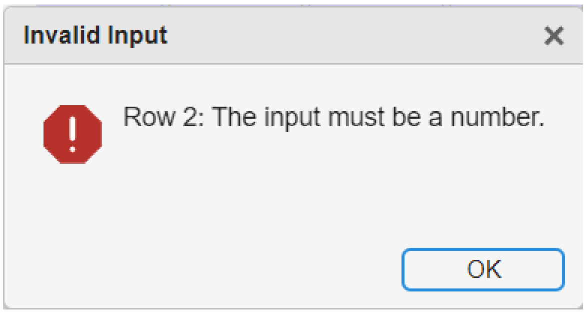


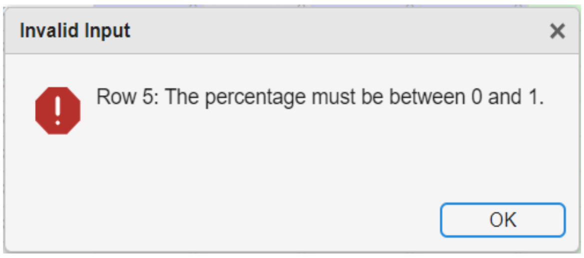


<u>Causes:</u> The user uploaded either one file or more than three files.

<u>Solution:</u> Re-upload the files, ensuring that both "Overall_FRAM_model-functions" and "Overall_FRAM_model-couplings" are uploaded together. These files can be obtained using the FMV app.

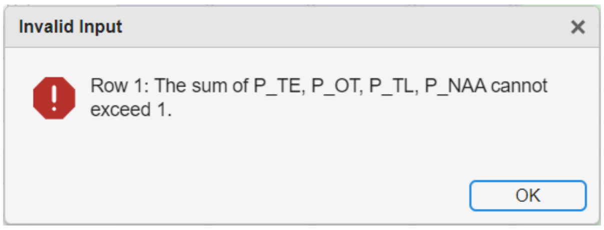
Problem with the definition of P_TE, P_OT, P_TL, P_NAA, P_I, P_A, and P_PR:

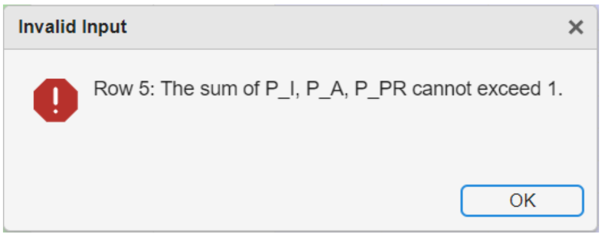




<u>Cause:</u> P_TE, P_OT, P_TL, P_NAA, P_I, P_A, and P_PR must be numbers between 0 and 1. They cannot be letters or numbers outside this range.

<u>Solution:</u> Re-enter valid numbers.

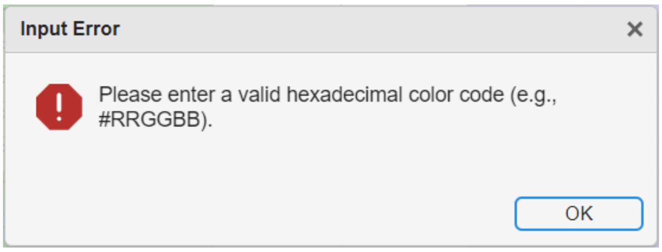




<u>Cause:</u> The sum of P_TE, P_OT, P_TL, and P_NAA is not equal to 1; the sum of P_I, P_A, and P_PR is not equal to 1.

<u>Solution:</u> Ensure that the sum of P_TE, P_OT, P_TL, and P_NAA equals 1; the sum of P_I, P_A, and P_PR must also equal 1.

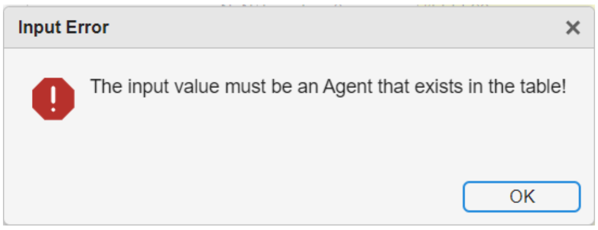
Problem with the definition of "Color of function type":

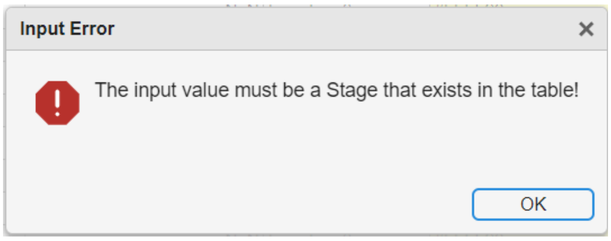


Cause: The input value is not a valid hexadecimal color code.

Solution: Double-click the cell to open the Dropdown and select a recommended value or enter a valid hexadecimal color code.

Problem with editing the tables "Order of Agent" and "Order of Stage":

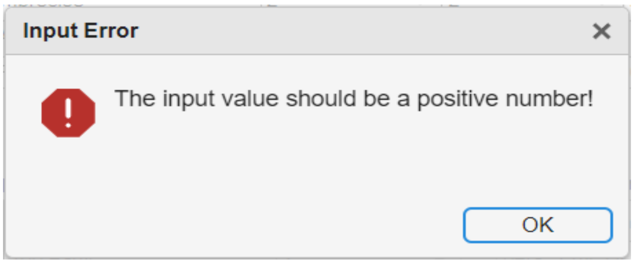




Cause: The user attempts to define the order for an Agent or Stage that does not exist in the Scenario.

Solution: Modify the input values in the tables "Order of Agent" and "Order of Stage" to ensure they match Agents and Stages present in the Scenario.

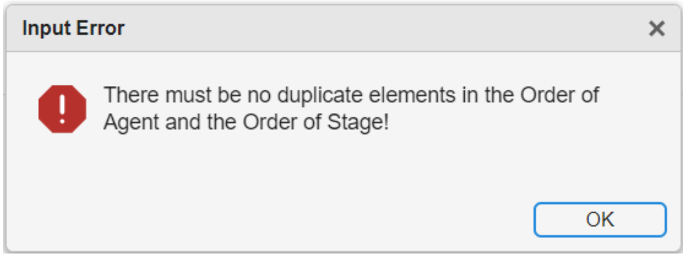
Problem with editing the tables in the "Variability Manifestation Impact and Propagation of Variability" tab:



Cause: The input values in the tables of the "Variability Manifestation Impact and Propagation of Variability" tab are not positive numbers.

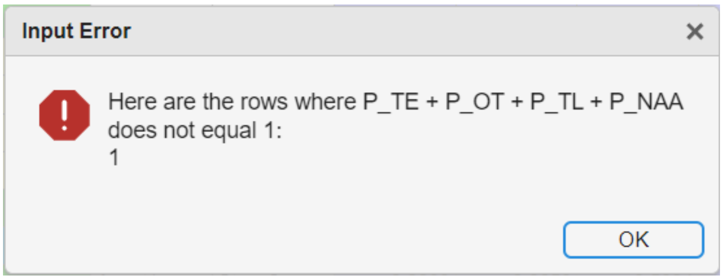
Solution: Change the input values to positive numbers.

Problem with clicking "Calculate metrics" button:



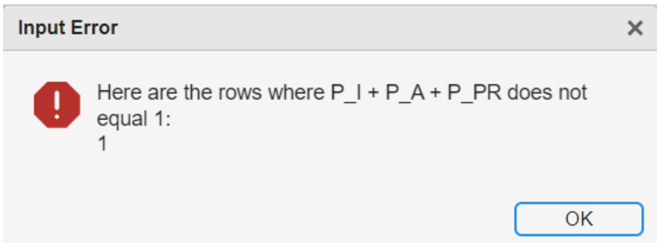
Cause: Duplicate elements exist in either the "Order of agent" table or the "Order of stage" table under the tab "Agents, stages and variability manifestation frequencies."

Solution: Edit the content of the "Order of agent" table or the "Order of stage" table to ensure there are no duplicate elements.



Cause: The sum of P_TE, P_OT, P_TL, and P_NAA in the displayed row of the dialog box does not equal one. For example, the sum of P_TE, P_OT, P_TL, and P_NAA in the first row of the displayed table does not equal one.

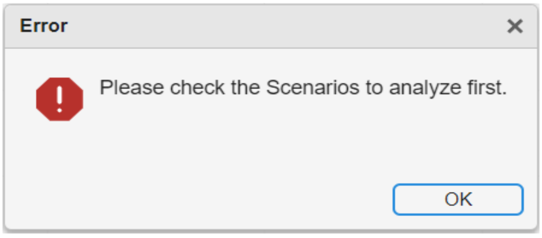
Solution: Locate the corresponding row (highlighted in red) in the "Agents, stages, and variability manifestation frequencies" tab and ensure that the sum of P_TE, P_OT, P_TL, and P_NAA equals one.



Cause: The sum of P_I, P_A, and P_PR in the displayed row of the dialog box does not equal one. For example, the sum of P_I, P_A, and P_PR in the first row of the displayed table does not equal one.

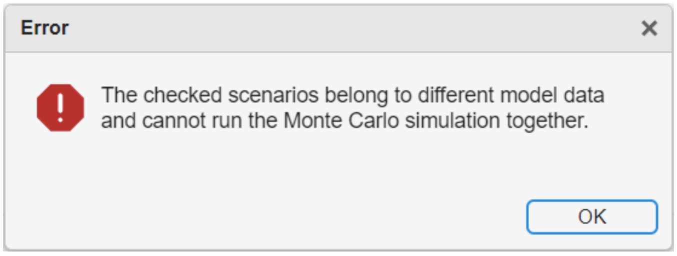
Solution: Locate the corresponding row (highlighted in red) in the "Agents, stages, and variability manifestation frequencies" tab and ensure that the sum of P_I, P_A, and P_PR equals one.

Problem with clicking the "All paths" button and the "Shortest paths" button in the "Monte Carlo Simulation" tab:



Cause: The user clicked the "All Paths" button or the "Shortest Paths" button without first checking scenarios in the "Instantiation/Scenario" table. As a result, the system was unable to identify which scenarios to use for the Monte Carlo simulation.

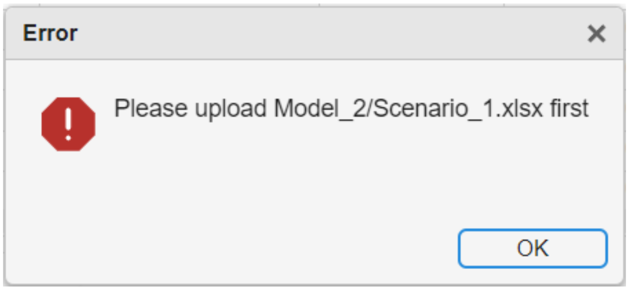
Solution: First, check the scenarios for the Monte Carlo simulation in the "Instantiation/Scenario" table. Then, click the "All Paths" button or the "Shortest Paths" button.



Cause: The scenarios checked by the user in the "Instantiation/Scenario" table belong to different model data, meaning their functions and couplings are not identical. As a result, Monte Carlo simulation cannot be performed on these scenarios collectively.

Solution: Ensure that the scenarios intended for Monte Carlo simulation have identical functions and couplings. Then, proceed to click the "All Paths" button or the "Shortest Paths" button.

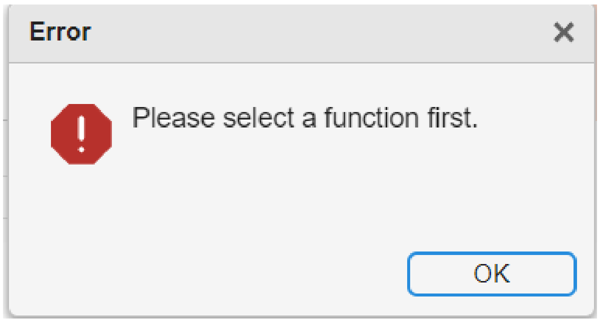
Problem with clicking the "Represent path in a network" dropdown menu in the "Two related critical upstream-downstream couplings" table and the "Represent critical longest path in a network" menu in the "Critical longest paths of couplings" table after uploading the Monte Carlo table in the "Monte Carlo Simulation" tab:



Cause: The scenario analyzed in the Monte Carlo data file uploaded via the "Upload the Monte Carlo Simulation Table" button does not exist in the "Instantiation/Scenario" table. As a result, the system cannot display the path of this scenario in the network.

Solution: The user must upload the scenario analyzed in the Monte Carlo data file to the "Instantiation/Scenario" table by clicking the "Upload Scenarios" button in the upper-left corner of the page. Additionally, ensure that the scenario name matches the name of the scenario analyzed in the Monte Carlo data file uploaded via the "Upload the Monte Carlo Simulation Table" button. After completing these steps, click the "All paths" button or the "Shortest paths" button. For detailed instructions on downloading and uploading Monte Carlo data files, refer to “Monte Carlo Siumlation”. For guidance on renaming scenarios in the "Instantiation/Scenario" table, consult "Instantiation/Scenario".

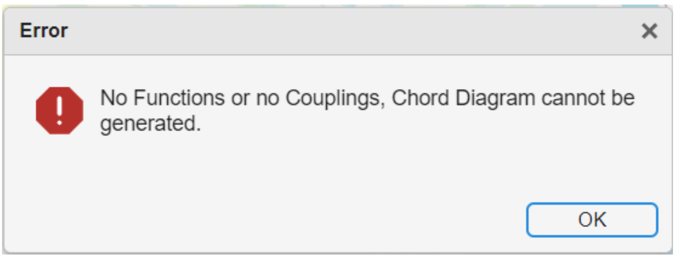
Problem with clicking the dropdown menus of bar charts and the Sankey diagram in the "Characteristics, Frequencies, and Interrelationships" tab:



Cause: The user did not select a specific function from the “Function list” on the left. The bar charts and Sankey diagram in the "Characteristics, Frequencies, and Interrelationships" tab are only applicable to a specific function.

Solution: First, select the target function from the “Function list” on the left, then click the dropdown menus of the bar charts and Sankey diagram in the "Characteristics, Frequencies, and Interrelationships" tab.

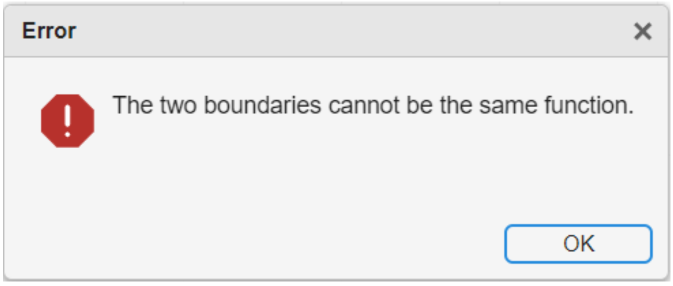
Problem with configuring the filter for the chord diagram:



Cause: The filter set by the user excludes all functions or couplings, preventing the generation of the chord diagram.

Solution: Reset the filter.

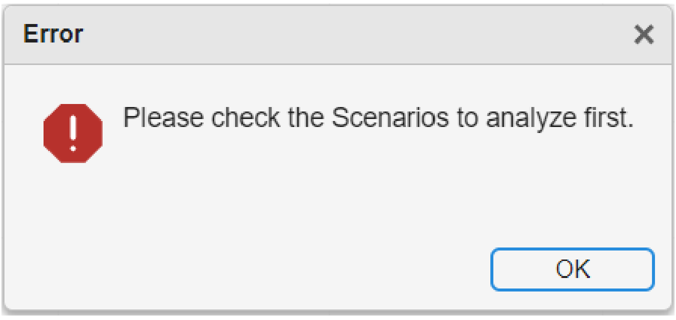
Problem with clicking the "Set as the boundary of risk functions" menu in the "List of Risk Functions" table within the "Risk Functions" tab:



Cause: The user has set the same function consecutively as the boundary of risk functions.

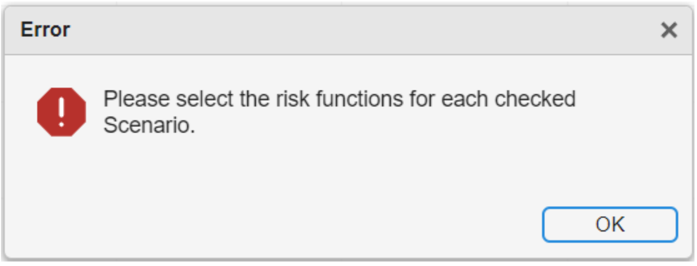
Solution: Select a different function in the "List of Risk Functions" table to set as the boundary of risk functions. For instructions on how to use the "Set as the boundary of risk functions" menu, refer to "Risk functions".

Problem with clicking the "Analyse" button in the "Risk Functions" tab:



Cause: The user clicked the "Analyse" button without first checking the scenarios in the "Instantiation/Scenario" table, resulting in the system being unable to identify which scenarios to analyze.

Solution: First, check the scenarios to analyze in the "Instantiation/Scenario" table, then click the "Analyse" button.

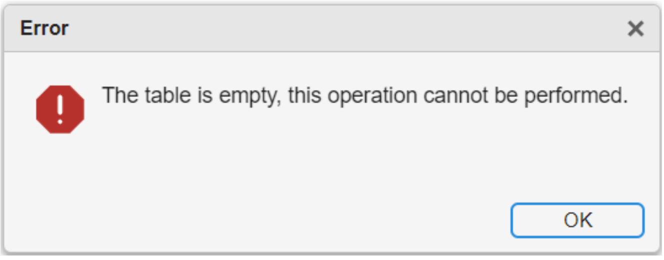


Cause: The user has not defined risk functions for each scenario to be analyzed.

Solution: In the left side table “Instantiation/Scenario”, click on the scenarios you want to analyze, check which scenario corresponding to the “List of risk functions” table is not defined, define the risk functions for it and then click the “Analyse” button. scenario, define risk functions for it and click “Analyse” button. See "Risk functions" for how to define a risk function.

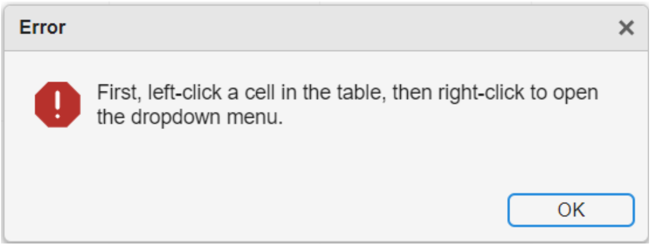
Problem with clicking the dropdown menus in the following tables:

1. **"Instantiation/Scenario"**
2. **"Two Related Critical Upstream-Downstream Couplings"**
3. **"Critical Longest Paths of Couplings"**
4. **"List of Risk Functions"**
5. **"Selected Functions" (under the "Functional Variability System Resonance Matrix" tab)**



Cause: When these tables are empty, the user clicked their dropdown menus, causing the system to be unable to determine which row to execute the dropdown operation for.

Solution: The dropdown menus can only be clicked when these tables are not empty.



Cause: The user directly clicked the dropdown menu without first left-clicking a cell in the table, causing the system to be unable to determine which row to execute the dropdown operation for.

Solution: First, left click a cell in the table to select the desired row. Then, right-click to open the dropdown menu and select an option from it. For detailed instructions on how to open the dropdown menu, refer to “Risk functions”.

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References

Grabbe, N., Gales, A., Höcher, M., & Bengler, K. (2022). Functional resonance analysis in an overtaking situation in road traffic: comparing the performance variability mechanisms between human and automation. Safety, 8(1), 3.

Hicklin, J. (2025). Treemap. MATLAB Central File Exchange. Retrieved January 23, 2025, from https://www.mathworks.com/matlabcentral/fileexchange/17192-treemap

Hill, R., & Hollnagel, E. (2016). Instructions for use of the FRAM model visualiser (FMV). Retrieved from http://functionalresonance.com/onewebmedia/FMV_instructions_0.4.0.pdf (accessed on 10 February 2023).

Hollnagel, E. (2012). FRAM, the Functional Resonance Analysis Method: Modelling Complex Sociotechnical Systems. Ashgate Publishing, Ltd.

Liu, Z. (2025). Sankey plot. MATLAB Central File Exchange. Retrieved January 23, 2025, from https://www.mathworks.com/matlabcentral/fileexchange/128679-sankey-plot

Patriarca, R., Bergström, J., & Di Gravio, G. (2017a). Defining the functional resonance analysis space: Combining Abstraction Hierarchy and FRAM. Reliability Engineering & System Safety, 165, 34-46.

Patriarca, R., Di Gravio, G., & Costantino, F. (2017b). A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems. Safety Science, 91, 49–6

Appendix

Definition and formulas of the metrics

The following definitions and formulas refer to Grabbe et al. (2022).

P_TE: Percentage distribution of cases where variability values occur too early.
P_OT: Percentage distribution of cases where variability values occur on time.
P_TL: Percentage distribution of cases where variability values occur too late.
P_NAA: Percentage distribution of cases where variability values do not occur at all.
P_I: Percentage distribution of cases where variability values are imprecise.
P_A: Percentage distribution of cases where variability values are acceptable.
P_PR: Percentage distribution of cases where variability values are precise.
V_TE: Numerical variability values for cases where variability values occur too early.
V_OT: Numerical variability values for cases where variability values occur on time.
V_TL: Numerical variability values for cases where variability values occur too late.
V_NAA: Numerical variability values for cases where variability values do not occur at all.
V_I: Numerical variability values for cases where variability values are imprecise.
V_A: Numerical variability values for cases where variability values are acceptable.
V_PR: Numerical variability values for cases where variability values are precise.

V_T: represents the upstream output score in terms of timing.

$$V\_T = P\_TE * V\_TE + P\_OT * V\_OT + P\_TL * V\_TL + P\_NAA * V\_NAA$$

V_P: represents the upstream output score in terms of precision.

$$V\_P = P\_I * V\_I + P\_A * V\_A + P\_PR * V\_PR$$

OV: Variability of the upstream output.

$$OV = V\_T * V\_P$$

a_TE: Upstream/downstream propagation of variability in cases where variability values occur too early.
a_OT: Upstream/downstream propagation of variability in cases where variability values occur on time.
a_TL: Upstream/downstream propagation of variability in cases where variability values occur too late.
a_NAA: Upstream/downstream propagation of variability in cases where variability values do not occur at all.
a_I: Upstream/downstream propagation of variability in cases where variability values are imprecise.
a_A: Upstream/downstream propagation of variability in cases where variability values are acceptable.
a_PR: Upstream/downstream propagation of variability in cases where variability values are precise.

a_T: Propagation factor in terms of timing.

$$a\_T = P\_TE * a\_TE + P\_OT * a\_OT + P\_TL * a\_TL + P\_NAA * a\_NAA$$

a_P: Propagation factor in terms of precision.

$$a\_P = P\_I * a\_I + P\_A * a\_A + P\_PR * a\_PR$$

CV: Coupling variability of the upstream output and the downstream function.

$$CV = OV * a\_T * a\_P$$

DLFCV: Downlink functional coupling variability, the sum of the CVs of all upstream couplings of a function.

$$DLFCV = \sum_{Uplinks} CV$$

ULFCV: Uplink functional coupling variability, the sum of the CVs of all downstream couplings of a function.

$$ULFCV = \sum_{Downlinks} CV$$

N_DL: Number of downlinks of a function.
N_UL: Number of uplinks of a function.

Intra_stage: calculates the number of downlinks and uplinks of a function *f* where the linked upstream *j* and downstream functions *i* are in the same stage *St* and executed by the same agent *Ag.*

$$Intra\_stage = [\sum_{i=1}^{f} if\left(\left(Ag_f = Ag_i \;\&\&\; St_f = St_i\right) then\ 1, else\ 0\right) + \sum_{j=1}^{f} if(\left(Ag_f = Ag_j \;\&\&St_f = St_j\right) then\ 1, else\ 0)]$$

Intra_agent: calculates the number of downlinks and uplinks for a function *f*, where the linked upstream function *j* and downstream function *i* are in different stages *St* but are executed by the same agent *Ag*.

$$Intra\_agent = [\sum_{i=1}^{f} if\left(\left(Ag_f = Ag_i \;\&\&\; St_f \neq St_i\right) then\ 1, else\ 0\right) + \sum_{j=1}^{f} if(\left(Ag_f = Ag_j \;\&\&St_f \neq St_j\right) then\ 1, else\ 0)]$$

Intrarelatedness: measures the interactions within a single agent and is determined by the total of Intra_stage and Intra_agent for a function *f*. The chosen value for *β* in this work is 2.

$$Intrarelatedness = Intra\_stage + \beta * Intra\_agent$$

Inter_agent: count the number of downlinks and uplinks for a function *f*, where the linked upstream function *j* and downstream function *i* are executed by different agents *Ag*.

$$Inter\_agent = [\sum_{i=1}^{f} if\left(\left(Ag_f \neq Ag_i\right) then\ 1, else\ 0\right) + \sum_{j=1}^{f} if(\left(Ag_f \neq Ag_j\right) then\ 1, else\ 0)]$$

Different_agent_count: calculate the number of different agents *k* with which a function *f* is directly connected through its upstream function *j* and downstream function *i*.

$$Different\_agent\_count = [\sum_{k=1}^{Number\ of\ agents} if\left(\left(Ag_f \neq Ag_i\ \&\&\ Ag_i = Ag_k\right) then\ 1, else\ 0\right) + \sum_{j=1}^{Number\ of\ agents} if(\left(Ag_f \neq Ag_j\ \&\&Ag_j = Ag_k\right) then\ 1, else\ 0)]$$

Interrelatedness: The Interrelatedness of a function *f* measures the interaction between agents and is calculated as the product of Inter_agent and Different_agent_count.

$$Interrelatedness_f = Inter\_agent_f * Different\_agent\_count_f$$

Direct_feedback_loops: occur when a downstream function *i* of a function *f* is also an upstream function *j* of the same function *f*, and vice versa. This creates a loop between the two functions, involving only these two functions.

$$Direct\_feedback\_loops = [\sum_{i=1}^{f} if((Coupling(f,i)\ \&\&Coupling(i,f))\ then\ 1, else\ 0) + \sum_{j=1}^{f} if(\left(Coupling(f,j)\&\&Coupling(j,f)\right) then\ 1, else\ 0)]$$

Indirect_loops_count: involve more than two functions. For example, function A calls function B, which is connected to function C, and function C, in turn, calls function A, thereby closing the loop. The function "Loops" calculates all cycles in the model that include function *f* and are not direct feedback loops of function *f*. In FRAMalyse, only loops consisting of fewer than eight functions are considered. This is because, for some structurally complex models, loops with no length limit may become excessively long, leading to extended computation times. Therefore, the maximum loop length is constrained to eight functions.

$$Indirect\_loops\_count_f = \sum Loops_f$$

Indirect_loops_length: calculates the number of functions per cycle, that is, the length of the cycle of function *f*.

mean_loop: represent the average number of functions occurring in the indirect feedback loops of function *f* and is calculated as follows:

$$mean\_loop_f = \frac{\sum Indirect\_loops\_length_f}{Indirect\_loops\_count_f}$$

Feedback_loop_factor: is composed of Direct_feedback_loops, Indirect_loops_count, and mean_loop.

$$feedback\_loop\_factor_f = Direct\_feedback\_loops_f + Indirect\_loops\_count_f * mean\_loop_f$$

CTV: The CTV was used to determine the extent of variability accumulation around a function *f*. To achieve this, the ULFCV of the coupled upstream functions *j*, the DLFCV of the coupled downstream functions *i*, and both the DLFCV and ULFCV of function *f* were summed together.

$$CTV_f = DLFCV_f + ULFCV_f + \sum\nolimits_{i=1}^{f} DLFCV_i + \sum\nolimits_{j=1}^{f} ULFCV_j$$

Katz: The Katz-centrality measures the relative influence of a function. This metric is the most suitable for function prioritization in a FRAM model analysis. For all connections that are reachable both upstream and downstream by function *f*, the CVs of the upstream functions of the respective connections are summed. To account for the indirect influence of functions—meaning that the farther a function is located, the lower its influence—the distances to the individual couplings are considered and weighted by a factor α. It should be noted that a direct connection has a distance of zero. The term d_{ii} represents the distance of a downstream connection to function *f*, where *ii* denotes both direct and indirect downstream functions. Similarly, d_{jjf} reflects the distance of an upstream connection to function *f*, where *jj* denotes both direct and indirect upstream functions. The weight factor α and Katz-centrality are calculated as follows:

$$\alpha_{iif} = \frac{1}{d_{iif} + 1}$$

$$\alpha_{jjf} = \frac{1}{d_{jjf} + 1}$$

$$Katz_f = \sum_{ii=1}^{f} CV_{ij} * \alpha_{iif} + \sum_{jj=1}^{f} CV_{ij} * \alpha_{jjf}$$

Incloseness: Incloseness-centrality and Outcloseness-centrality indicate how centrally a node (i.e., a function) is positioned within a network. Each centrality measure is the sum of the reciprocal distances to reachable functions, weighted by the CV of the respective upstream functions. Incloseness-centrality specifically considers only the upstream functions *j* of function *f*. The number of upstream functions that can be reached from function *f* is denoted by *n*. Incloseness-centrality is calculated as follows:

$$Incloseness = \frac{n-1}{\sum_{jj=1}^{f}(CV_{ij} \times d_{jjf})}$$

Outcloseness: Outcloseness-centrality focuses solely on the downstream functions *i* of function *f* and is calculated as follows:

$$Outcloseness = \frac{n-1}{\sum_{ii=1}^{f}(CV_{ij} \times d_{iif})}$$

Betweenness: Betweenness-centrality measures how frequently a function *f* serves as the shortest path between two other functions in the model:

$$Betweenness = \sum_{ii \neq jj \neq f \epsilon V} \frac{\sigma_{iijj}(f)}{\sigma_{iijj}}$$

where $\sigma_{iijj}$and $\sigma_{iijj}(f)$ represent the number of shortest paths between functions *i* and *j*, and the number of shortest paths between functions *i* and *j* that pass through function *f*, respectively. *V* denotes the total number of functions in the model, and *ii* and *jj* indicate that indirect downstream and upstream functions are also taken into account.

The metrics N_DL, N_UL, Intrarelatedness, Interrelatedness, feedback_loop_factor, CTV, Katz, Incloseness, Outcloseness, and Betweenness were converted into relative metrics ($Met^{relative}$), representing the effect of a function as a percentage compared to all other functions within a given metric. This standardization ensures that all metrics carry equal weight in subsequent calculations. Specifically, Met_f, the value of a particular metric for function *f*, is divided by the total value of the same metric across all functions k. However, this approach would produce values below 1, which is problematic in calculations involving multiplications, as it would cause the resulting values to diminish. To address this, the percentage values are divided by the inverse of the total number of functions N in the model, ensuring values remain above 1. This amplification highlights the influence of a function in further calculations. The formula for $Met^{relative}$was as follows:

$$Met_f^{relative} = \frac{\frac{Met_f}{\sum_{k=1}^{N} Met_k}}{\frac{1}{N}}$$

Beta_1, Beta_2, Beta_3, Beta_4, Beta_5, Beta_6, Beta_7, Beta_8 are the numerical values of the weighting factors used for the calculation of WaU and WaD. Beta_1 corresponds to N_DL/N_UL, Beta_2 to Intrarelatedness, Beta_3 to Interrelatedness, Beta_4 to the feedback_loop_factor, Beta_5 to CTV, Beta_6 to Katz, Beta_7 to In-/Outcloseness, and Beta_8 to Betweenness.

The Weight as Upstream (WaU) and Weight as Downstream (WaD) are the two main indicators of system resonance, reflecting the system impact of a function as an upstream and downstream function, respectively.

$$\begin{aligned} WaU = {} & Beta\_1 * N\_DL\_relativ + Beta\_2 * Intrarelatedness\_relativ + Beta\_3 \\ & * Interrelatedness\_relativ + Beta\_4 * feedback\_loop\_factor\_relativ \\ & + Beta\_5 * CTV\_relativ + Beta\_6 * Katz + Beta\_7 * Outcloseness \\ & + Beta\_8 * Betweenness \end{aligned}$$

$$\begin{aligned} WaD = {} & Beta\_1 * N\_UL\_relativ + Beta\_2 * Intrarelatedness\_relativ + Beta\_3 \\ & * Interrelatedness\_relativ + Beta\_4 * feedback\_loop\_factor\_relativ \\ & + Beta\_5 * CTV\_relativ + Beta\_6 * Katz + Beta\_7 * Incloseness \\ & + Beta\_8 * Betweenness \end{aligned}$$

$$DLFCV_j^{relative} = \sum_{i=1}^{j} CV_{ij} * WaU_j * WaD_i$$

$$ULFCV_i^{relative} = \sum_{j=1}^{i} CV_{ij} * WaU_j * WaD_i$$

OFCV: the overall functional coupling variability (OFCV) of a function *f.*

$$OFCV_f = ULFCV_i^{relative} + DLFCV_j^{relative}$$

GSV: Global system variability (GSV) is the sum of the OFCVs of n functions within the entire system, showing the accumulated variability of all functions and their interactions within the system under specific conditions.

$$GSV = \sum_{f=1}^{n} OFCV_f$$

FRAMalyse