User Guide

Version 2.1

Sponsor: Intelligence Advanced Research Projects Activity (IARPA) | Coldflux Project

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June 6, 2023

License

The development of this tool was supported by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA) SuperTools program, via the U.S. Army Research Office grant W911NF-17-1-0120.

Contents

1 Introduction

1.1 Overview

qCS (Cell Synthesis) is a tool for analyzing and changing component values of superconducting logic cells such as Rapid Single Flux Quantum (RSFQ) and Adiabatic Quantum-Flux-Parametron (AQFP) cells. It also helps generate critical margin/yield-optimized variants of designed cells by utilizing the following built-in capabilities such as critical margin calculation, parametric yield analysis and critical margin range optimization.

The purpose of this document is to provide an insight into the available features of qCS and the following sections discuss the details with examples. Images and screenshots may differ in appearance on each operating system. Every session can be exported and imported at any time. The generated files are independent of the operating system. Thus, the files initially exported on a system with Windows OS can be imported to a system with CentOS 7 and vice versa.

1.2 Audience

This document is prepared for the superconducting circuit designers. They are expected to be familiar with testbench preparation, circuit simulation, and design verification.

1.3 System Requirements

- *Certificates (non-Windows OS)*: If the installer doesn't start and the error is about certificates, use the following command:
  $ sudo ln -s /etc/ssl/certs/ca-bundle.trust.crt /etc/ssl/certs/ca-certificates.crt
- *JoSIM (non-Windows OS)*: It is the user's responsibility to satisfy JoSIM requirements (setting up the environment and installing packages). For details, visit the link below.
  https://joeydelp.github.io/JoSIM/#linux
- *MATLAB Compiler Runtime (MCR) 9.13*: The qCS installer will automatically download MCR from Mathworks website. If it is already installed, the system will detect the installed path (Windows OS only). Minimum 2 GB of disk capacity is required to accommodate MCR installation. Any installation directory is permitted for MCR.
- *Directory*: Create a parent folder for qCS installation directory since qCS deletes its parent folder upon uninstallation. The recommended directory is an appropriate location where the user has read/write permissions.

1.4 Installation

These instructions are also available in the README file in the package (".tar.gz" or ".zip").

1.4.1 Windows OS

1.4.1.1 Preparation for Installation

- Extract zip file (example: "qCS_Windows_2-1.zip")
  1. R-click
  2. Extract using any installed Zip program

1.4.1.2 Installation

- Open folder which contains the installer (example: "qCS_Windows_2-1")
  1. L-click twice on "qCS_installer.exe"
  2. Click "Yes" if a permission pop-up window appears
  3. Installation wizard appears
  4. Install to any directory that does not require administrator permissions
  5. Remove the tick in the checkbox for a shortcut if it is initially selected

1.4.2 CentOS 7 / Ubuntu 22

1.4.2.1 Preparation for Installation

- Extract tar.gz file (example: "qCS_CentOS_2-1.tar.gz")
  1. R-click
  2. Open with Archive Manager
  3. Select folder
  4. L-click Extract
  5. Select location
  6. L-click Extract
- Open folder (example: "qCS_CentOS_2-1")
  1. R-click "qCS_installer.install"
  2. Properties
  3. Tab: Permissions
  4. Check: Allow executing file as program
  5. Close

1.4.2.2 Installation

- Open folder which contains the installer (example: "qCS_CentOS_2-1")
  1. R-click
  2. Open Terminal
  3. $ sudo ./qCS_installer.install
  4. Installation wizard appears
  5. Install to a directory (example: /home/userName/qCS_x-x where "x-x" is the version number)

1.4.3 macOS

1.4.3.1 Preparation for Installation

- Extract zip file (example: "qCS_MacOS_2-1.zip")
  1. R-click
  2. Extract using any installed Zip program

1.4.3.2 Installation

- Open folder which contains the installer (example: "qCS_MacOS_2-1")
  1. L-click twice on "qCS_installer"
  2. Installation wizard appears
  3. Install to any directory that does not require administrator permissions

1.5 Key Features

The following chapters are organized to describe the main steps of qCS and they do not correspond to a specific design flow.

- *Circuit specification*: File selection as an input and netlist adjustments on the interface
- *Simulation*: Waveform analysis and desired node selection for confirming the correct behavior using JSIM, JSIM_n and JoSIM
- *Variable parameter specification*: Flexible parameter selection from a single cell or a multiple cell structure with various fanin and fanout counts to bring flexibility to the designer
- *Margin calculation*: Parametric sweeps around a design value for all selected cell components
- *Yield analysis*: Sampling and evaluating the randomized netlists with Monte Carlo simulations
- *Circuit optimization*: Flexible adjustments on the predefined values of the algorithm for efficient optimizations and observing the trend during the process

1.6 Tool Flow

qCS requires a netlist as an input. Upon browsing for the file, it converts the circuit into an object while making a copy of the selected netlist. Any adjustment on the interface will not be reflected in the original file other than the qCS copy. The simulations are performed using the circuit object by converting them back to a netlist after some adjustments. If there is any issue with the file, there will be a pop-up error. After confirming and selecting desired waveforms, cell components must be selected as the next step. Search space for the optimization can be changed in this step as well. Even if the output behavior is not as expected, the user can manually provide pattern texts. Otherwise, qCS is capable of automatically creating the patterns for the waveforms, and the pulse information is automatically assigned based on the selected waveforms. At this point, the built-in features with default settings are ready to use. The related flow graph is shown in Fig. 1.

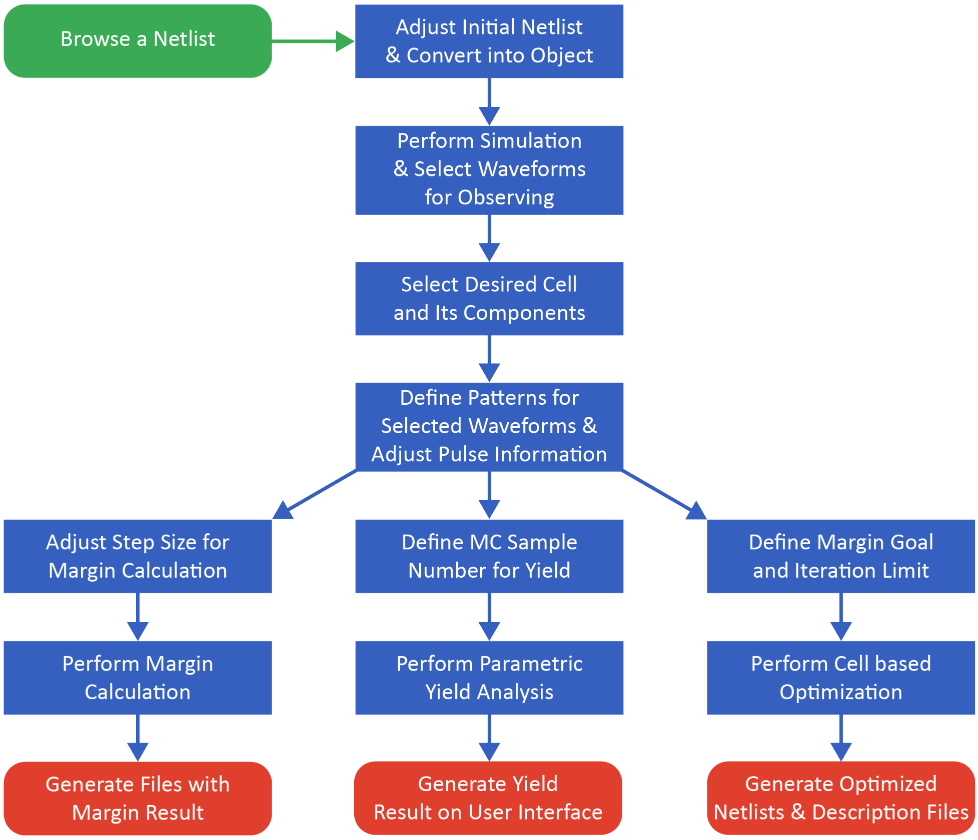

Figure 1: qCS workflow

1.7 Interface Introduction

After installing qCS, locate the installation directory/application. Click on qCS.exe to run the tool. Initially, there will be a loading screen but the main interface of the tool will appear afterwards. Each qCS tab is explained in the following sections. Note that qCS has two circuit modes: RSFQ and AQFP. The default mode is assigned as RSFQ; however, to run on AQFP mode, the netlist file must include "AQFP" inside of the file or on its filename.

1.7.1 Netlist

Netlist tab contains the testbench environment for the cells to be analyzed. In this tab, the user can import a previously saved qCS session or browse a new circuit netlist. In order to successfully load a netlist, the user must follow the netlist rules for qCS given in Section 2. The interface is shown in Fig. 2 and each interface component is listed as follows.

- *Simulator Choice*: The options for netlist simulator. The default selection is assigned as JSIM. PJSIM and PJSIM_n options are currently disabled.
- *Browse*: Loads a netlist file.
- *Import Session*: Imports previously saved qCS session.
- *Export Session*: Exports current qCS session.
- *File Information*: Contains file name and its directory information.

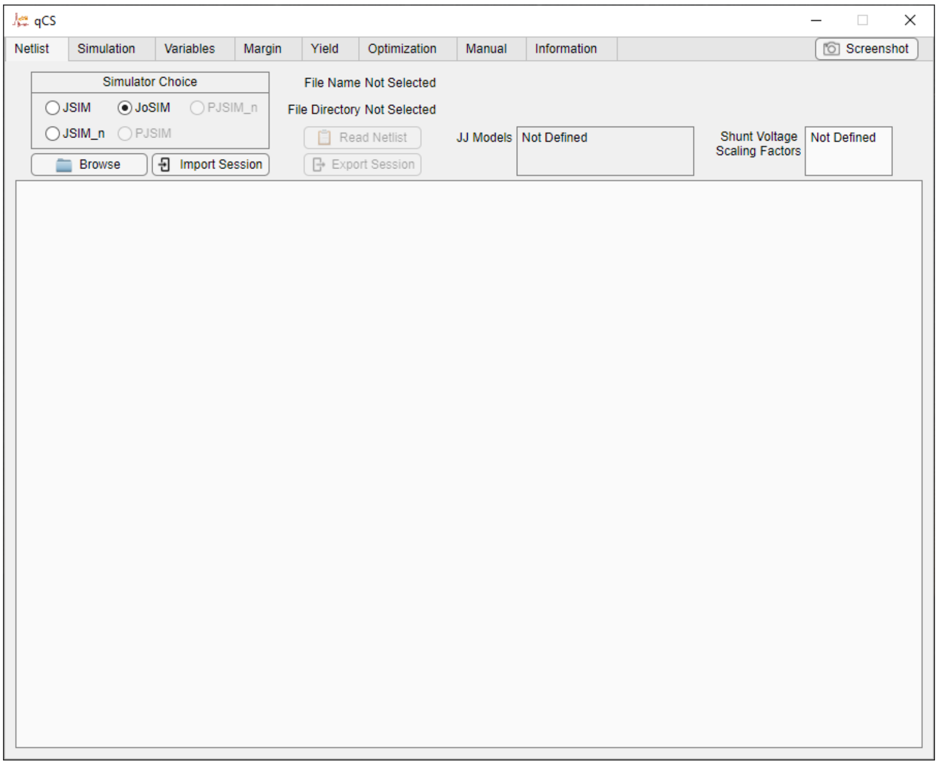

Figure 2: qCS: Netlist tab

- *Netlist Panel*: Shows the content in the netlist file and allows the user to change values on the interface.
- *JJ Models*: Josephson Junction model names defined in the selected netlist.
- *Shunt Voltage Scaling Factors*: The scaling factor is calculated by multiplying two values (junction area and its shunt resistor). For unshunted junctions, create a separate model and assign 0 to its scaling factor.
- *Read Netlist*: Every line of netlist will be assigned to an object. In order to activate qCS features, the netlist has to be read.

1.7.2 Simulation

Simulations are completed in this tab. qCS reads the output data file and plots the waveforms within the available panel space. The interface is shown in Fig. 3 and each interface component is listed as follows.

- *Run*: Starts the simulation of selected netlist. In order to verify the compatibility of the selected netlist with the selected simulator, this step has to be performed.
- *Cells to Be Optimized*: This number is determined by the number of ".file" commands in the netlist. Each file command corresponds to a possible cell analysis. The number of independent cell analyses depends on this value.
- *Total Pattern #*: This number is determined by the number of ".print" commands in the netlist.
- *Waveform Panel*: Shows the waveform data obtained from the output file(s).

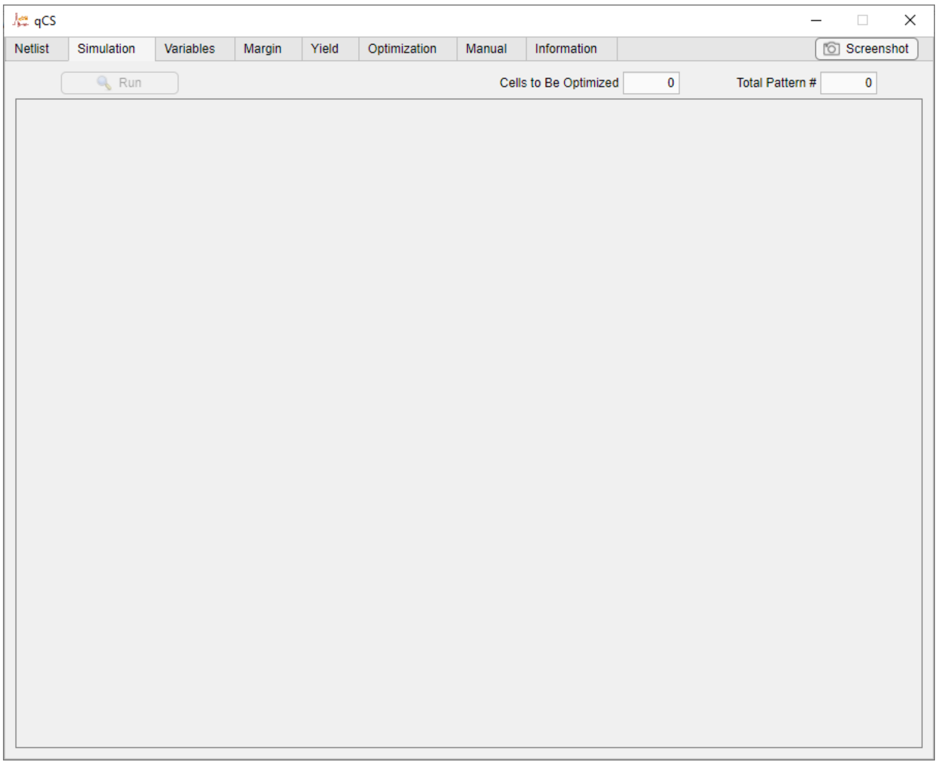

Figure 3: qCS: Simulation tab

1.7.3 Variables

After reading the netlist file, it is converted into an object. The object can be edited in this tab and cell component values are assigned here. The interface is shown in Fig. 4 and each interface component is listed as follows.

- *Import*: Imports previously saved variable setting.
- *Export*: Exports current variable setting.
- *Add*: Adds any selected element into the value table. The selection of a circuit branch will add all of its elements.
- *Remove*: Removes any selected element. L-click mouse and go over the other elements to select multiple elements.
- *Netlist Cell Panel*: A netlist tree is a converted object of the netlist file. The parent nodes represent the cells in the netlist and child nodes represent the components within the cells. All adjustable elements will be listed in this panel.
- *Optimization Spread Panel*: These spread values define the minimum and maximum limits for the optimization process. They don't affect margin calculation or yield analysis. Ranges for margin analysis are internally defined as -50% and +50% of initial values. Spreads for yield analysis are internally defined as 3σ which depends on relative STD values.
- *Hard Limit Panel*: Hard limits define the minimum and maximum values for designs in the chip. They create the borderline for optimization search space by changing the minimum and maximum component values in the columns below. Leaving them

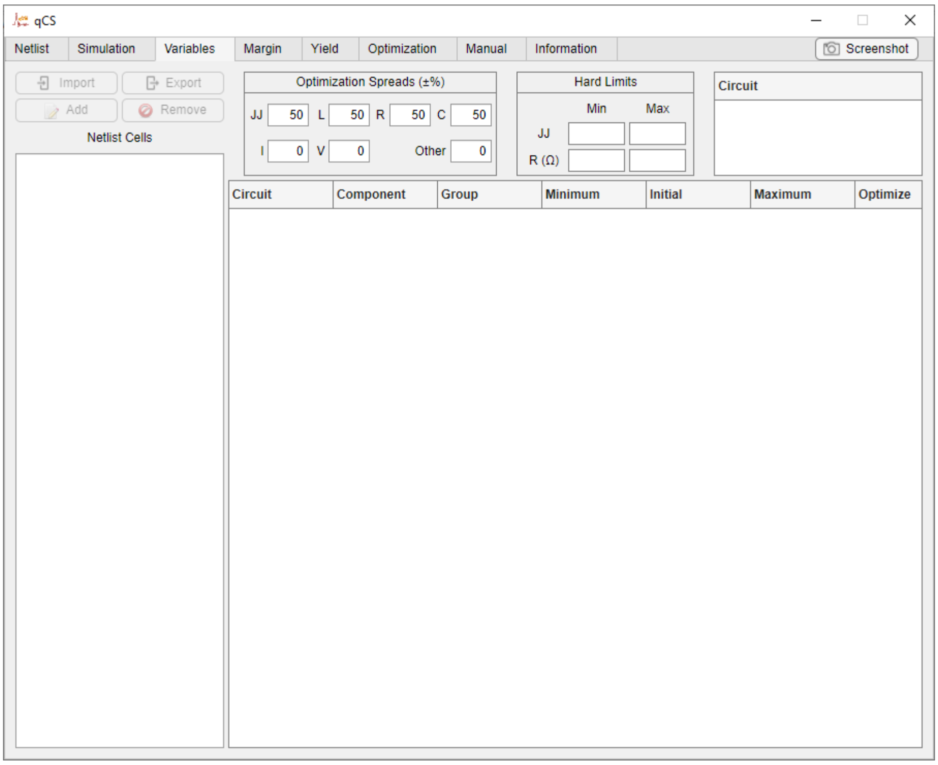

Figure 4: qCS: Variables tab

empty means that optimization limits are defined by spread percentages. Note that these limits are not considered for margin calculation or yield analysis. During these processes, component values depend on the initial values.

- *Circuit Table*: Depending on the component selection, a corresponding cell number is assigned to each cell. For multiple-cell optimization, select the cells in the same order as ".file" commands in the netlist. Output patterns are internally matched to the cell selections in the same order.
- *Value Table*: Any added netlist element will be listed here. They can be grouped together to have the same values for the analysis. Grouping does not affect the margin calculation.

1.7.4 Margin

This tab contains the margin analysis feature of qCS. The user automatically or manually puts the output pattern and starts the analysis to see the circuit performance by using Calculate button. The interface is shown in Fig. 5 and each interface component is listed as follows.

- *Fill*: Automatically fills the expected output pattern area. It uses the expected output band, minimum pulse height, and pulse width values.
- *Check*: Depending on the pulse height and width, it shows the pulses that will be considered as logic 1 or 0. This feature is added for the user to verify the pattern and pulse timings.
- *Expected Output Pattern Panel*: Defines the number of pulses that are expected to appear within a certain time interval.

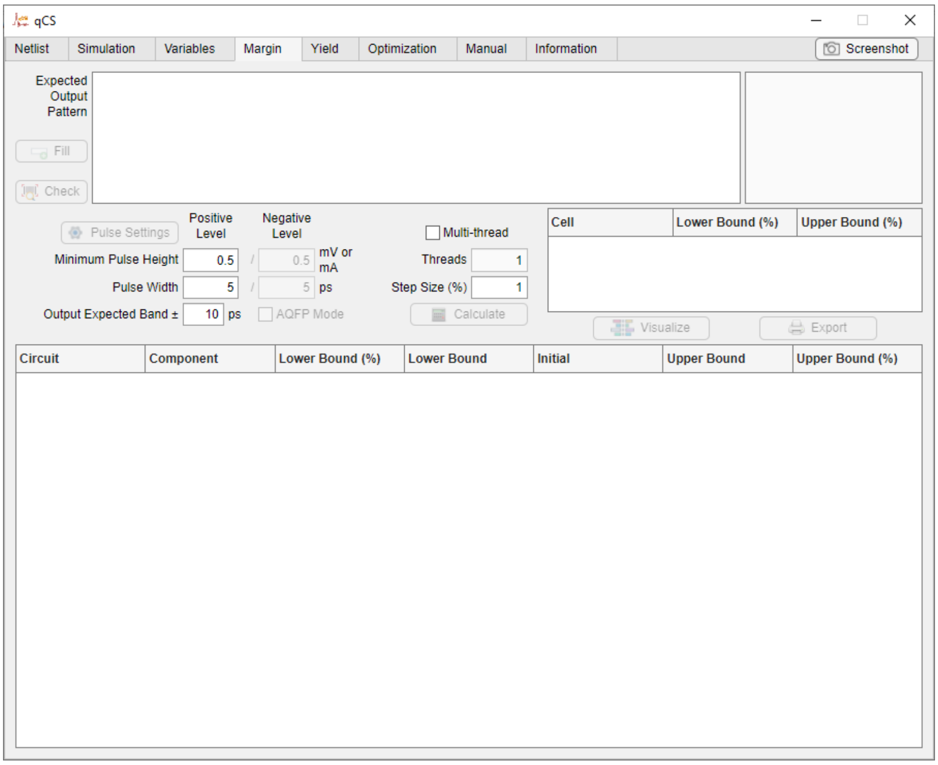

Figure 5: qCS: Margin tab

- *Pulse Settings*: A visual representation of a pulse for its settings. This feature is currently disabled.
- *Minimum Pulse Height*: Any pulse that goes above the expected voltage/current will be counted as logic 1. Assign at least 70% of the expected pulse height. The same feature for logic 0 is available in AQFP mode.
- *Pulse Width*: Expected distance between pulse rising edge and falling edge (i.e. pulse width) for the logic 1. The same feature for logic 0 is available in AQFP mode.
- *Output Expected Band* $\pm$: The expected band value will be used to determine a symmetric valid band for pulses and it is used for the pattern fill option.
- *AQFP Mode*: Allows to check negative pulses which will be considered as logic 0. This option is automatically selected by detecting the "AQFP" word within the netlist file and its name.
- *Multi-threading*: Allows utilization of more resources.
- *Threads*: Number of assigned threads that define the parallelism.
- *Step Size (%)*: Each parameter value will be scanned by using the defined step size. Recommended: 1 (1%)
- *Calculate*: To enable, select cell components and fill the pattern textbox. This feature performs a margin calculation for all selected cell components independently. The upper and lower limits are internally defined as -50% and +50%.
- *Visualize*: Creates a bar graph of margin results for better visualization.

- *Export*: Saves the tables into an Excel file and other variables into a text file.
- *Cell Table*: Displays the critical margins for each selected cell.
- *Margin Table*: Displays the detailed margin scores for all selected elements.

1.7.5 Yield

Yield analysis can be performed within this tab. The listed items from Fill to Threads in Margin tab are also available here; thus, they are omitted from the item list in Yield tab. Note that the randomization of components is only applied to the selected components in Variables tab. The interface is shown in Fig. 6 and each interface component is listed as follows.

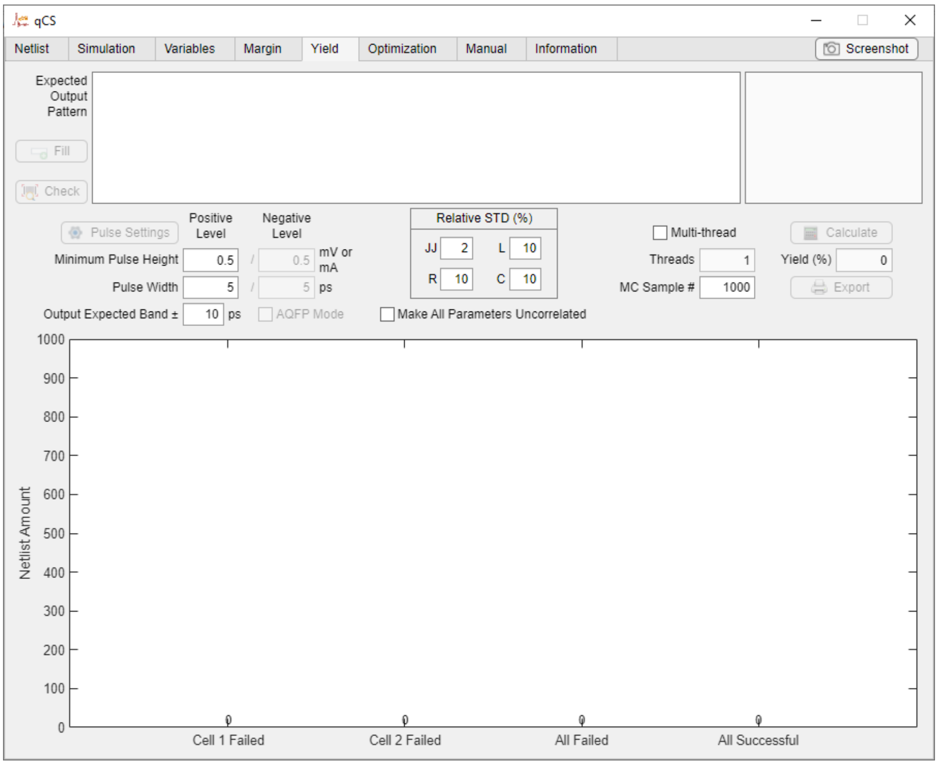

Figure 6: qCS: Yield tab

- *Relative STD (%)*: Measure of the amount of parameter variation (on-chip variation). Each selected component will be randomized within the 3σ range. Variations on each component are assigned independently except for the grouped components. Grouped component values will be the same after the randomization but with a relatively small random difference. These values are only applied to the selected parameters.
- *Make All Parameters Uncorrelated*: Even if there is a defined cell component correlation, everything will be considered independent. This can be considered as a worst case.
- *MC Sample #*: Defines the number of netlists that will be created to compare the output with the expected output pattern.
- *Calculate*: To enable, select cell components and fill the pattern textbox. This feature performs parametric yield analysis.

- *Yield (%)*: The number of working netlists is divided by the total number of netlists.
- *Export*: Save the yield figure and other variables into a text file.

1.7.6 Optimization

This tab contains the optimization feature and its settings. The listed items from Fill to Threads in Margin tab are also available here; thus, they are omitted from the item list in Optimization tab. Blue colored parameters don't affect the algorithm, and the others are provided for experienced users. The interface is shown in Fig. 7 and each interface component is listed as follows.

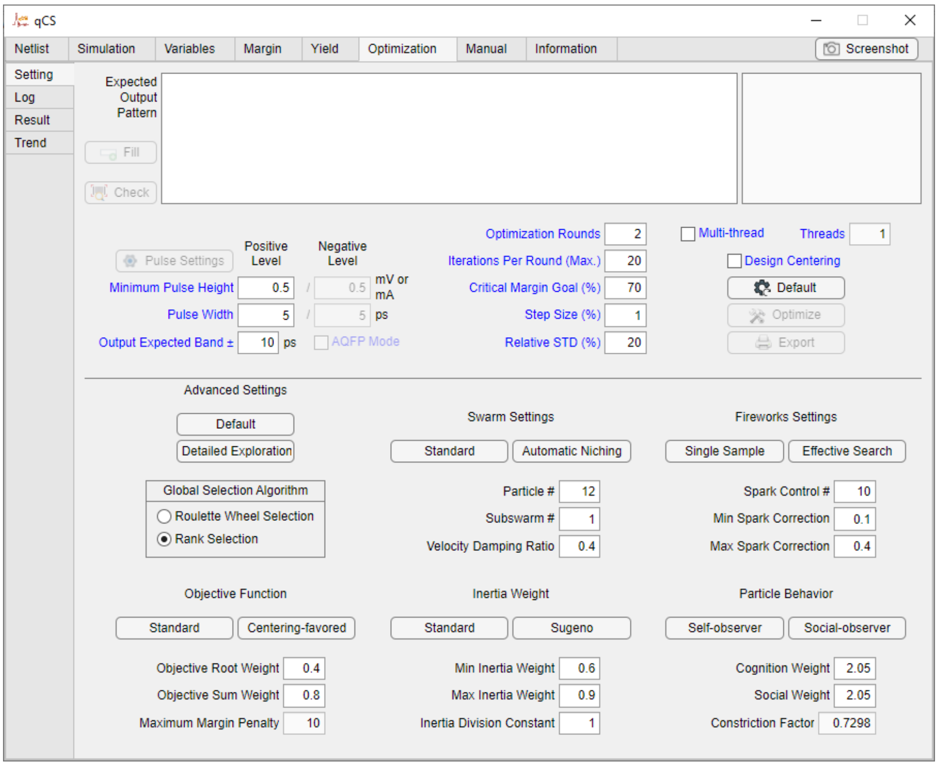

Figure 7: qCS: Optimization tab

- *Optimization Rounds*: Number of re-optimization process. In each round, the best value is selected and assigned into a single particle. The other particles are randomized.
- *Iterations Per Round (Max.)*: Terminates the optimization when search iteration limit is reached.
- *Critical Margin Goal (%)*: Stops the optimization after reaching the goal. The goal is the minimum critical margin range of all selected cells. This condition is only compared to the scores of global particles.
- *Step Size (%)*: Each parameter value will be scanned by using the defined step size. Recommended: 1 (1%)
- *Relative STD (%)*: Relative STD defines the shape of the normal distribution used for the probabilistic mutations. Small values limit the exploration space while large values cover larger areas. 20% is a good value for typical situations.

- *Design Centering*: At the end of each round, the best result values are centered relative to their critical margin. qCS generates additional files for the netlist with centered values at the end of the optimization.
- *Default*: Resets the values of optimization parameters.
- *Optimize*: To enable, select cell components and fill the pattern textbox. This feature performs critical margin optimization.
- *Export*: Saves the tables into an Excel file and other variables into a text file.
- *Global Selection Algorithm Panel*: Roulette Wheel Selection will do a probabilistic approach but Rank Selection will do a greedy approach and pick the particles with the highest scores. For a small number of particles and sparks, Rank Selection is recommended.
- *Particle #*: Defines the number of particles searching through space. Search space is defined by using the minimum and maximum columns on Variables Tab.
- *Subswarm #*: Number of global particles that will lead the subswarms.
- *Velocity Damping Ratio*: Affects the lower and upper bound of velocity range. Defines how much a circuit parameter can change on each iteration.
- *Spark Control #*: Controls the number for spark amount of each firework. It will be used with spark correction limits.
- *Min Spark Correction*: Lower Bound for spark amount of each firework. It will be used with a spark control number.
- *Max Spark Correction*: Upper Bound for spark amount of each firework. It will be used with a spark control number.
- *Objective Root Weight*: Defines the weight for the square root of upper and lower bounds' product on a given margin range.
- *Objective Sum Weight*: Defines the weight for the summation of upper and lower bounds on a given margin range.
- *Maximum Margin Penalty*: Determines the range of difference between the centering-favored and standard critical margin scores for the corner cases. Example: Upper and lower bounds of a netlist are 50% and 0%, respectively. The standard margin score is 50% but the new score will be (50 - Penalty).
- *Min Inertia Weight*: Defines the effects of the previous velocity on the next iteration and creates a lower bound.
- *Max Inertia Weight*: Defines the effects of the previous velocity on the next iteration and creates an upper bound.
- *Inertia Division Constant*: Affects the velocity by using Sugeno inertia law.
- *Cognition Weight*: Defines how much a particle listens to its own best location.
- *Social Weight*: Defines how much a particle listens to the closest global particle.
- *Constriction Factor*: Downscales the total velocity of a particle. Calculated by using Cognition and Social Weights.

Besides the optimization parameters, there are preset values defined with the buttons listed below.

- *Default*: Assigns recommended values to the optimization algorithm parameters.
- *Detailed Exploration*: Assigns convenient values to the parameters that allow better local and global search with increased runtime.
- *Standard (Swarm Settings)*: A single point convergence setting.
- *Automatic Niching (Swarm Settings)*: Multiple points convergence setting.
- *Single Sample (Fireworks Settings)*: Every particle is randomized and sampled once.
- *Effective Search (Fireworks Settings)*: Utilizes Fireworks Algorithm by assigning more sparks. Increases runtime but local search becomes better.
- *Standard (Objective Function)*: Eliminates the margin penalty and focuses on increasing the overall margin.
- *Centering-favored (Objective Function)*: Increases the margin penalty to prioritize well-centered results.
- *Standard (Inertia Weight)*: Inertia weight remains the same.
- *Sugeno (Inertia Weight)*: Inertia weight decreases over time to carefully search while converging.
- *Self-observer (Particle Behavior)*: Prioritizes local results.
- *Social-observer (Particle Behavior)*: Prioritizes global results.

1.7.7 Manual

This tab provides the documentation for the simulators (JSIM and JoSIM) and qCS. The interface is shown in Fig. 8.

1.7.8 Information

License and all release information is given in this tab. All notable changes to qCS will be also documented here. The interface is shown in Fig. 9.

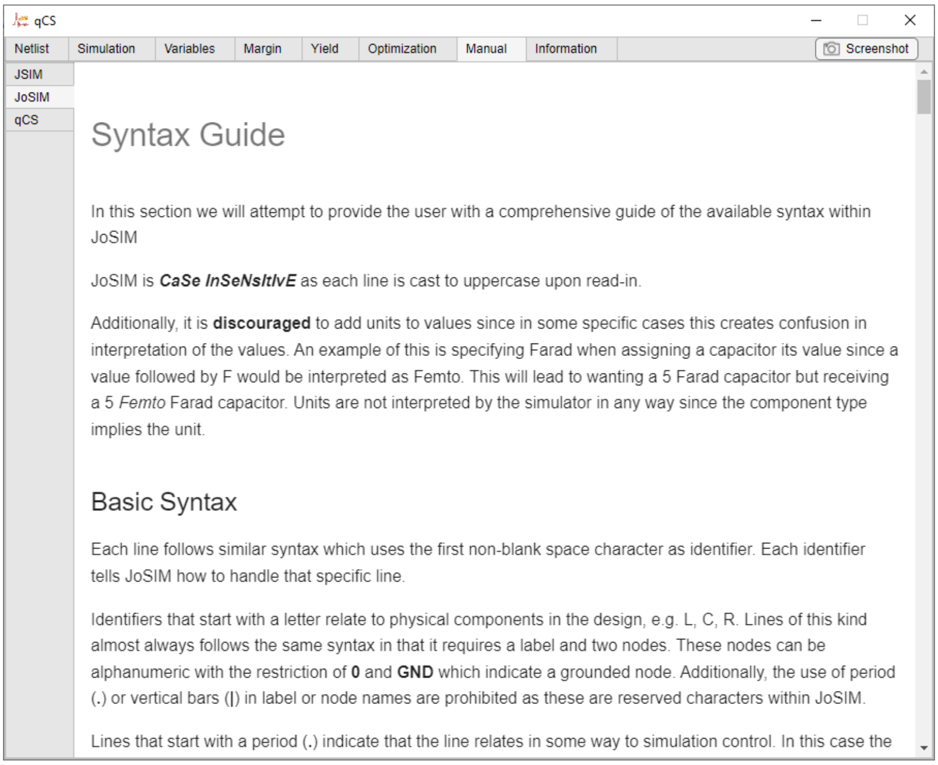

Figure 8: qCS: Manual tab

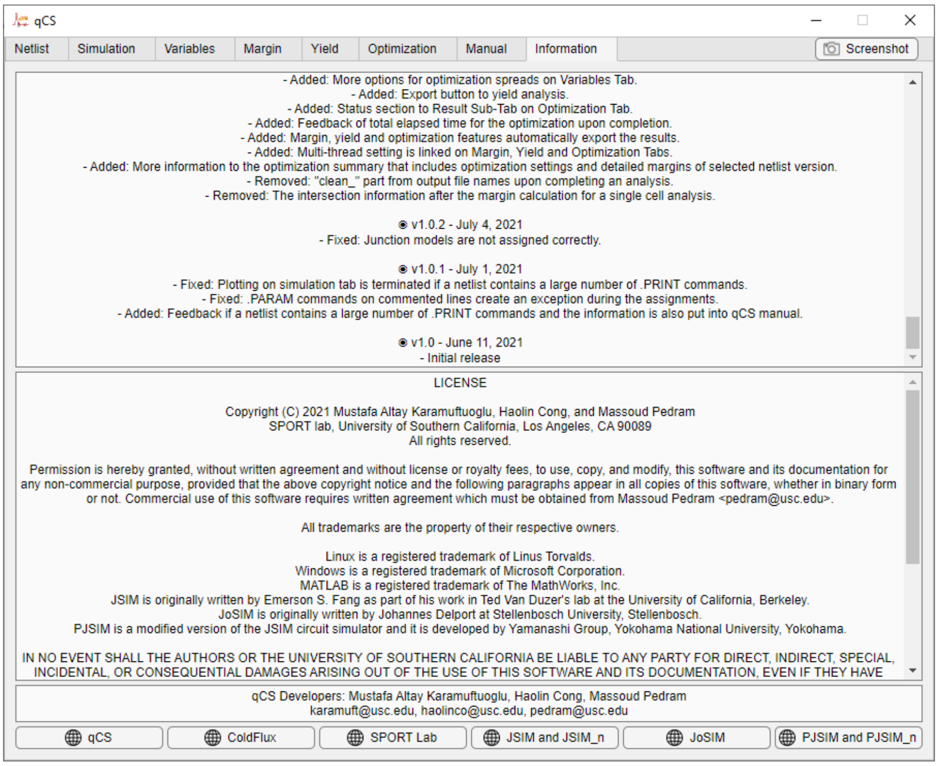

Figure 9: qCS: Information tab

2 Netlist File Selection and Editing

The tool allows only a single file selection, and it automatically detects if the netlist is used for an AQFP cell by searching the word "AQFP" in the file or on the file name. If the file does not find the word "AQFP", qCS will run in RSFQ mode. Before loading a netlist, make sure to select the simulator of choice among JSIM, JSIM_n, and JoSIM. The default simulator selection for qCS is defined as JSIM. The difference between JSIM and JSIM_n is only the noise component which allows adding local noise. The JSIM manual provided with qCS covers both versions. The selected netlist file will be presented in the text field. JJ model types are acquired from the netlist file, and they will be presented on the same tab. Additionally, shunt voltage scaling factors are automatically assigned for each model. This scaling factor is defined as the multiplication of a junction area and its shunt resistor value. If there is no shunt resistor, the value will be assigned as zero. For different scaling factors, different junction models should be created. The tool internally uses the first found junction and its shunt resistor. Afterwards, it applies the calculated scaling factors to the junction models. After obtaining the scaling factors, the user can make changes to the netlist on the interface and the Read Netlist button will be enabled to proceed with further configurations. The user must follow parameter definitions given in the manual of the selected simulator.

Even though the simulators have a way of defining the parameters, there are restrictions for the parameter assignments in the netlist. "RB" naming is restricted to use only on shunt resistors. The shunt resistor is placed parallel to its corresponding Josephson junction. If there is a series inductor, its name must start with "LRB". Each shunt resistor and inductor must contain its corresponding junction's name. The supported Josephson junction models are shown in Fig. 10. For example, if a junction is labeled as B01, its shunt resistor and inductor must be RB01 and LRB01, respectively.

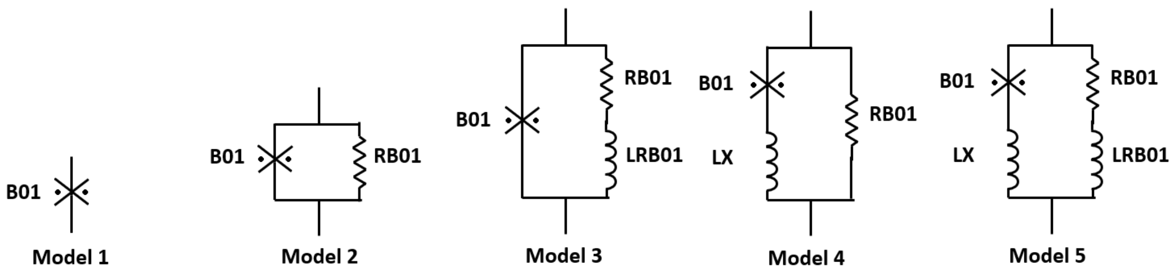

Figure 10: Supported Josephson junction models

Since there are different rules for different simulators, component declarations are important and they should be adjusted as stated in the following subsections. These declarations are given for qCS input file and the user must follow the restrictions to avoid errors. Otherwise, qCS might fail while reading the netlist or it might ignore some components even if they are suitable for the selected simulator. While using JoSIM, qCS changes the declarations with the syntax of WRspice mode into JSIM mode syntax. The bold **VALUE**s will be selected by qCS to put into a component table on the interface for the adjustments and the red colored texts in *Not Allowed* parts are the reason for the errors. One of the common reasons is the direct use of exponential values on component values.

Values in the declarations may use the suffixes given in Table 1. Note that the component values in the general forms must include prefix symbols, and for JoSIM, .PARAM netlist commands must use e-notation. This limitation is due to some MATLAB toolboxes which are not included in MCR, but this may be fixed in future releases. The assignments in qCS are case insensitive; thus, it treats or interprets uppercase and lowercase letters as being the same. Once the netlist file is loaded into qCS, everything will be internally assigned as uppercase letters.

Table 1: Available suffixes in qCS

Prefix Symbol	Prefix Name	E-Notation
F	Femto	1E-15
P	Pico	1E-12
N	Nano	1E-9
U	Micro	1E-6
M	Milli	1E-3
K	Kilo	1E+3
MEG	Mega	1E+6
G	Giga	1E+9

2.1 Resistor

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* R* NODE1 NODE2 **VALUE**
- *Example 1:* R01 11 12 1KOHM
- *Example 2:* R02x4 13 14 1000
- *Not Allowed:* R3 15 16 1E+3

qCS also supports [temp=<TEMP>] [neb=<FREQ>] optional parameters for JoSIM. Resistors' names starting with "RB" will be considered as possible shunt resistors. Shunt resistor names must start with "R" followed by the name of a Josephson junction. For example, RB01 will match with a junction named B01, but not with a junction named B01RX. Components identified as shunt resistors will not appear in the component list as they are internally assigned.

2.2 Inductor

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* L* NODE1 NODE2 **VALUE**
- *Example 1:* L11 11 12 1PH
- *Example 2:* L2 13 14 0.001U
- *Not Allowed:* L03rX 15 16 1E-12

qCS also supports [<FCHECK>] [IC=<VALUE>] optional parameters for JSIM and JSIM_n. The tool will automatically put FCHECK to the declaration when using JSIM and JSIM_n. Inductor names starting with "LRB" will be considered as possible inductor which is series to a shunt resistor. Inductor names must start with "L" followed by the name of a shunt resistor. For example, LRB01 will match with a junction named B01 and a shunt resistor named RB01, but not with a junction named B01TX or a shunt resistor named RB01TX. Components identified as inductors which are series to shunt resistors will not appear in the component list as they are internally assigned.

2.3 Capacitor

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* C* NODE1 NODE2 **VALUE**
- *Example 1:* C1 11 12 1PF
- *Example 2:* C2L4 13 14 0.001U
- *Not Allowed:* C03 15 16 1E-12

qCS also supports [IC=<VALUE>] optional parameter for JSIM and JSIM_n. Since there is no default assignment for this parameter, the internal assignment will be empty if it is not provided. This applies to all initial values stated as [IC=<VALUE>].

2.4 Josephson Junction

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* B* NODE1 NODE2 MODELNAME AREA=**VALUE**
- *Example 1:* B01rxTX 11 12 JJMITLL
- *Example 2:* B2 13 14 JJMITLL AREA=0.9
- *Not Allowed:* B3 15 16 JJMITLL AREA=900M
- *Not Allowed:* B04 17 18 JJMITLL AREA=9E+2M

If there is a third node that is defined for a JJ, qCS will erase the third node of the JJ and it will keep NODE1 and NODE2. The tool will automatically assign [AREA=1] to JJs with no scaling factor [AREA=<VALUE>]. qCS also supports [IC=<VALUE>] optional parameter for JSIM, JSIM_n and JoSIM. Additionally, there is support for the [<CON-DEV=DEVNAME>] optional parameter for JSIM and JSIM_n.

2.5 Transmission Line

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* T* NODE1 NODE2 NODE3 NODE4 TD=VALUE Z0=**VALUE**
- *Example 1:* T1 11 12 111 112 TD=100PS Z0=50OHM
- *Example 2:* T022 13 14 113 114 LOSSLESS Z0=50 TD=100P
- *Example 3:* Tx3 15 16 115 116 LOSSLESS TD=100P
- *Not Allowed:* TX4 17 18 117 118 TD=100E-12 Z0=0.05E+3

If there is no assignment for TD and Z0, qCS will assign 50OHM and 1S, respectively. The tool will also automatically put LOSSLESS to the declaration.

2.6 Mutual Inductance

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* K* LXX1 LXX2 **VALUE**
- *Example 1:* K011 L01 L02 0.5
- *Example 2:* K2B L03 L04 -0.5
- *Not Allowed:* K3 L05 L06 500E-3

2.7 Subcircuits

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* X* SUBCKTNAME NODE1 NODE2 ...
- *Example 1:* Xjtl1 JTL 11 12
- *Example 2:* XSPL2 JTL 13

If SUBCKTNAME is placed at the end of the declaration which is acceptable for JoSIM, qCS will automatically adjust it in the way shown in the general form above. Moreover, the user must follow the wrapping control syntax (.SUBCKT and .ENDS) stated in simulator manuals for subcircuit designs. The subcircuit components (X* in the general form) will not be shown in the component table since there is no value to adjust.

2.8 Dependent Sources

There are four different dependent sources.

2.8.1 Current Controlled Current Source

- *Applies to:* JoSIM
- *General Form:* F* NODE1 NODE2 NODE3 NODE4 **VALUE**
- *Example 1:* F01x 11 12 13 14 1
- *Not Allowed:* F2 15 16 17 18 10E-1

2.8.2 Current Controlled Voltage Source

- *Applies to:* JoSIM
- *General Form:* H* NODE1 NODE2 NODE3 NODE4 **VALUE**
- *Example 1:* H1X 11 12 13 14 1
- *Not Allowed:* H022 15 16 17 18 10E-1

2.8.3 Voltage Controlled Current Source

- *Applies to:* JoSIM
- *General Form:* G* NODE1 NODE2 NODE3 NODE4 **VALUE**
- *Example 1:* G1y 11 12 13 14 1
- *Not Allowed:* G22 15 16 17 18 10E-1

2.8.4 Voltage Controlled Voltage Source

- *Applies to:* JoSIM
- *General Form:* E* NODE1 NODE2 NODE3 NODE4 **VALUE**
- *Example 1:* Etx1 11 12 13 14 1
- *Not Allowed:* ETX2 15 16 17 18 10E-1

2.9 Independent Sources

There are two different independent sources (voltage and current), but each source has multiple source types. Additionally, JoSIM has an extra independent source for phase. The same source types can be used for the phase source as well.

2.9.1 Voltage Source

The first type of source is a Voltage source. Inside the source type definition, the units should be written as Voltage (V).

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* V* NODE1 NODE2 **SOURCE TYPE**

2.9.2 Current Source

The second type of source is the Current source. Inside the source type definition, the units should be written as Ampere (A).

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* I* NODE1 NODE2 **SOURCE TYPE**

2.9.3 Phase Source

The third type of source is the Phase source. Phase source uses radians. Inside the source type definition, the units should be written as multiples of π (*pi).

- *Applies to:* JoSIM
- *General Form:* P* NODE1 NODE2 **SOURCE TYPE**

2.9.4 Source Types

The declarations should be placed to the source type part of the source component which includes a label and two nodes.

2.9.4.1 Piecewise Linear (PWL)

Only the first time point can be selected for the analysis.

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* PWL(0 0 T1 **A1** [T2 A2 ...])
- *Example 1:* pwl(0 0 10p 2.5m)
- *Not Allowed:* PWL(0 0 10ps 2.5E-3)

2.9.4.2 Pulse

The second amplitude can be selected for the analysis. Even though some parameters are optional for different simulators, qCS expects that the components as in the general form.

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* PULSE(V1 **V2** TD TR TF PW PER)
- *Example 1:* puLSe(0 1M 0PS 2PS 2PS 10PS 50PS)
- *Not Allowed:* PULSE(0 1E-3 0 2E-12 2E-12 10E-12 50E-12)

2.9.4.3 Sinusoidal (SIN)

The second amplitude can be selected for the analysis. Even though some parameters are optional for different simulators, qCS expects that the components as in the general form.

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* SIN(A0 **A** FREQ TD THETA)
- *Example 1:* SiN(0 1MV 100MEGHZ 0US 0)
- *Not Allowed:* sIN(0 1E-3 100E+6 0U 0)

2.9.4.4 Custom Waveform (CUS)

The scaling factor can be selected for the analysis. Even though some parameters are optional for the simulator, qCS expects that the components as in the general form.

- *Applies to:* JoSIM
- *General Form:* CUS(WAVEFILE TS **SF** IM TD PER)
- *Example 1:* cus(*/home/waveform_file* 1P 2 2 10PS 0)
- *Not Allowed:* CUS(*/home/waveform_file* 1E-12 2 2 10E-12S 0)

2.9.4.5 DC

The amplitude can be selected for the analysis.

- *Applies to:* JoSIM
- *General Form:* DC **A**
- *Example 1:* dc 2.5m
- *Not Allowed:* dC 25E-4

2.9.4.6 Noise

The amplitude can be selected for the analysis. Even though some parameters are optional for the simulator, qCS expects that the components as given in the general form.

- *Applies to:* JSIM_n and JoSIM
- *General Form (JSIM_n):* NOISE(0 **A** TSTEP TD)
- *Example 1:* Noise(0 10U 1P 1P)
- *Not Allowed:* NOISE(0 10U 1E-12 1E-12)
- *General Form (JoSIM):* NOISE(**A** TD TSTEP)
- *Example 1:* Noise(10U 1PS 1P)
- *Not Allowed:* NOISE(10E-6 1E-12S 1E-12)

2.9.4.7 Exponential (EXP)

The second amplitude can be selected for the analysis.

- *Applies to:* JoSIM
- *General Form:* EXP(A1 **A2** TD1 TAO1 TD2 TAO2)
- *Example 1:* EXP(1 5 0S 2PS 1PS 1PS)
- *Not Allowed:* exp(1 5 0S 2E-12S 1E-12S 1E-12S)

2.10 Model

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* .MODEL MODELNAME JJ([PARAMETER=VALUE])
- *Example 1:* .model JJMODEL1 JJ(RTYPE=0, ICRIT=250uA, CAP=1.32PF)
- *Example 2:* .modEL jjmod1 JJ(RTYPE=1, VG=2.6mV, ICRIT=0.1mA)

qCS assigns a scaling factor for each defined model for JJs. Therefore, the user must make sure to define multiple models if they have shunted and unshunted JJs at the same time and assign them to corresponding JJs. For other optional parameters of the model command, the user must check the simulator manuals.

2.11 Transient Analysis

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form:* .TRAN TSTEP TSTOP PSTART PSTEP
- *Example 1:* .TRAN 1PS 100PS 20PS 1PS
- *Example 2:* .tran 0.2P 2.2N 0 0.2P
- *Not Allowed:* .TRAN 0.2E-12S 2.2E-9S 0 0.2E-12

It should be noted that PSTART and PSTEP parameters are optional for all simulators. However, qCS uses the default values of JSIM for these parameters. The default values for PSTART and PSTEP are 0S and 1PS, respectively. Therefore, when assigning a value to these parameters while using JoSIM, the user must make sure that PSTEP is larger or equal to TSTEP as is stated in the JoSIM manual. Moreover, it is the user's responsibility to determine transient values for the correct operation. Simulators might give an integration error and qCS will consider this case as an incorrect operation. Note that if any error is detected by qCS, it might interrupt the process and terminate the analysis.

2.12 Option Specifications

- *Applies to:* JSIM and JSIM_n
- *General Form:* .OPTIONS [PARAMETER=VALUE]
- *Example 1:* .options RELTOL=0.01 MAXPHISTEP=1.5
- *Example 2:* .OPTIONS NUMDGT=3

If there is no option command in the netlist, qCS automatically assigns default values to the option values while using JSIM and JSIM_n. See the simulator document for the details of this command.

2.13 Parameters

- *Applies to:* JoSIM
- *General Form:* .PARAM VARNAME=EXPRESSION
- *Example 1:* .PARAM SCALING=1.0
- *Example 2:* .param L01=1e-3*(1/SCALING-(1-SCALING))
- *Example 3:* .PARAM L02=2u*L01

As mentioned in the beginning of this section, even though exponential expressions are not allowed for direct component value assignments in qCS while using JoSIM, the user can adjust or assign values by using ".PARAM" command. qCS will calculate these parameters and assign them to the related component values. After assigning the values, ".PARAM" commands will be removed from the imported netlist. To make sure that there is no error during the calculation, do not put any whitespace. Whitespaces are allowed but not every corner case is tested.

2.14 Include

- *Applies to:* JoSIM
- *General Form:* .INCLUDE RELATIVE_PATH_TO_FILE
- *Example 1:* .include /home/ABC/example_CENTOS.cir
- *Example 2:* .INCLUDE C:\Users\ABC\Downloads\example_WINDOWS.cir

The example 1 and 2 given above are for CentOS 7 and Windows 10 operating systems, respectively. Make sure that the file path is correct and avoid whitespaces in the directory. Upon accessing the file, qCS will take the data and merge it with the imported netlist since the tool only allows accessing one file at a time.

2.15 Output

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form 1:* .PRINT PRINTTYPE DEVICE
- *General Form 2:* .PRINT PRINTTYPE NODE
- *Example 1:* .print DEVI R01
- *Example 2:* .PRINT NODEV 11 22

JoSIM has three different commands for generating the output data. Among ".PRINT", ".PLOT" and ".SAVE", use ".PRINT" command to keep the consistency. qCS still converts every ".PLOT" and ".SAVE" commands into ".PRINT". Furthermore, the tool will divide the multiple devices stated after ".PRINT". It should be noted that the separator between the subcircuit name and its components for ".PRINT" command is a period or a vertical bar for JoSIM while JSIM and JSIM_n use an underscore for the same purpose. By following this idea, same operation can be performed with the following examples 3 and 4 for JSIM/JSIM_n and JoSIM, respectively.

- *Example 3 (JSIM/JSIM_n):* .PRINT DEVI X01_L01
- *Example 4 (JoSIM):* .print DEVI L01|X01

These printing commands can be placed into a control block which has a control syntax of ".CONTROL" and ".ENDC". The devices or nodes within the control block do not require any printing command. However, qCS gets the control block and puts all devices and nodes into the individual ".PRINT" command. Each of these printing commands should be placed after ".FILE" command which puts the data into the corresponding file. ".FILE" commands define the number of cells to be optimized. For multiple cell analysis, the user must provide multiple ".FILE" commands which have unique file names. Each selected cell should be in the same order with ".FILE" commands and the data within the files will be assigned to the corresponding selected cell.

- *Applies to:* JSIM, JSIM_n and JoSIM
- *General Form 3:* .FILE FILENAME
- *Example 5:* .file FILENAME1.DAT

- *Ex. 5 Data:* .PRINT DEVI L01|OR2
- *Example 6:* .FILE FILENAME2.DAT
- *Ex. 6 Data:* .PRINT DEVI L01|XOR2

For instance, if we use examples 5 and 6 within the same netlist for the optimization of OR and XOR logic gates, data provided in example 5 will be considered for the analysis of OR gate, and example 6 will be considered for the analysis of XOR gate. Therefore, the user needs to match the file order in the case of multiple-cell optimization. On the other hand, if there is no file command in the netlist, qCS will automatically create one for the user.

2.16 Unused Netlist Commands

Global thermal noise temperature and bandwidth commands are disabled to keep the analysis accurate. Therefore, additional ".TEMP" and ".NEB" commands in JoSIM are not supported on qCS. Moreover, since parameter spread is applied on the selected parameters for the analysis, the global spread command ".SPREAD" in JoSIM is not supported on qCS. The purpose of the IV curve for a specified JJ model does not fit the concept of qCS. Thus, it also not supported on qCS.

3 Simulation

To optimize the circuit parameters, the netlist simulation must be completed without an error. The user must run the selected netlist on this tab to enable margin calculation, yield calculation, and optimization features. Depending on the number of parameters to be plotted, the interface will adjust its result windows. Additionally, this Simulation tab helps the user to identify the pattern and use the correct desired timing.

Upon successfully running the simulation, there will be checkboxes for observing the data in the analysis. This feature allows the user to run the simulation for comparing multiple nodes and it is possible to exclude plotting data for the analysis by making its checkbox value zero. Moreover, since qCS performs pulse-based analysis, the user must select the plotted data that contains pulses. This will delete the internally assigned ".PRINT" command on the netlist.

For JSIM and JSIM_n, only one node at a time is allowed while using ".PRINT" command. However, JoSIM allows multiple observabilities on the same command. When loading the netlist, if JoSIM is selected for the simulator, ".SAVE" and ".PLOT" commands will be changed into ".PRINT" commands and multiple nodes on a single ".PRINT" command will be divided into unique lines to give qCS more flexibility.

For writing the output data into a file, ".FILE" command is used. Each ".FILE" command corresponds to a different cell optimization. It means that if the user wants to independently analyze two cells at a time, they need to define two ".FILE" commands in the netlist. After this command, the related data should be written into the output file by using the corresponding ".PRINT" command. So, each ".PRINT" command is assigned to a parent ".FILE" command that occurs first on top of ".PRINT" command. The number of cells to be optimized will be shown on the interface together with the number of observation points. The user can zoom to the plotted data and qCS allows them to save the plotted data.

JSIM has an undocumented limit for printing data to output files. This limit is observed as 19. Therefore, the simulation window limit is set to 19 plots for the simulators. Additionally, since the resize function is not activated yet, the number of ".PRINT" commands is recommended to be a maximum of 10 for the current window size.

4 Variable Parameter Specification

A single component selection or a single complete sub-circuit selection is allowed on this panel. After the selection on the netlist component tree, related components will be added to the component table. Each component has correlation group ID, minimum, default, and maximum columns. The group ID column represents the components that carry the same values as their correlated component during the yield analysis or optimization process. To assign the same group ID, the component must be in the same cell. Minimum and maximum limits are used for the optimization process and are initially defined as -50% and +50% of the default value. These columns do not affect the margin calculation or yield analysis, but they define the search space for the optimization. The maximum number of cells to be optimized will be set as the number of ".FILE" lines in the netlist. Each circuit that is required to be optimized individually should have its own ".FILE" line and ".PRINT" lines for its components. If the user exceeds the limit of the assigned number of cells, the additional cells will be assigned as global cells and their components will be global components. It means that these global components will be affecting both of the cells at the same time and the cells are not independent anymore. The components that are assigned as global can be grouped with other cell components even though this is not allowed in normal cases. This feature gives more flexibility to the tool user.

Warning: When editing the values of a component in the table, use the ENTER key from the keyboard or simply click on the empty area of the table. There is an internal assignment and control issue due to MATLAB 2020b App Designer limitations. Thus, when putting a new value, avoid L-clicking with the mouse on the table's other rows/columns.

5 Margin Calculation

To calculate the working margin range of the given netlist, the tool uses several parameters to identify the correct operation. For the calculation on each simulation, the tool finds analog pulses and the expected height of these pulses is defined with the "Minimum Pulse Height" parameter. The sensitivity of margin calculation is adjusted with the "Step Size" parameter. Additionally, to speed up the calculation process, multi-threading can be enabled by the user and the maximum number of threads is defined as the number of computer's cores. The output pattern number should be equal to the number of nodes that are printed to the simulator output file. Multiple patterns can be written if the number of ".PRINT" lines increased on the netlist for a related ".FILE" line.

The pattern has three different parameters for each definition: start time, end time, and the number of pulses. Start time and end time define the time interval and the next information provides the number of pulses within this period. Relations for pulse number specifications include ==, <=, >=, << and >>. The tool simply checks the number of pulses that are above the defined pulse height and compares the number for the expected time interval. If the process requires checking negative pulses, the pattern should include a fourth parameter that defines the number of negative pulses for AQFP mode. It should be noted that the initial values of pulse height, pulse width, and expected output band for the pulse are internally calculated depending on the simulation data. The user must verify this before proceeding to the analysis. Depending on pulse specification values, the user can decide to automatically generate the expected pattern timing by using the Fill button. Fill button will check the data simulated in Simulation tab and put the pulse conditions accordingly. To compare and verify the timing, use Check button.

Note that the complete margin analysis can be achieved by adding all the cell components to the component table. Partial selections do not indicate the correct results.

The pattern definition examples are shown below.

- **Example 1:** 100ps 1ns ==0 1ns 1.2ns ==1
- **Example 2:** 100ps 500ps >>2 300ps 700ps ==2
- **Example 3:** 0s 500ps >=0 >=0 500ps 1000ps ==0 ==2

In example 1, there is only one equality condition after a given time interval. It means that this pattern is applied when qCS is in RSFQ mode. In this example, there is no expected pulse between 10 ps and 1 ns. The next time interval means that there must be a pulse between the simulation time of 1 ns and 1.2 ns.

Example 2 above is also given for RSFQ mode. However, there is a maximum limit for found pulses which is set as 1. This means that even if there is no pulse between the specified times, it will be considered as a correct operation. Another point is that the time intervals can overlap and there is no limitation for it. However, it is the user's responsibility to confirm the time specification. qCS provides an automated filling option and it makes sure that there is no overlap between the specified intervals.

The last example has two inequalities and it corresponds to AQFP mode. For this example, any pulse that arrives before 500 ps will be ignored. The next time interval states that there will be no positive pulses but two negative pulses will appear. A negative pulse corresponds to logic-0 in AQFP. In order to find and obtain these pulses correctly, the user needs to provide additional pulse specifications which will be discussed later in this document.

Once the specifications are completed, the user can start the calculation by L-clicking to Calculate button. Note that if the simulator gives an error such as an integration error during the calculation, that particular parameter set for the netlist will be considered as an incorrect operation and the margin calculation will continue. There will be no pop-up warning regarding this case. Therefore, it is the user's responsibility to assign satisfactory transient values in the netlist for the selected simulator.

6 Yield Analysis

To calculate the yield, there are additional parameters that need defining. MC sample parameter simply provides the information for the number of netlists. Parameter STD is given for the standard deviation of selected parameters. It should be noted that the adjustments will only affect the components that are selected and their values will be within 3σ control limits during the randomization process. The adjustment box for this value can be added to the interface in future releases.

After the yield analysis, the Yield percentage will be shown, and the bar graph will be updated. Additionally, if there are correlated components, the tool internally assigns them and as a result, grouped components will have similar values but with minor differences to make the scenario more realistic. However, by selecting the uncorrelated checkbox, the randomization of components will be independent even if they are initially assigned as correlated components. If there are multiple selected cells, qCS will create a unique netlist for each cell and check them individually. However, there might be cases where multiple cells fail at the same time. Therefore, the number assigned to all failed bars might not be the summation of individual failure on the cell bars. If there are global components, they will be put into the cell component listing and evaluated together. The user can save the data by hovering the mouse to the top right corner of the graph.

7 Optimization

The tool uses a hybrid algorithm (Automatic Niching Particle Swarm Optimization, ANPSO, algorithm and Fireworks Algorithm, FA) to optimize the circuits. It compares the expected control patterns with the patterns obtained from the simulation and it uses a hybrid algorithm called ANPS-FW (Automatic Niching Particle Swarm Optimization algorithm and Fireworks algorithm) for the optimization of RSFQ and AQFP circuits. This algorithm is specifically developed for qCS.

In this tool, a set of particles will search through the search space for global search, and on each iteration, every particle will act as a firework which will create sparks for better local search. By combining these two algorithms, the tool can search for better component values locally and globally. If the user is satisfied with the current result and wants to terminate the optimization process, it can be simply stopped by using the Stop button under the Log subtab. There are breakpoints between the optimization steps and some of the loops are uninterruptible. Therefore, upon clicking the Stop button, it might take some time to terminate the process depending on how many components are selected and how many particles are assigned. If the result table is filled with data, Export button will be enabled for creating related data files. The parameters in blue color on the interface are not affecting the algorithm and the other parameters are for experienced users to manipulate the optimization process. Moreover, the users can track the improvements and progress in Trend sub-tab.

qCS also supports the analysis utilizing phase data. Thus, if there is no pulse in the selected waveforms, the related boxes will be disabled. Otherwise, the tool will initially assign values obtained from the waveforms and it is expected that the user must verify them before proceeding.

8 Examples

This guide provides two files for each of the RSFQ and AQFP netlists. These files are adjusted by following the restrictions stated in Section 2. RSFQ netlist is obtained from JoSIM GitHub which can be accessed through the hyperlink on Information tab and AQFP netlist is provided by Professor Christopher Ayala from Yokohama National University, Japan. The related netlist files stated below are provided with qCS.

- *RSFQ JSIM Example File:* EX_DCSFQ_JTL_SINK_JSIM.cir
- *RSFQ JoSIM Example File:* EX_DCSFQ_JTL_SINK_JOSIM.cir
- *AQFP JSIM Example File:* AQFP_BUFFER_CHAIN_JSIM.cir
- *AQFP JoSIM Example File:* AQFP_BUFFER_CHAIN_JOSIM.cir

The user has the flexibility to create a unique testbench for a cell but note that if there are a series of cells, the pulse timing error will be accumulated. Thus, in these files, appending "_TEST" on a subcircuit name identifies it as the one to be tested and this labeling is on the subcircuit definition.

8.1 RSFQ

8.1.1 Loading Netlist

A single netlist file can be loaded by using Browse button on Netlist tab. Upon successful operation, a message will appear. If there is a problem with the input file, qCS will state what the problem might be.

For this example, EX_DCSFQ_JTL_SINK_JOSIM.cir file under the Netlists folder is used as an input. Related operations are shown in Fig. 11 and 12.

As mentioned in Section 2, the shunt voltage scaling factor will be automatically calculated after reading the netlist by using the first Josephson junction scaling factor (AREA) and its shunt resistor value. This value is assigned to the defined Josephson junction (JJ) model and it will be applied to all JJs which have the same model definition. Before proceeding further, the user is allowed to make changes to the component values or add new commands to the netlist.

The netlist data will be converted into an object by clicking on the Read Netlist button. The confirmation message for this operation will appear on the interface as shown in Fig. 13.

8.1.2 Simulation

At this point, the user needs to proceed to Simulation tab in order to confirm the correct operation of the netlist. The number of plots will be automatically adjusted depending on the number of ".PRINT" commands in the netlist. It should be noted that each check box corresponds to a data set to be observed and the suitable selected data should contain pulses. Therefore, any other type of data selection may result in incorrect operation. As an example, only one plot (NODEV 4 0) is selected and shown in Fig. 14.

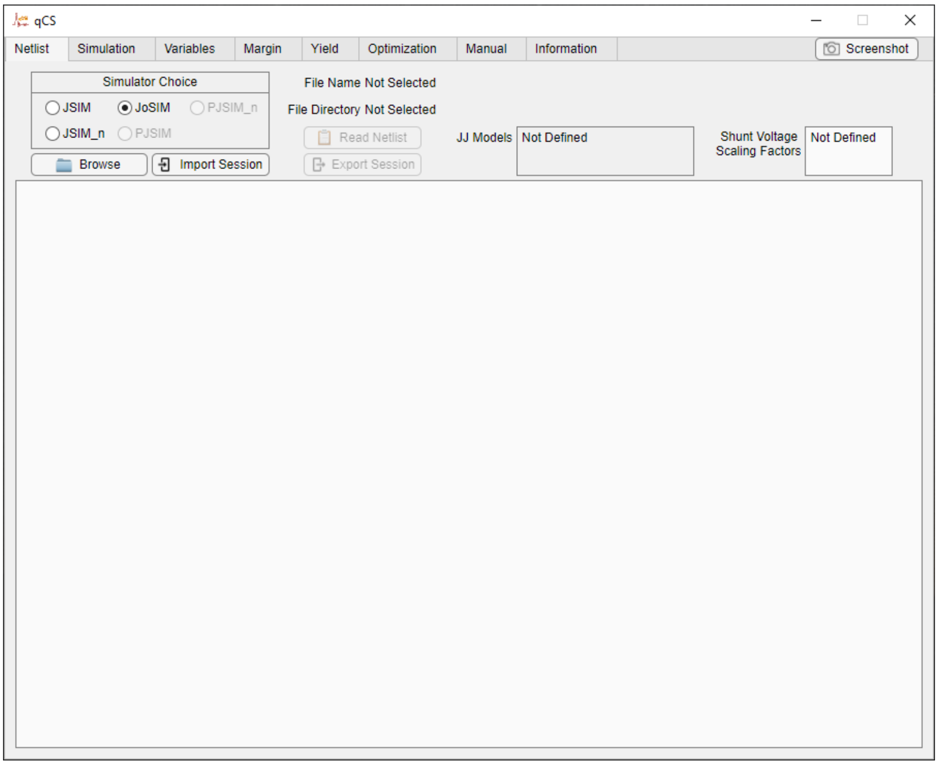

Figure 11: Netlist tab before opening a file.

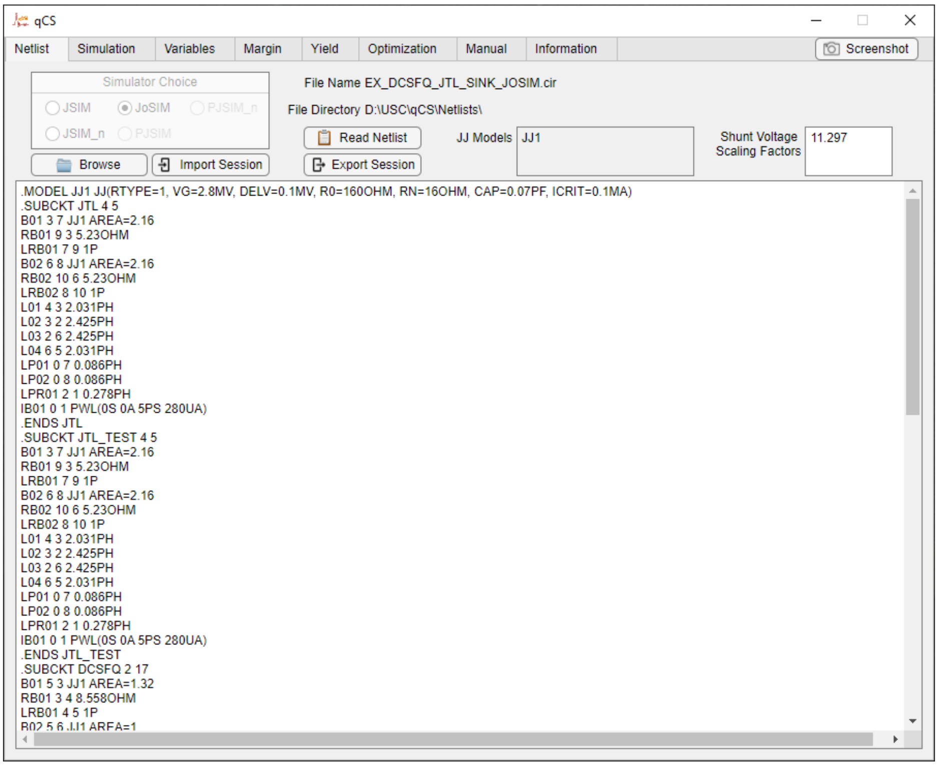

Figure 12: Netlist tab after opening a file.

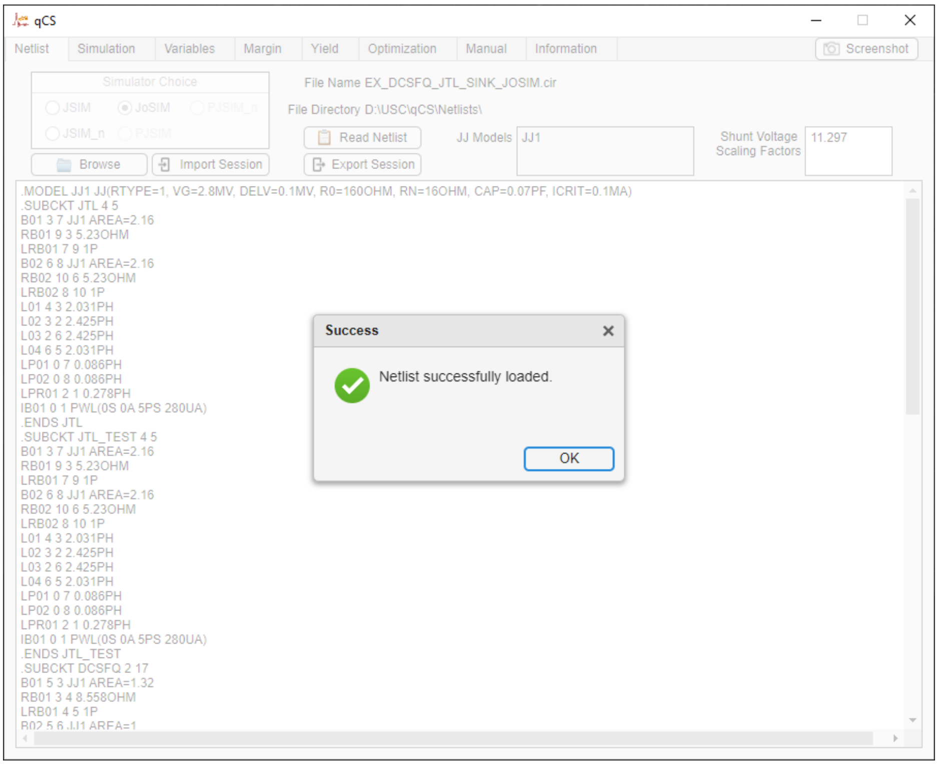

Figure 13: Netlist tab after reading the netlist.

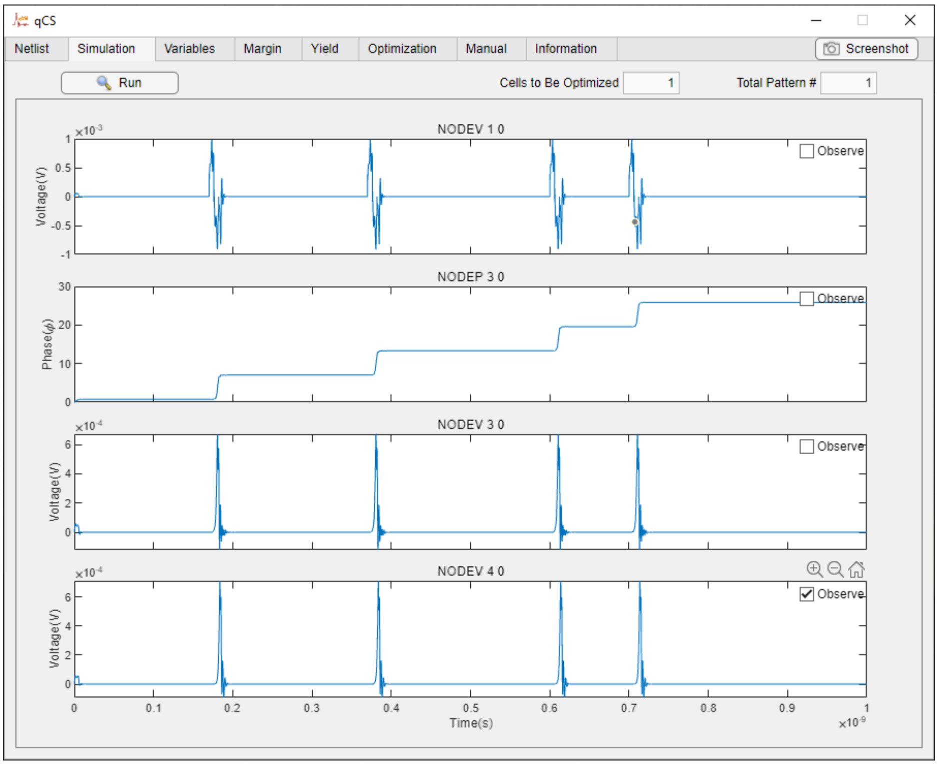

Figure 14: Simulate tab after completing the simulation.

8.1.3 Selecting Components

On Variables tab, the user is allowed to select the parameters included for the analysis. The parameters that are not selected will be ignored and their values will not be changed. To perform a correct analysis of a cell, select all components that possibly affect the results. For this example test, only two JJs are selected from the JTL_TEST cell by pressing the Add button. The selected components will appear in the large table. It is possible to assign a correlation between components; however, the component types should remain the same. The correlated components will have the same values for the optimization process. However, to make the situation more realistic, there will be a minor difference during the randomization process of yield analysis. Here, both of JJs are assigned to be correlated and their group ID is 1.

Upon selection, the list of cells will appear in the table at the top right corner with their corresponding cell number. If the cell number exceeds the number of ".FILE" commands, those cells will be assigned as global and their components will be considered as global components which will affect all selected cells at the same time. In other words, global parameters will create a dependency between other cells.

The parameter spread values shown at the top assign minimum and maximum boundary values for the optimization process. These values do not affect margin calculation or yield analysis. The default values are assigned as ±50%. The completed process mentioned above is shown in Fig. 15.

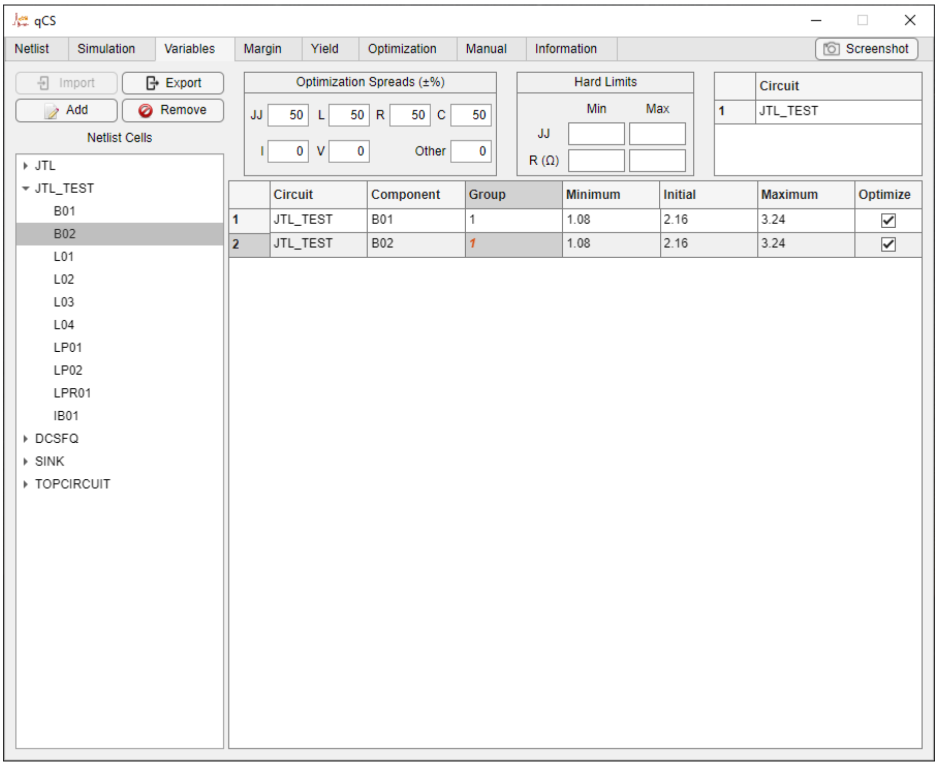

Figure 15: Variables tab after adding components.

8.1.4 Critical Margin Calculation

qCS is now ready to perform an analysis of the netlist. On Margin tab, the pulse height, pulse width, and output expected band information will be automatically assigned. These values are obtained from the data plotted on Simulation tab. It is the user's responsibility to check these values since they might give tight specifications. Additionally, the user needs to enter the expected output pattern. However, the Fill button can automatically fill this area by using the pulse specifications given in the same tab. To verify the found pulses, use the Check button. A new window will appear with the timing information of pulses. It should be noted that these pulses are found by using the pulse specifications and they are not related to the information given in the expected output pattern text box. The expected output pattern will be used deep in the calculation process for comparing the timing of pulses. The interface for the mentioned process is shown in Fig. 16 and 17.

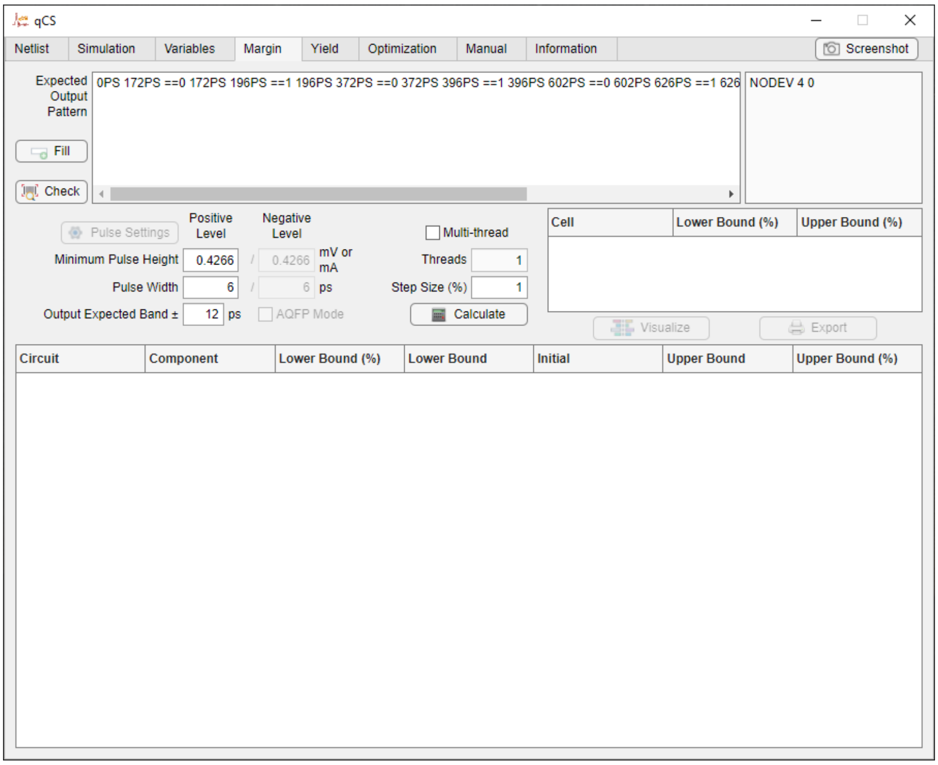

Figure 16: Margin tab after providing the specifications.

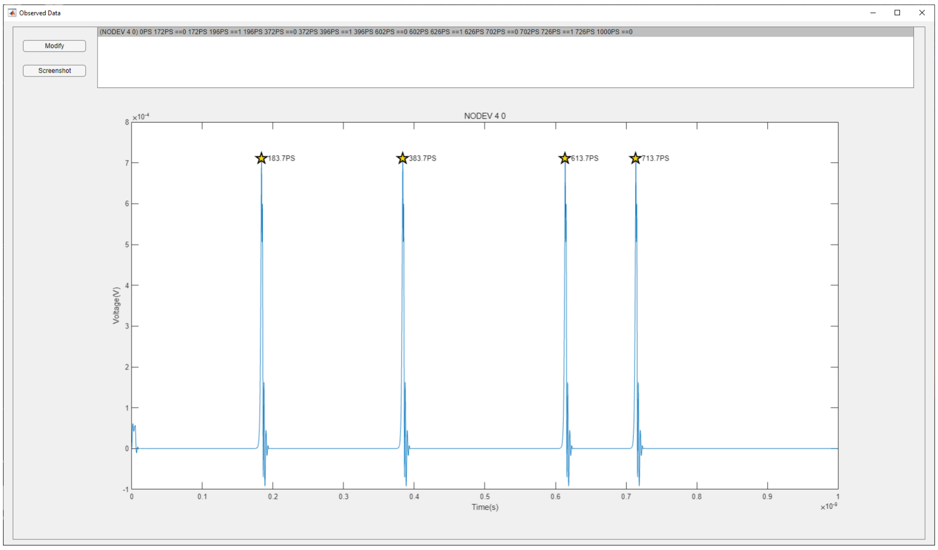

Figure 17: Waveform window after using Check button on Margin tab.

To start the margin calculation, click on the Calculate button. Upon the completion of the margin calculation, the results will appear in the table. Export button will create an Excel file that contains all the data presented. Moreover, the other specifications such as pulse height and pulse width will also be exported and put into a text file. The results for the example run are shown in Fig. 18.

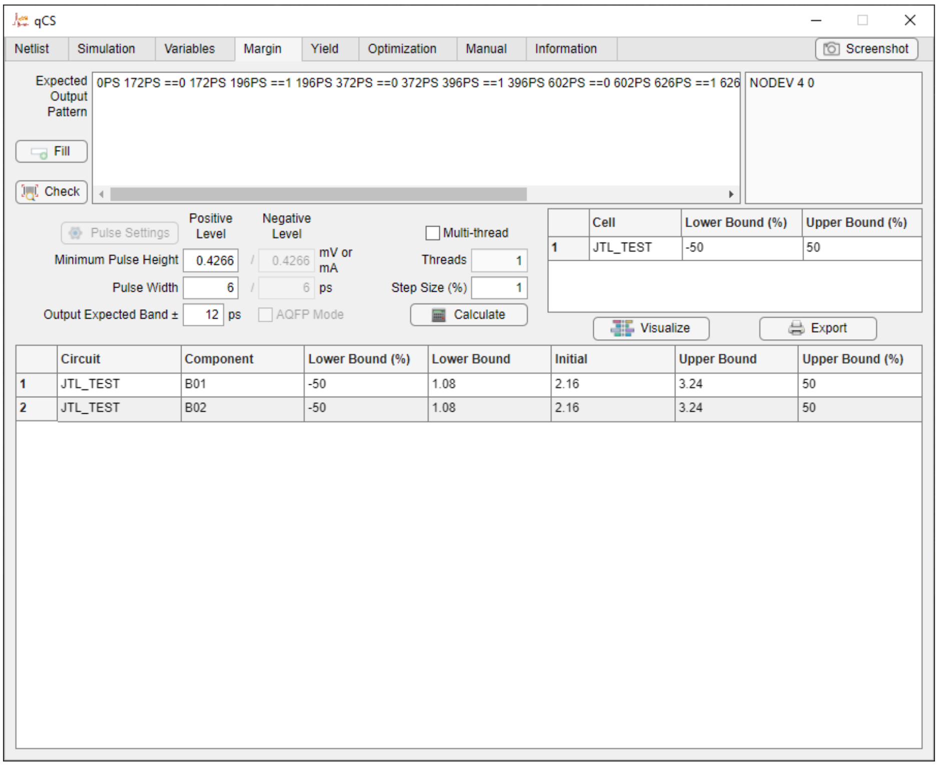

Figure 18: Margin results on Margin tab.

8.1.5 Yield Analysis

The pulse specifications and the expected output pattern will also be assigned into the related fields on Yield tab. For yield analysis, MC Sample # is set to 100. After the run is completed, the graph on this tab will be updated. The result of yield analysis is shown in Fig. 19.

8.1.6 Critical Margin Optimization

The other feature of qCS is cell optimization. In Optimization tab, there are several parameters that can adjust the optimization algorithm. Each parameter information is provided by tooltips on the interface. By going over each parameter, a related text will appear near the pointer. The parameters that are not blue are provided for experienced users since these parameters change the optimization algorithm significantly. For parameter details, see Section 1.7.6. By pressing the Optimize button, the process will start and the Result sub-tab will be automatically selected. In this sub-tab, the results will be shown and the Stop button under the Log sub-tab allows the termination of the optimization process. However, it should be noted that there are certain process loops that cannot be interrupted during the optimization. Therefore, the user might wait for a period of time after pressing the Stop button. The

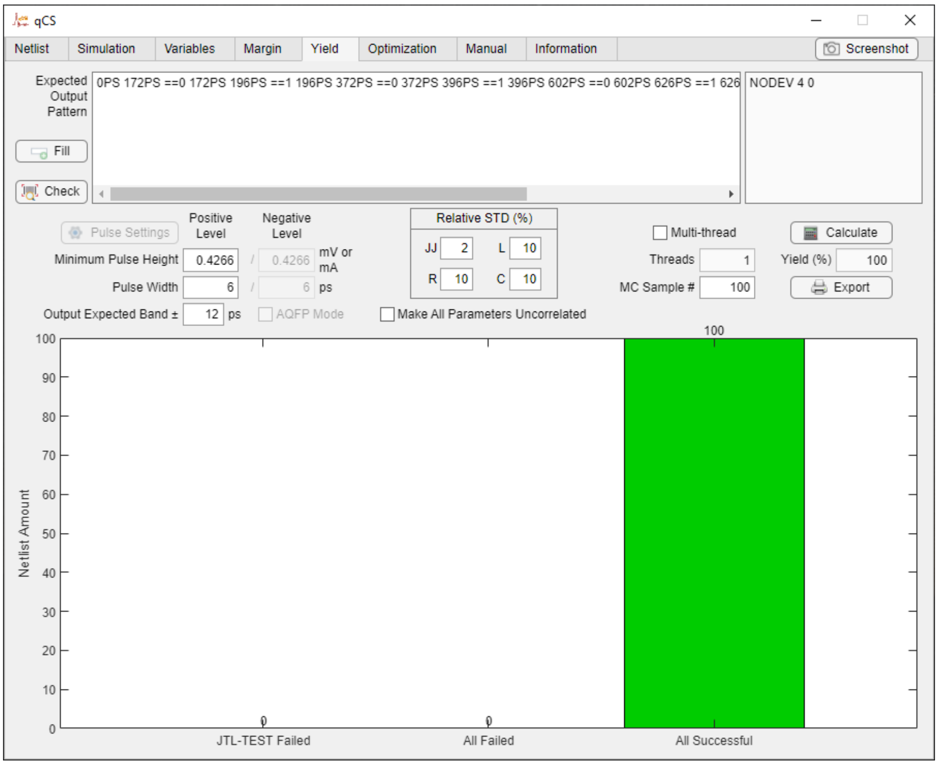

Figure 19: Yield analysis on Yield tab.

interface examples for the steps mentioned above are shown in Fig. 20, 21, 22, and 23.

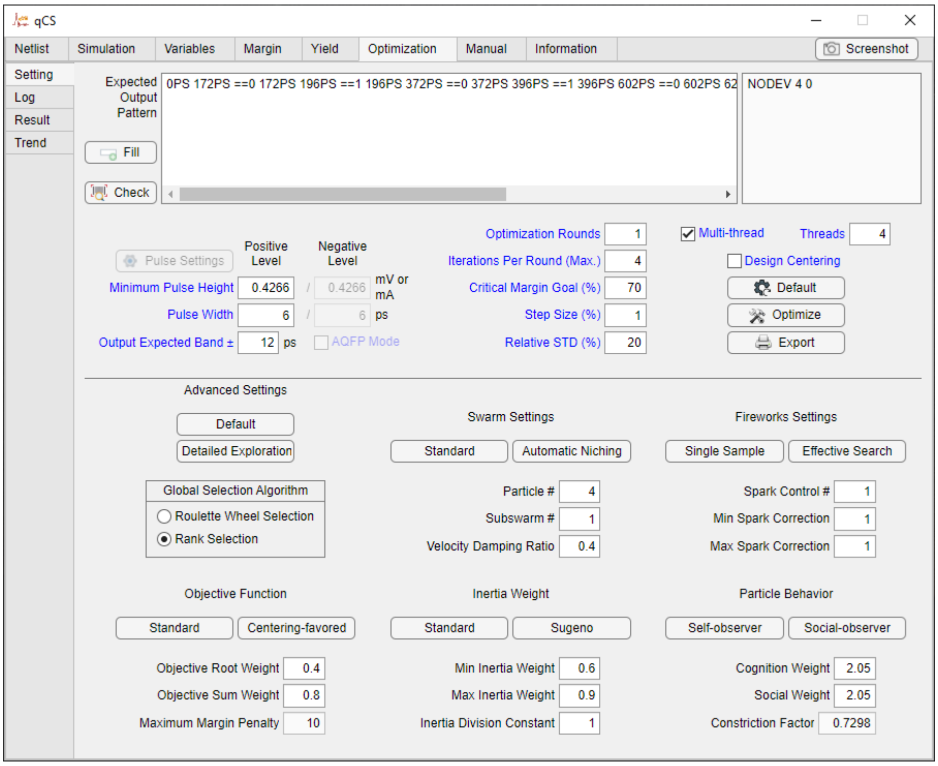

Figure 20: Optimization settings on Optimization tab.

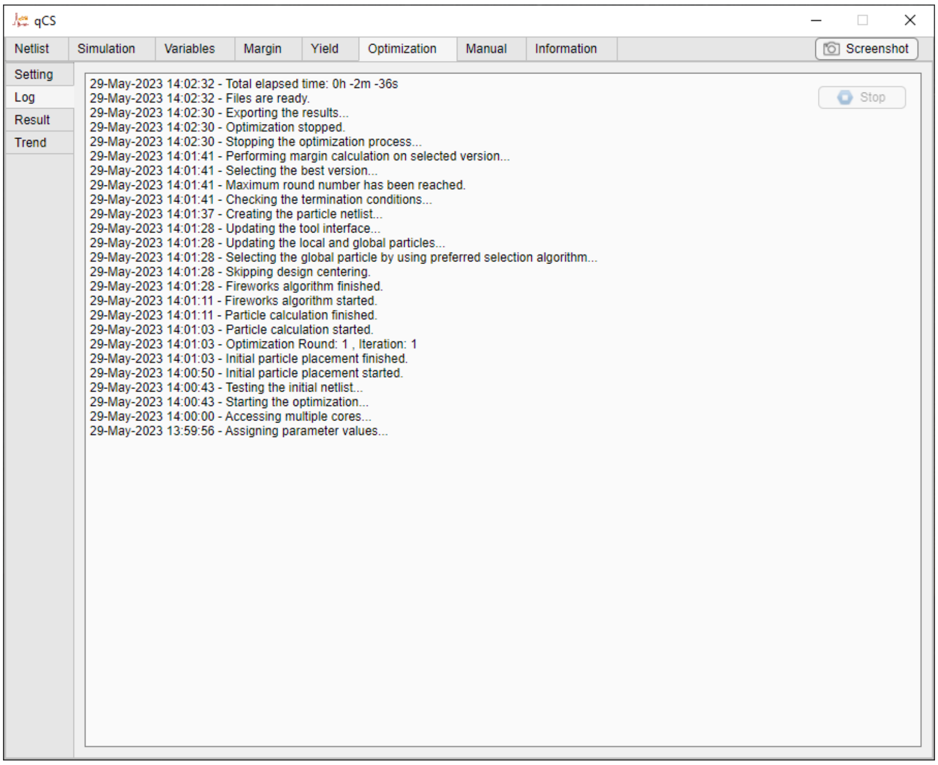

Figure 21: Optimization log on Optimization tab.

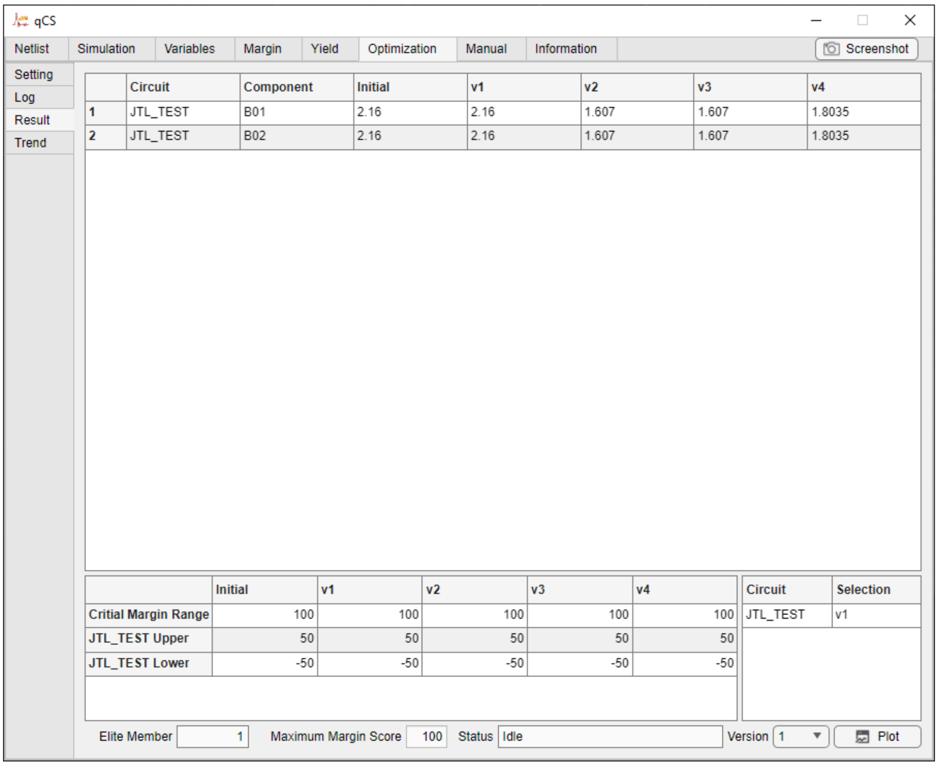

Figure 22: Optimization results on Optimization tab.

After obtaining results, qCS will automatically generate the netlist files and select the best among different versions. Even if some of the versions share the same critical margin, the tool will select the one with the smallest Euclidean distance to the original values. Here,

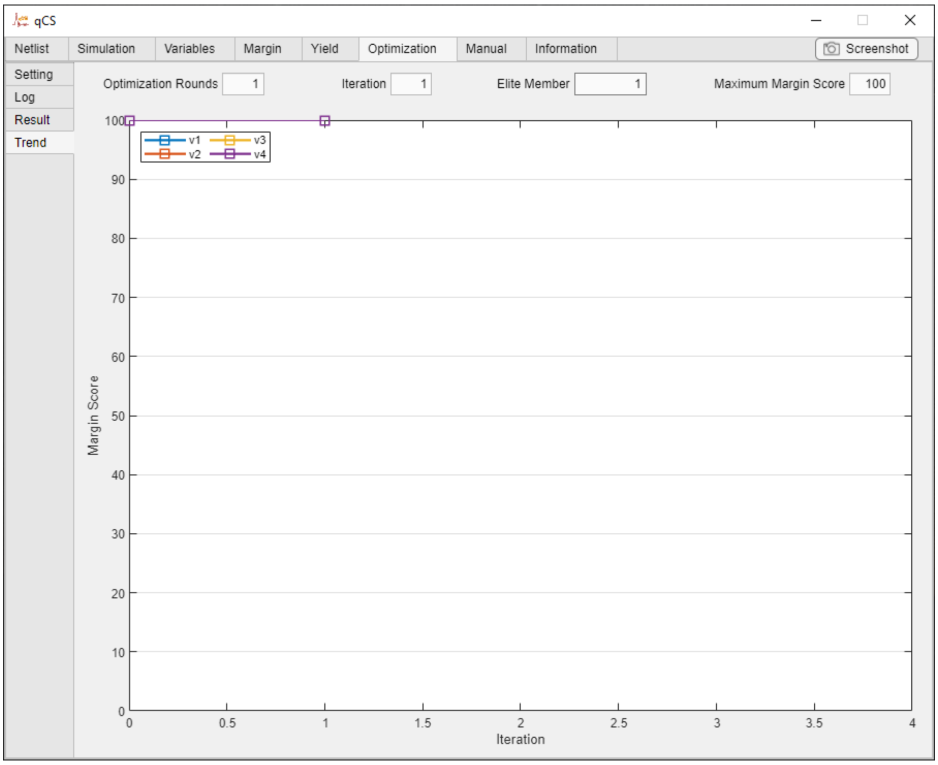

Figure 23: Optimization trend on Optimization tab.

the initial critical margin range already satisfies the margin goal. Therefore, the optimization is stopped after the first iteration, and the initial netlist values are returned. However, it should be noted that other components might have a lower margin range and they might be the component that determines the critical margin. Therefore, as previously stated, select all components that can affect the analysis. By using Plot button, the waveforms can be compared with the original waveform in Simulation tab. If the results are acceptable, the data shown on the interface can be placed into files by clicking Export button. Each iteration result will be plotted into Trend sub-tab. This concludes the qCS RSFQ JoSIM example.

8.2 AQFP

8.2.1 Loading Netlist

This process is similar to RSFQ mode except that there will be negative pulses for logic-0 in AQFP mode. A single netlist file can be loaded by using the Browse button on the interface. Upon successful operation, a message will appear. If there is a problem with the input file, qCS will state what the problem might be.

For this example, AQFP_BUFFER_CHAIN_JSIM.cir file under the Netlists folder is used as an input. Related operations are shown in Fig. 24 and 25.

As mentioned in Section 2, the shunt voltage scaling factor will be automatically calculated after reading the netlist by using the first Josephson Junction scaling factor (AREA) and its shunt resistor value. This value is assigned to the defined Josephson Junction (JJ) model and it will be applied to all JJs which have the same model definition. In this example, JJs are unshunted which means there is no shunt resistor parallel to a JJ. Before proceeding

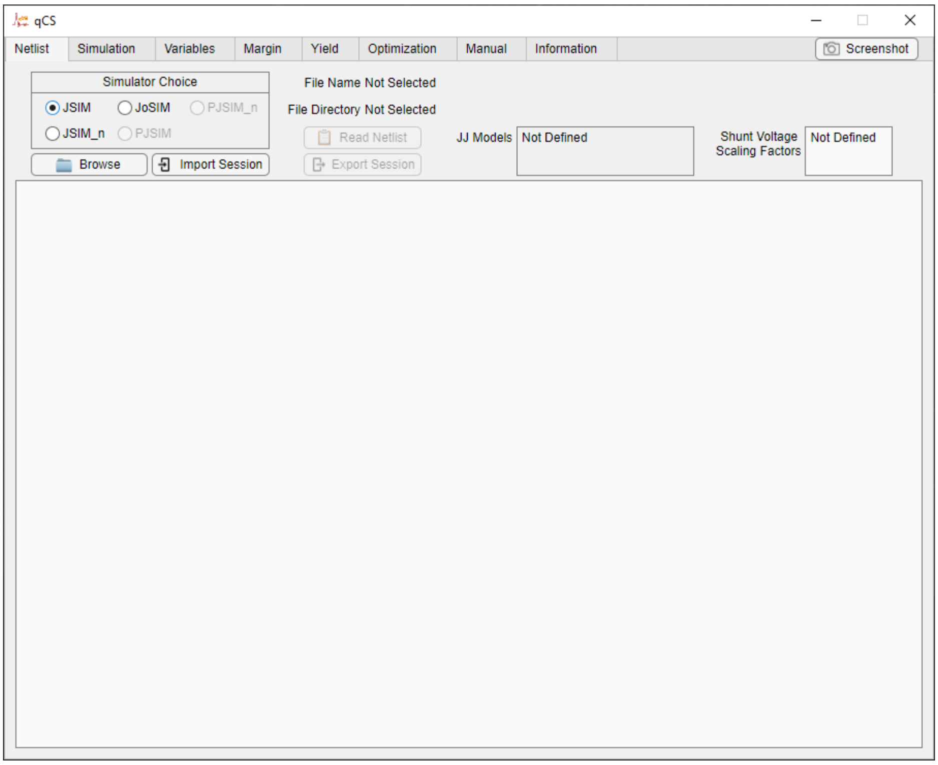

Figure 24: Netlist tab before opening a file.

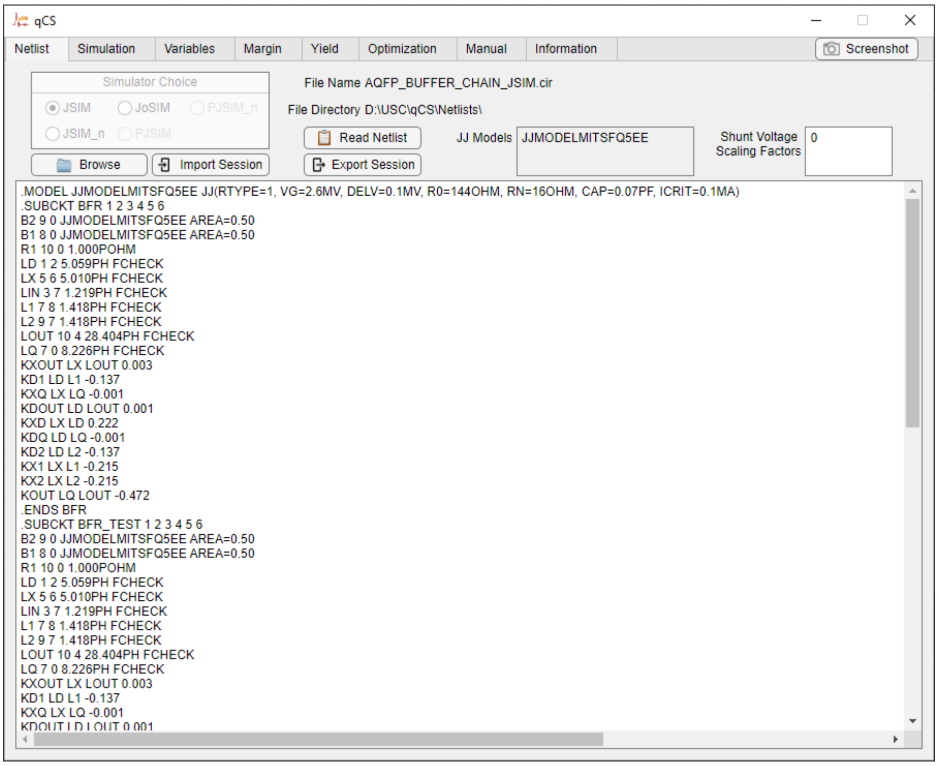

Figure 25: Netlist tab after opening a file.

further, the user is allowed to make changes to the component values or add new commands to the netlist.

The data will be converted into an object by clicking on the Read Netlist button. The confirmation message for this operation will appear on the interface as shown in Fig. 26.

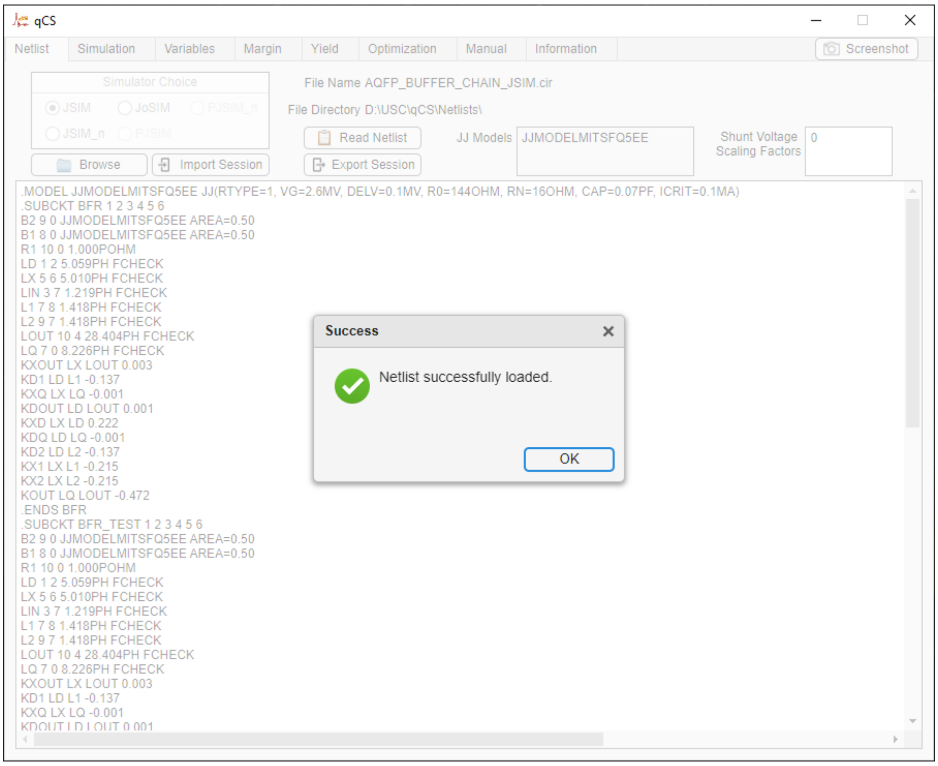

Figure 26: Netlist tab after reading the netlist.

8.2.2 Simulation

At this point, proceed to Simulation tab in order to confirm the correct operation of the netlist. The number of plots will be automatically adjusted depending on the number of ".PRINT" commands in the netlist. Each corresponds to a data set to be observed and the suitable selected data must contain pulse or phase data. Therefore, any other type of data selection may result in incorrect operation. As an example, only one plot (DEVI XI6-LQ) is selected and shown in Fig. 27.

8.2.3 Selecting Components

On Variables tab, the user is allowed to select the parameters included for the analysis. The parameters that are not selected will be ignored and their values will not be changed. To perform a correct analysis of a cell, select all components that possibly affect the results. For this example test, only two JJs are selected from BFR_TEST cell by pressing Add button. The selected components will appear in the large table. It is possible to assign a correlation between components; however, the component types should remain the same. The correlated components will have the same values for the optimization process but there will be a minor difference during the randomization process of yield analysis to make the situation more realistic. Here, both of JJs are assigned to be correlated and their group ID is 1.

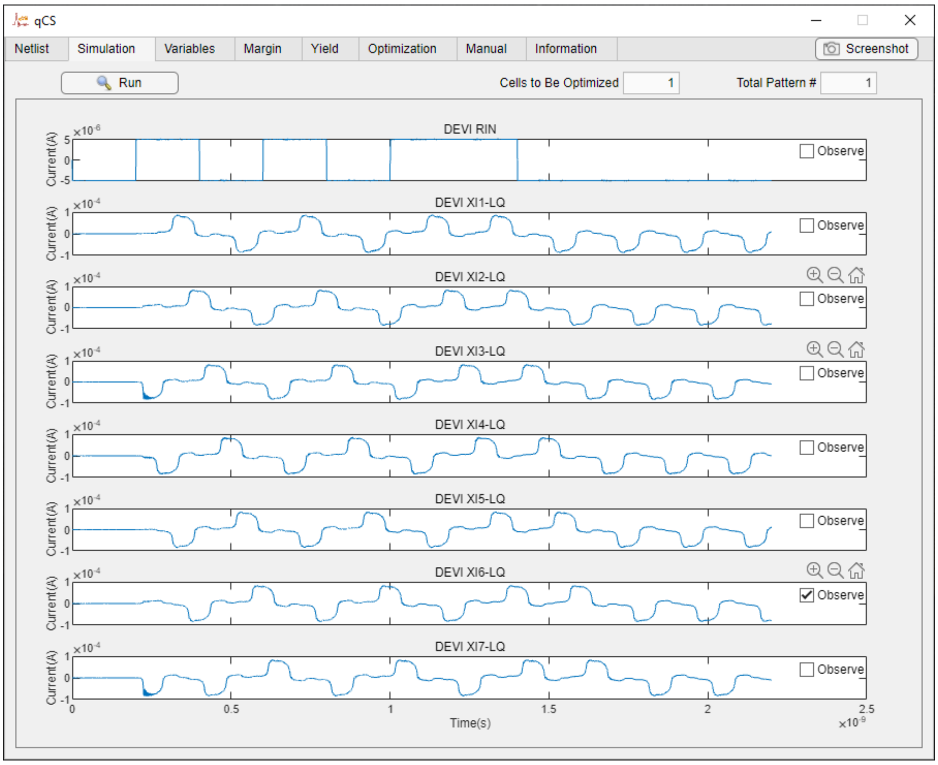

Figure 27: Simulate tab after completing the simulation.

Upon selection, the list of cells will appear in the table at the top right corner with their corresponding cell number. If the cell number exceeds the number of ".FILE" commands, those cells will be assigned as global and their components will be considered as global components which will affect all selected cells at the same time. In other words, global parameters will create a dependency between other cells. The parameter spread values shown at the top assign minimum and maximum boundary values for the optimization process. These values do not affect margin calculation or yield analysis. The default values are assigned as $\pm$50%. The completed process mentioned above is shown in Fig. 28.

8.2.4 Critical Margin Calculation

qCS is now ready to perform an analysis of the netlist. On Margin tab, the pulse height, pulse width, and output expected band information will be automatically assigned. Additionally, the negative pulse height and width will also be enabled since qCS is in AQFP mode. These values are obtained from the data plotted on Simulation tab. It is the user's responsibility to check these values since they might give tight specifications. It should be noted that the pulse width and its output expected band depend on the operating frequency. Additionally, the user needs to enter the expected output pattern. However, the Fill button can automatically fill this area by using the pulse specifications given in the same tab. To verify the found pulses, use the Check button. A new window will appear with the timing information of pulses. It should be noted that these pulses are found by using the pulse specifications and they are not related to the information given in the expected output pattern text box. The expected output pattern will be used deep in the calculation process for comparing the timing of pulses. The interface for the mentioned process is shown in Fig. 29 and 30.

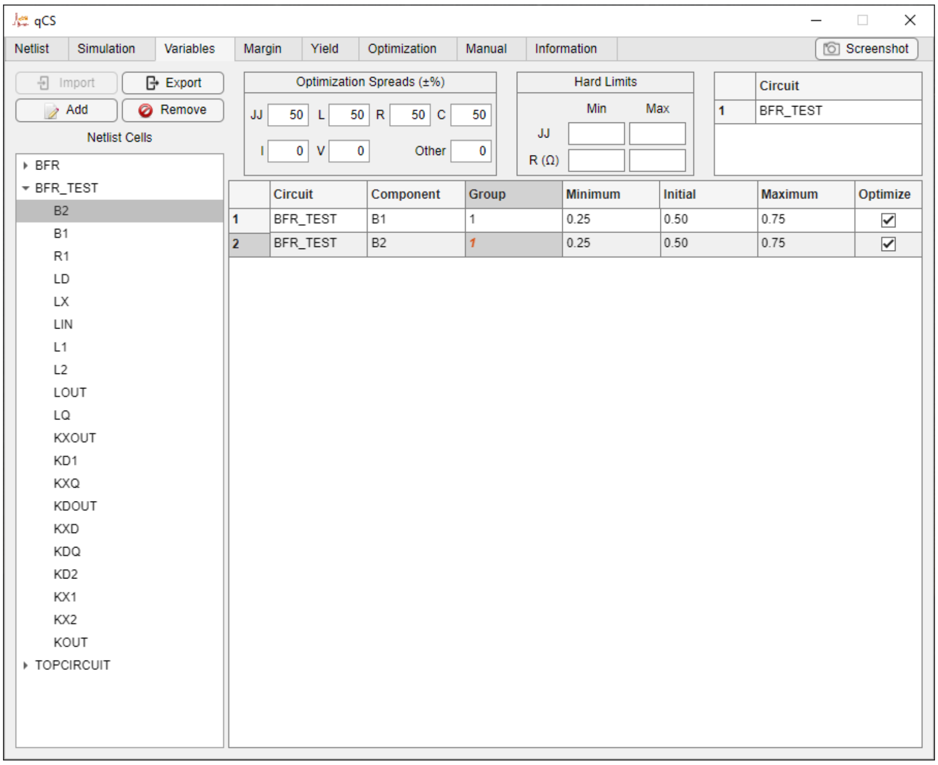

Figure 28: Variables tab after adding components.

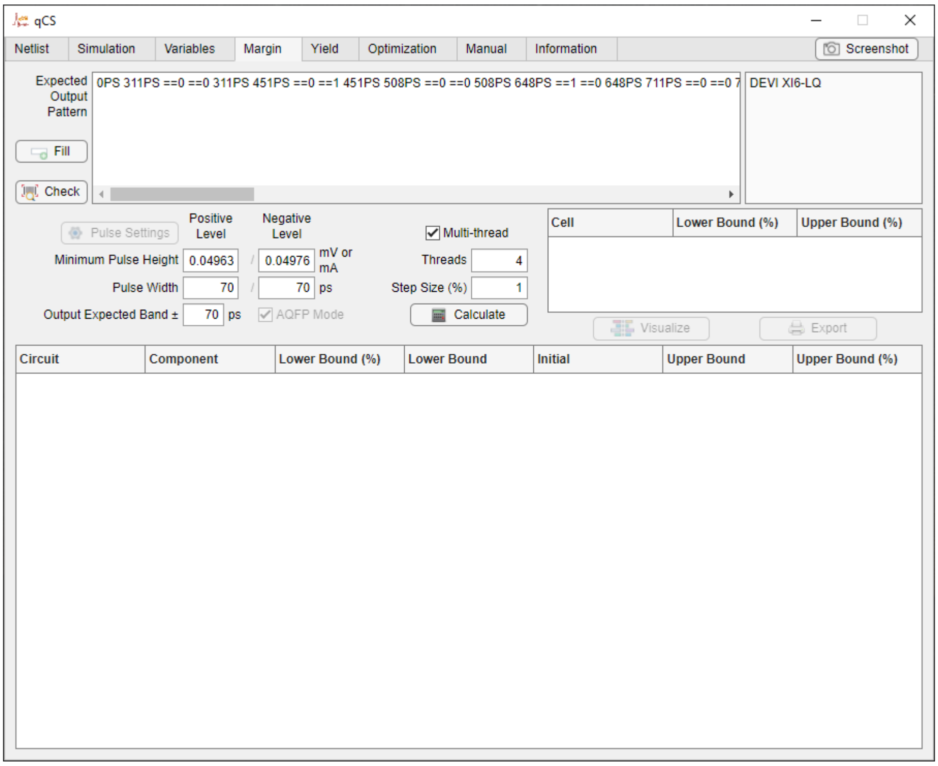

Figure 29: Margin tab after providing the specifications.

To start the margin calculation, click on the Calculate button. Upon the completion of the margin calculation, the results will appear in the table. Export button will create an Excel file that contains all the data presented. Moreover, the other specifications such as pulse height

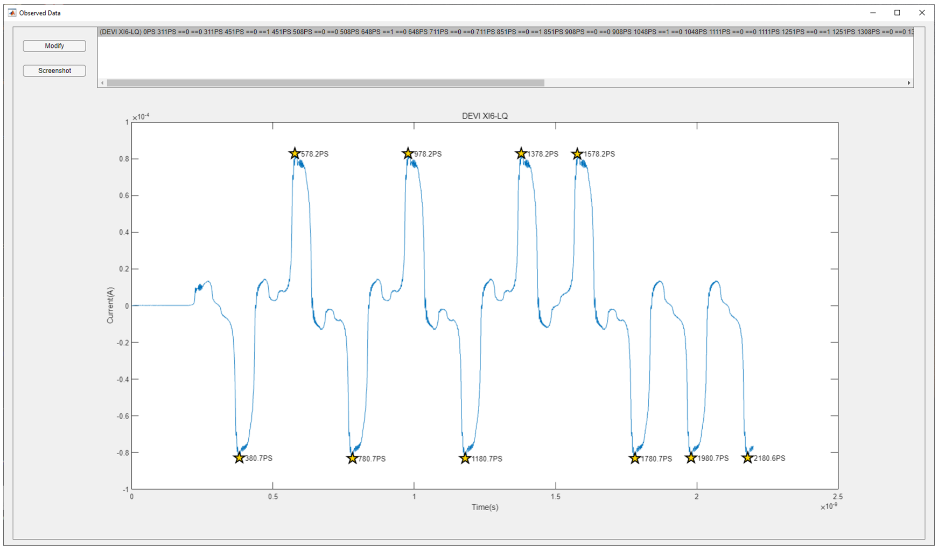

Figure 30: Waveform window after using Check button on Margin tab.

and pulse width will also be exported and put into a text file. The results for the example run are shown in Fig. 31.

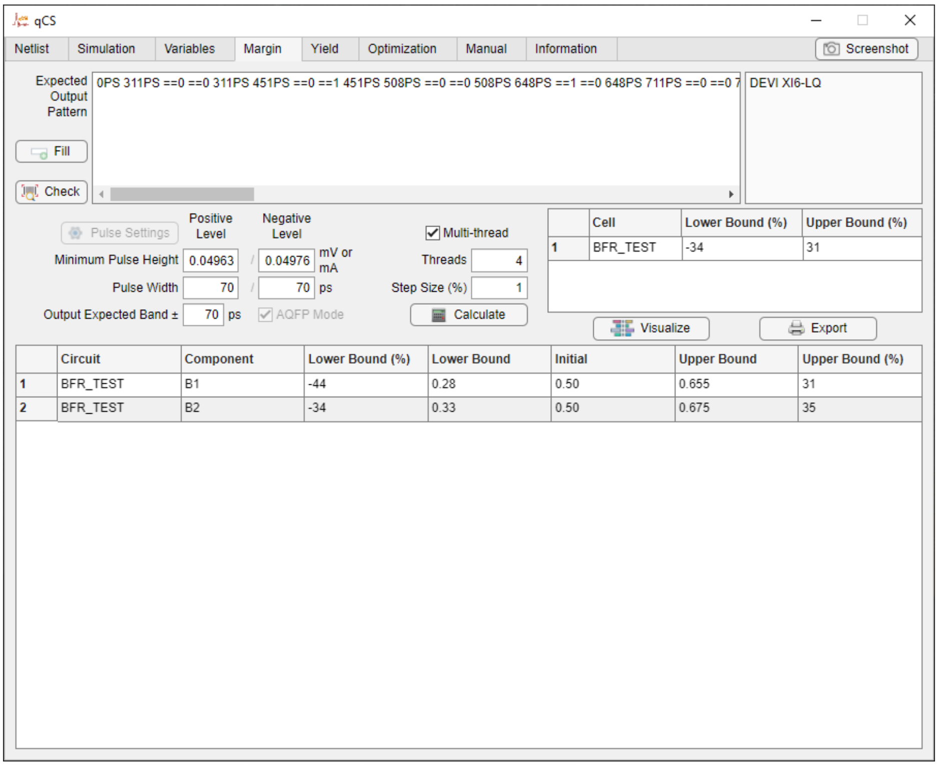

Figure 31: Margin results on Margin tab.

8.2.5 Yield Analysis

The pulse specifications and the expected output pattern will also be assigned into the related fields on Yield tab. For yield analysis, MC Sample # is set to 100. After the run is completed, the graph on this tab will be updated. The result of yield analysis is shown in Fig. 32.

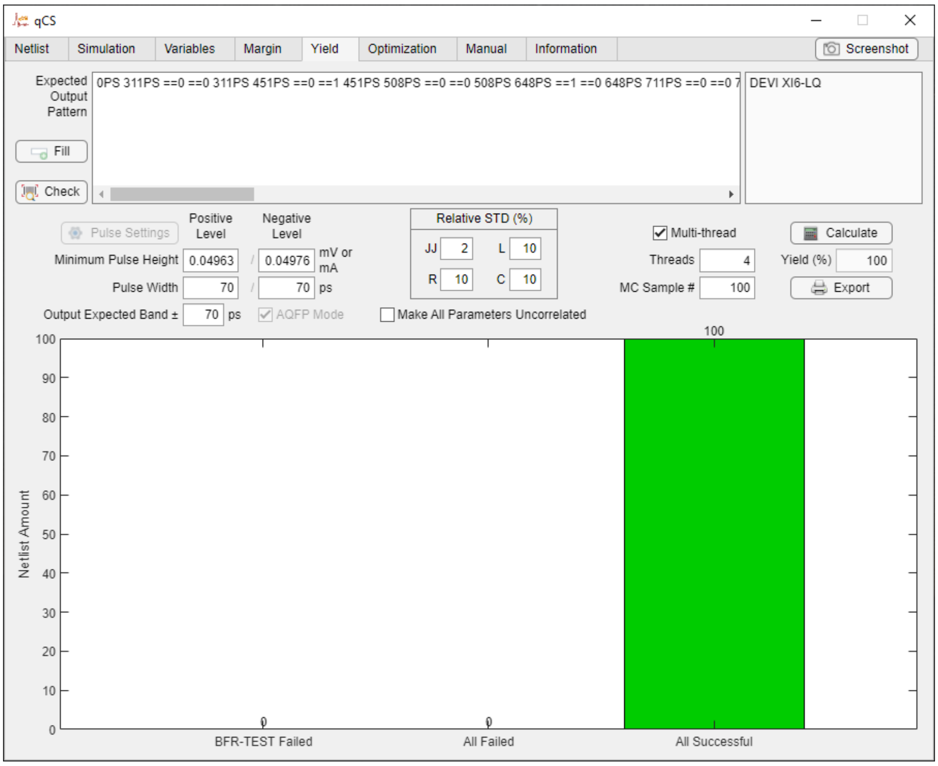

Figure 32: Yield analysis on Yield tab.

8.2.6 Critical Margin Optimization

The other feature of qCS is cell optimization. In Optimization tab, there are several parameters that can adjust the optimization algorithm. Each parameter information is provided by tooltips on the interface. By going over each parameter, a related text will appear near the pointer. The parameters that are not blue are provided for experienced users since these parameters change the optimization algorithm significantly. For parameter details, see Section 1.7.6. By pressing the Optimize button, the process will start and the Result sub-tab will automatically be selected. In this sub-tab, the results will be shown and the Stop button under the Log sub-tab allows the termination of the optimization process. However, it should be noted that there are certain process loops that cannot be interrupted during the optimization. Therefore, the user might wait for a period of time after clicking the Stop button. The interface examples for the steps mentioned above are shown in Fig. 33, 34, 35, and 36.

After obtaining results, qCS will automatically generate the netlist files and select the best among different versions. Even if some of the versions share the same critical margin, the tool will select the one with the smallest Euclidean distance to the original values. Here, the initial critical margin range does not satisfy the margin goal. However, after one iteration, the optimization is stopped due to the new set of values that satisfy the margin goal. Version 6 shows that JJs now have improved margins and the corresponding netlist will be selected by qCS. It should be noted that these results only represent the selected two JJs. Any change in these JJs might also affect the margin range of other components. Therefore,

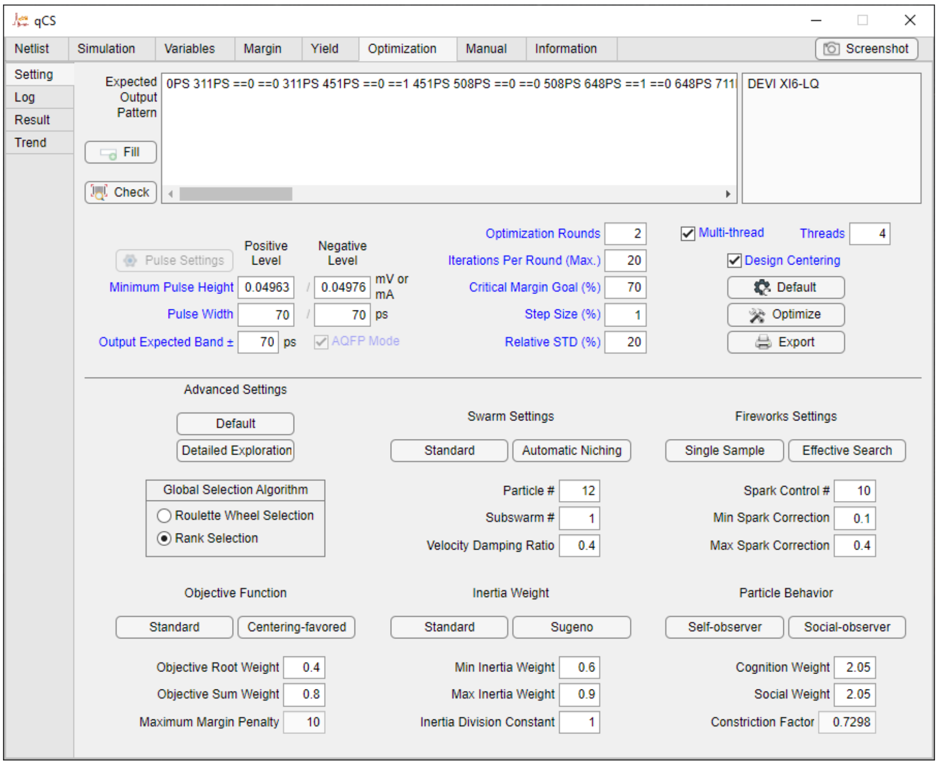

Figure 33: Optimization settings on Optimization tab.

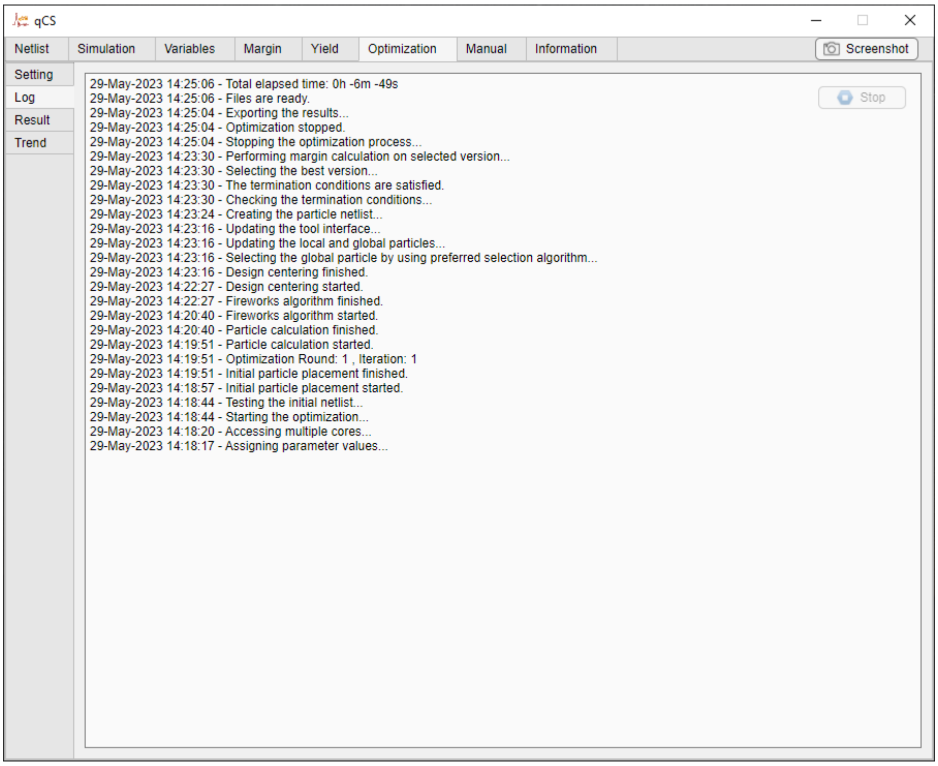

Figure 34: Optimization log on Optimization tab.

as previously stated, select all components that can affect the analysis. By using the Plot button, the waveforms can be compared with the original waveform in Simulation tab. If the results are acceptable, the data shown on the interface can be placed into files by clicking

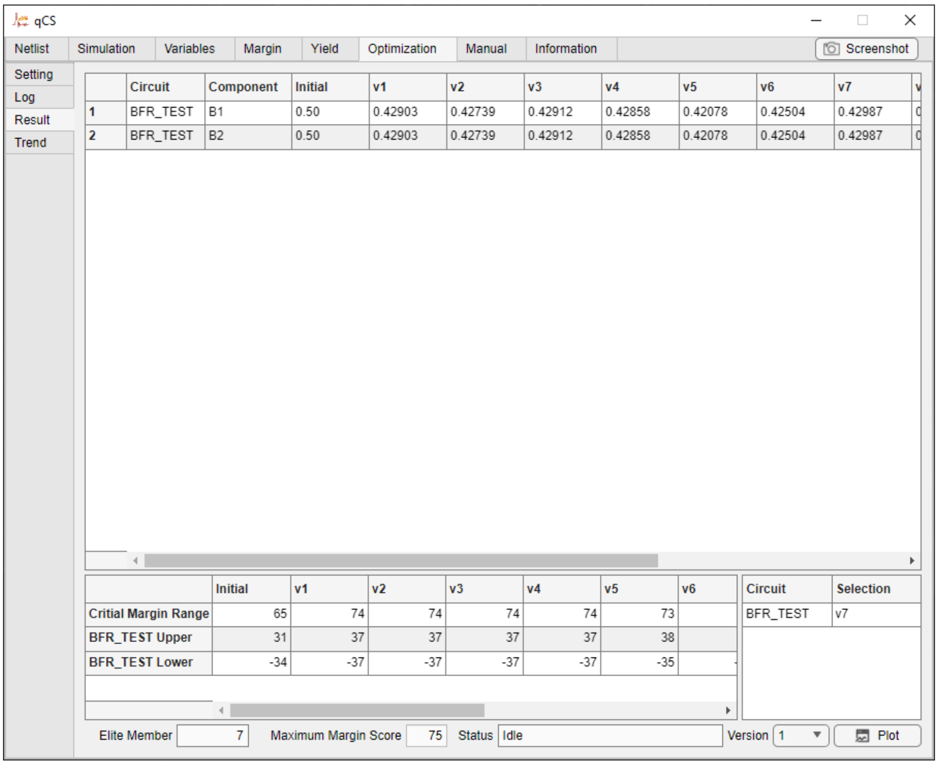

Figure 35: Optimization results on Optimization tab.

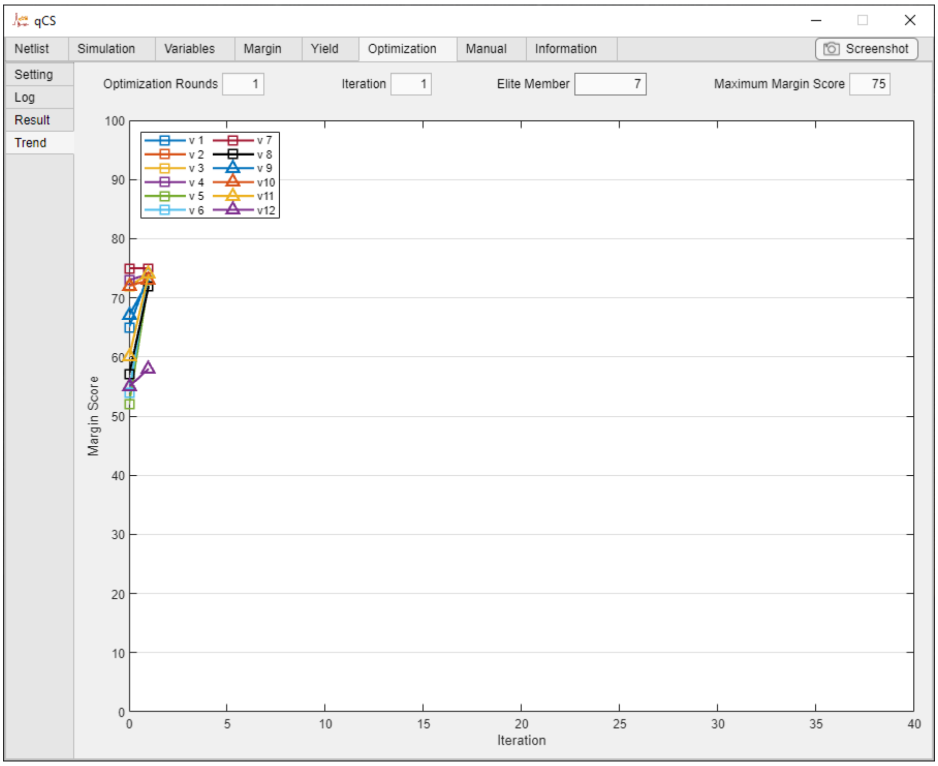

Figure 36: Optimization trend on Optimization tab.

the Export button. Each iteration result will be plotted into Trend sub-tab. This concludes the qCS AQFP JSIM example.

9 Notes

9.1 Known issues

- JoSIM supports different local and global .PARAM netlist commands. MCR does not include certain toolboxes, e.g. symbolic math toolbox, for public use. For this reason, the current version of qCS turns all .PARAM into global for evaluation. Note that .PARAM for component value assignments must be unique to avoid value overwriting.
- On Information tab, the useful links given as a button may not open the browser. This depends on the user's system settings. However, the links can still be seen as a tooltip on the interface.
- In case of transient errors during the simulations, qCS is supposed to skip that particular sample evaluation; however, we still observed exceptions in some cases only in JSIM. We see that the simulation is not terminated and output data is only written halfway to the file. We will further analyze and solve it for the upcoming releases.

9.2 Future plan

- For debugging purposes, we will add a feature that will create a log file for the whole tool. qCS 2.1 currently provides a log for only the optimization process.
- We will add a visualization for minimum pulse height, minimum pulse weight, and output expected band adjustments. Pulse Settings button on the Margin, Yield, and Optimization tabs are disabled.
- For the analysis of circuits with π junctions, we will support PJSIM. Its radio button within Simulator Choice panel on Netlist tab is disabled.
- Once the optimization converges into a local point, we do not expect a significant change on the margin score. Thus, the remaining iterations may just increase the run time while not significantly benefiting the results. For this reason, we plan to add an additional termination condition for the optimization process while tracking the improvements.

9.3 Referencing qCS

There are two papers and a book chapter for qCS. One paper and the book chapter are for its algorithm with performance metrics and the second paper is for the tool itself. The related links for them will be provided here once they are published.

- Book chapter: Karamuftuoglu, M.A., Nazar Shahsavani, S., Pedram, M. (2023). Margin Optimization of Single Flux Quantum Logic Cells. In: Topaloglu, R.O. (eds) Design Automation of Quantum Computers. Springer, Cham. https://doi.org/10.1007/978-3-031-15699-1_6
- Algorithm paper: M. A. Karamuftuoglu, S. N. Shahsavani and M. Pedram, "Margin and Yield Optimization of Single Flux Quantum Logic Cells Using Swarm Optimization Techniques," in IEEE Transactions on Applied Superconductivity, vol. 33, no. 1, pp. 1-10, Jan. 2023, Art no. 1300110, doi: 10.1109/TASC.2022.3223883.
- Tool paper: Mustafa Altay Karamuftuoglu, Haolin Cong and Massoud Pedram, "qCS: Design Analysis and Optimization Tool for Superconductor Circuits", in preparation.

9.4 Useful links

- *ColdFlux*: https://coldflux.usc.edu/
- *SPORT Lab*: https://sportlab.usc.edu/
- *JSIM and JSIM_n (1)*: https://github.com/coldlogix/jsim
- *JSIM and JSIM_n (2) (under "Free Tools")*: https://www.sun-magnetics.com/resources/
- *JoSIM*: https://github.com/JoeyDelp/JoSIM
- *PJSIM*: http://www.nashilab.ynu.ac.jp/eng/pjsim.html

9.5 Acknowledgments

The authors would like to thank Dr. Scott Holmes (IARPA) for feedback on tool features and Christopher Ayala (Yokohama National University) for discussions about Adiabatic Quantum-Flux-Parametron (AQFP) circuits during the development.