An Open Source Tool for Rotorcraft Tradespace Exploration incorporating Reliability Engineering (TsERE)

University of Massachusetts Dartmouth

Executive Summary

Recently tradespace analysis and exploration has emerged as an important focus area within the Department of Defense (DoD) Engineered Resilient System (ERS) initiative, which draws upon engineering concepts, science, and design tools to produce trusted and effective solutions for a wide range of operational contexts. Most of the previous research on tradespace analysis, including research in the context of rotorcraft, emphasizes performance. However, non-functional requirements such as reliability, availability, and maintainability (RAM) have received minimal consideration, despite their direct influence on program level concerns such as operation and support (O&S) as well as affordability.

Tradespace Exploration incorporating Reliability Engineering (TsERE) is an open source tool developed using Python programming language, which incorporates our previous research [1], [2] to incorporate reliability engineering into tradespace analysis. The open source tool presents a simple graphical user interface to allow the user to make quantitative assessment of optimal subsystem[1] investment to achieve desired level of availability and a larger fleet size.

[1]The words 'component' and 'subsystem' are used interchangeably.

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I. Introduction

The open source tool for rotorcraft tradespace exploration (TsERE) incorporating reliability engineering includes models characterizing the relationship between reliability investment and life-cycle support costs. The tool enables

1) Support cost projection through optimal allocation of budget between subsystem reliability investment and vehicle purchase
2) Subsystem reliability investment optimization to maximize availability and fleet size
3) Trade-off between availability and fleet size through reliability investment as well as comparison of optimal investments with and without reliability investment

TsERE runs under the Python programming framework and can be used on computers running Windows, Mac OS X, or Linux. Please report any issues to lfiondella@umassd.edu.

II. Installation

An automated installation script is available on the Github repository at: https://github.com/LanceFiondella/ARL. The user can run this file on the command prompt to install python using the command **pip install -r requirements.txt** along with required packages to run the TsERE.

For manual installation, the necessary steps are as follows:

- Install Python 2.x or Python 3.x from https://anaconda.org/anaconda/python. Unix/Linux and MAC based machines may already have python installed. Type 'python' in the command prompt to see the python version available if it is already installed on your machine.
- Install the following packages by typing **pip install packagename in python 2.x** or **pip3 install packagename** in case of python 3.x. This command should be typed in the terminal on Unix/Mac and on command prompt such as Anaconda on Windows.
  1) matplotlib
  2) math
  3) scipy
  4) numpy
  5) mystic

  Note: Anaconda includes most of the libraries listed above.

Once python is successfully installed on your machine, download the source code from the Github repository from https://github.com/LanceFiondella/ARL/tree/develop and save the folder in a desired location on your computer.

III. User Interface

This section describes the components of the graphical user interface including application launch, input data format, navigation between different tabs in the tool, and interpretation of the results.

A. Starting the tool

To start the TsERE tool, open the **start.py** file or open the terminal or Anaconda command prompt on your machine and navigate to the folder using **cd /Downloads/ARL-develop**, then type **python start.py** to launch the application. Figure 1 shows the initial view of the TsERE tool immediately after launch.

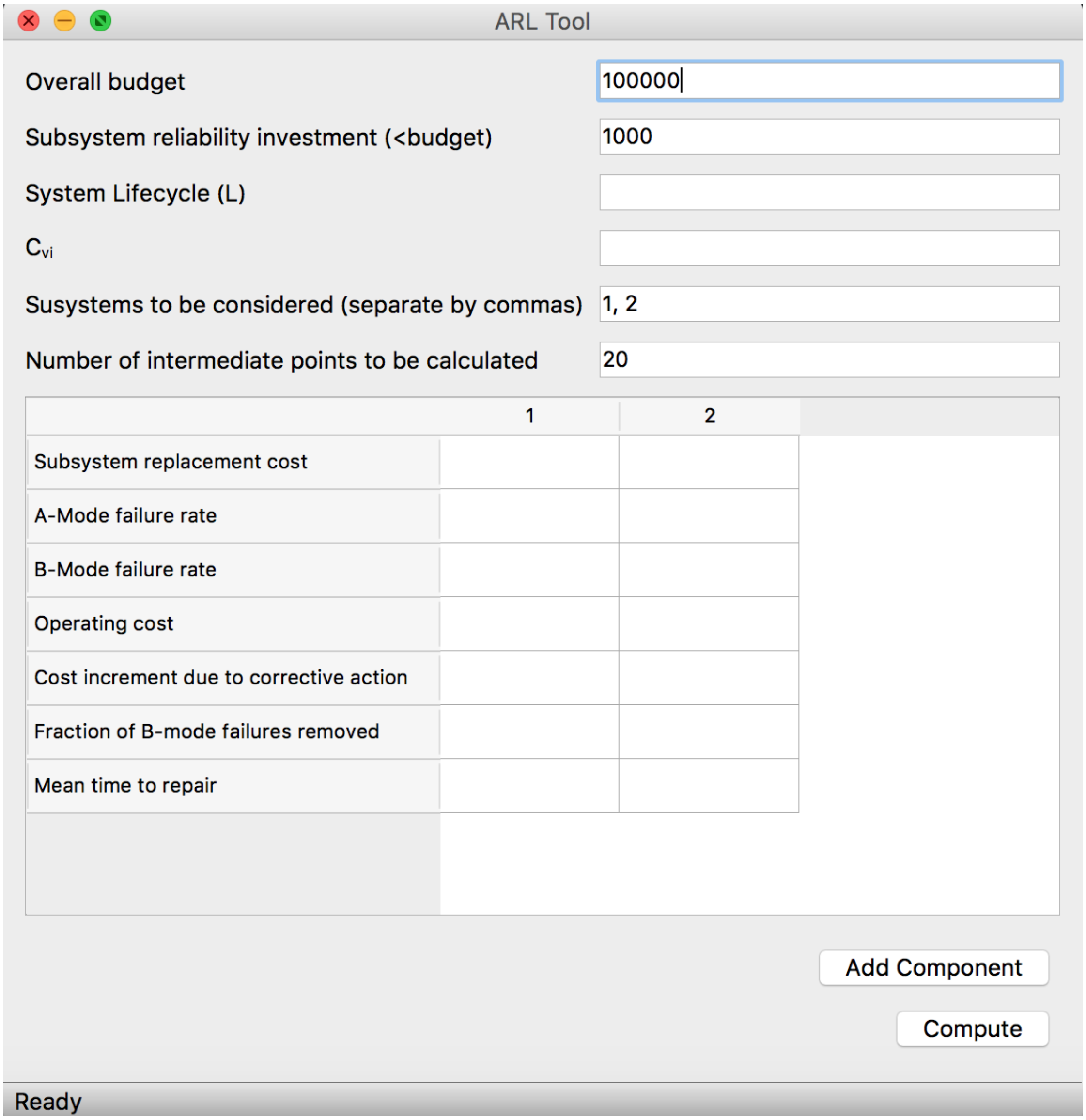


Fig. 1: Initial view of the TsERE tool

The upper half of the interface in Figure 1 includes system level inputs, while the lower half indicates component level input parameters. All the input tabs are model parameters in Reference [1]. The **Overall Budget** indicates the total budget allocated to the project, the second row **Subsystem reliability investment (<budget)** is some fraction of the overall budget that is invested on subsystems to improve system reliability and availability considering cost. The third row **System Lifecycle (L)** is the overall system lifecycle and C_{vi} in the fourth row indicates the coefficient

of variation, which is ideally assumed to be equal to 1.0. The fifth row **Subsystems to be considered (separate by commas)** allows the user to select the number of components/subsystems for analysis. At least two subsystems should be specified in order to proceed with the computation. The sixth column **Number of intermediate points to be calculated** indicates the number of iterations or steps in the computation. Higher values of iterations may slow tool performance.

The subsystem level input parameters includes replacement cost, A and B mode failure rate that indicates simple and critical failures, cost of operating Test Analysis and Fix (TAAF), increment in cost due to corrective actions to fix B-mode failures, fraction of B-mode failures removed (fix effectiveness factor), and mean time to repair.

B. Input data

All the input values can be either manually entered or uploaded as a excel spreadsheet. The **Add Component** radio button option in Figure 1 enables manually adding components. To import the values through an excel spreadsheet, click on **File**→ **Import Data** as shown in Figure 2.

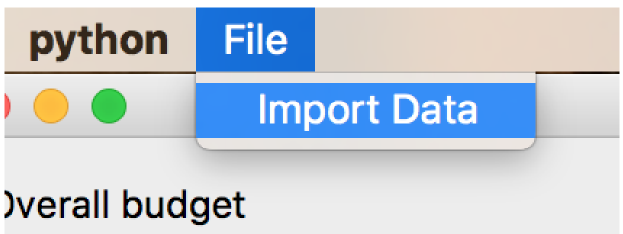


Fig. 2: File upload

In Figure 2, selecting the **Import Data** will enable the user to browse through the file system to upload the input data file.

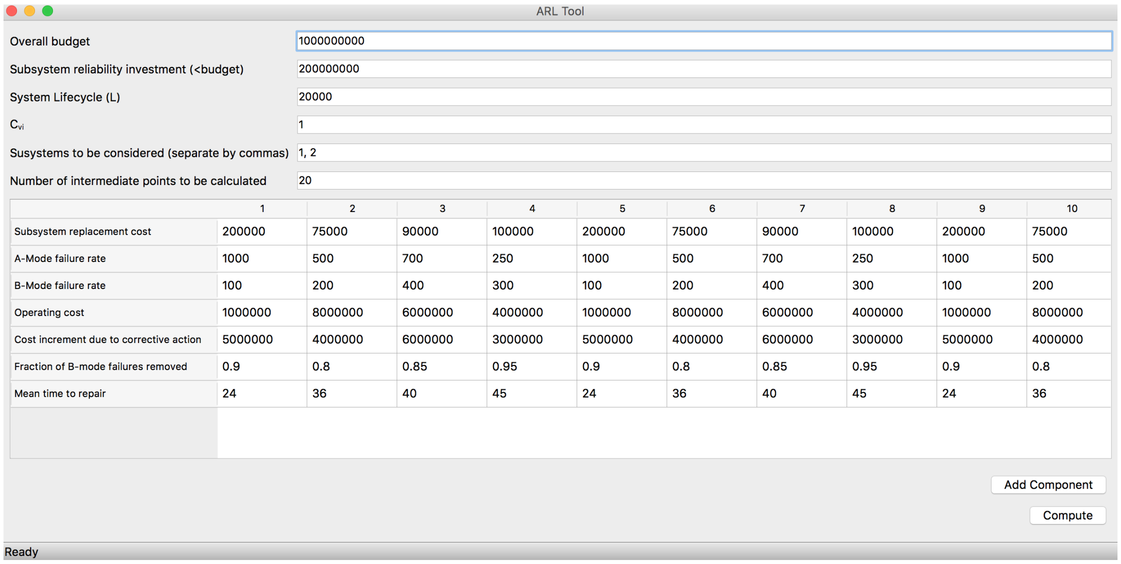
Figure 3 shows an example of the input excel file with parameters for 10 components.

c1	Ma	Mb	c0	mub	mud	MTTRi	L	cv	gamma	B	BA
200000	1000	100	1000000	5000000	0.9	24	20000	1	20000000	1E+09	2E+08
75000	500	200	8000000	4000000	0.8	36	20000	1	20000000	1E+09	10000000
90000	700	400	6000000	6000000	0.85	40	20000	1	20000000	1E+09	10000000
100000	250	300	4000000	3000000	0.95	45	20000	1	20000000	1E+09	10000000
200000	1000	100	1000000	5000000	0.9	24	20000	1	20000000	1E+09	10000000
75000	500	200	8000000	4000000	0.8	36	20000	1	20000000	1E+09	10000000
90000	700	400	6000000	6000000	0.85	40	20000	1	20000000	1E+09	10000000
100000	250	300	4000000	3000000	0.95	45	20000	1	20000000	1E+09	10000000
200000	1000	100	1000000	5000000	0.9	24	20000	1	20000000	1E+09	10000000
75000	500	200	8000000	4000000	0.8	36	20000	1	20000000	1E+09	10000000
90000	700	400	6000000	6000000	0.85	40	20000	1	20000000	1E+09	10000000
100000	250	300	4000000	3000000	0.95	45	20000	1	20000000	1E+09	10000000

Fig. 3: Input data file

In Figure 3, rows represents individual subsystems and columns represent different input parameters corresponding to each component. Here, $c1$ is the subsystem replacement cost, Ma and Mb are the mean time to A- and B-mode failures, $c0$ is the operating cost, mub and mud are the increment in cost due to corrective actions and fraction of B-mode failures removed, $MTTRi$ is the mean time to repair, L is the system lifecycle, cv is the coefficient of variation, B is the overall budget, and B_A is the subsystem reliability investment.

Figure 4 shows the view of TsERE tool when the input data file has been successfully uploaded.



ARL Tool

Overall budget: 1000000000

Subsystem reliability investment (<budget): 200000000

System Lifecycle (L): 20000

C_{vi}: 1

Susystems to be considered (separate by commas): 1, 2

Number of intermediate points to be calculated: 20

	1	2	3	4	5	6	7	8	9	10
Subsystem replacement cost	200000	75000	90000	100000	200000	75000	90000	100000	200000	75000
A-Mode failure rate	1000	500	700	250	1000	500	700	250	1000	500
B-Mode failure rate	100	200	400	300	100	200	400	300	100	200
Operating cost	1000000	8000000	6000000	4000000	1000000	8000000	6000000	4000000	1000000	8000000
Cost increment due to corrective action	5000000	4000000	6000000	3000000	5000000	4000000	6000000	3000000	5000000	4000000
Fraction of B-mode failures removed	0.9	0.8	0.85	0.95	0.9	0.8	0.85	0.95	0.9	0.8
Mean time to repair	24	36	40	45	24	36	40	45	24	36

Add Component

Compute

Ready

Fig. 4: TsERE upon data upload

In Figure 4, the user can again select specific subsystems that they would like to consider in system level assessment using the option **Subsystems to be considered (separated by commas)**. For example, $\{1, 2\}$ assesses the impact of component 1 and 2 on the system availability and fleet size, whereas specifying $\{1,2,3,5,6\}$ will consider component 1, 2, 3, 5, and 6 towards system level assessment. In addition, the user can select the number of intermediate points or iteration using the option **Number of intermediate points to be calculated**. This number should be less than 50 in order to avoid slowing down the computation performance of the tool. Clicking **Compute** initiates the computation. In this document, we consider the first two components for the sake of illustration. For more discussion on the results refer to [1], [2].

C. TsERE analysis

The output of TsERE is categorized into three tabs:

- Subsystem Level Assessment
- Fleet size optimization
- Availability optimization

Figure 5 shows the three tabs of the TsERE after a successful computation.

The drop down menu below the Subsystem Level Assessment as shown in Figure 6 indicates the list of assessment corresponding to the tab highlighted above in blue. The user can choose the view the output as Plot or Table by selecting the appropriate option below the dropdown menu.

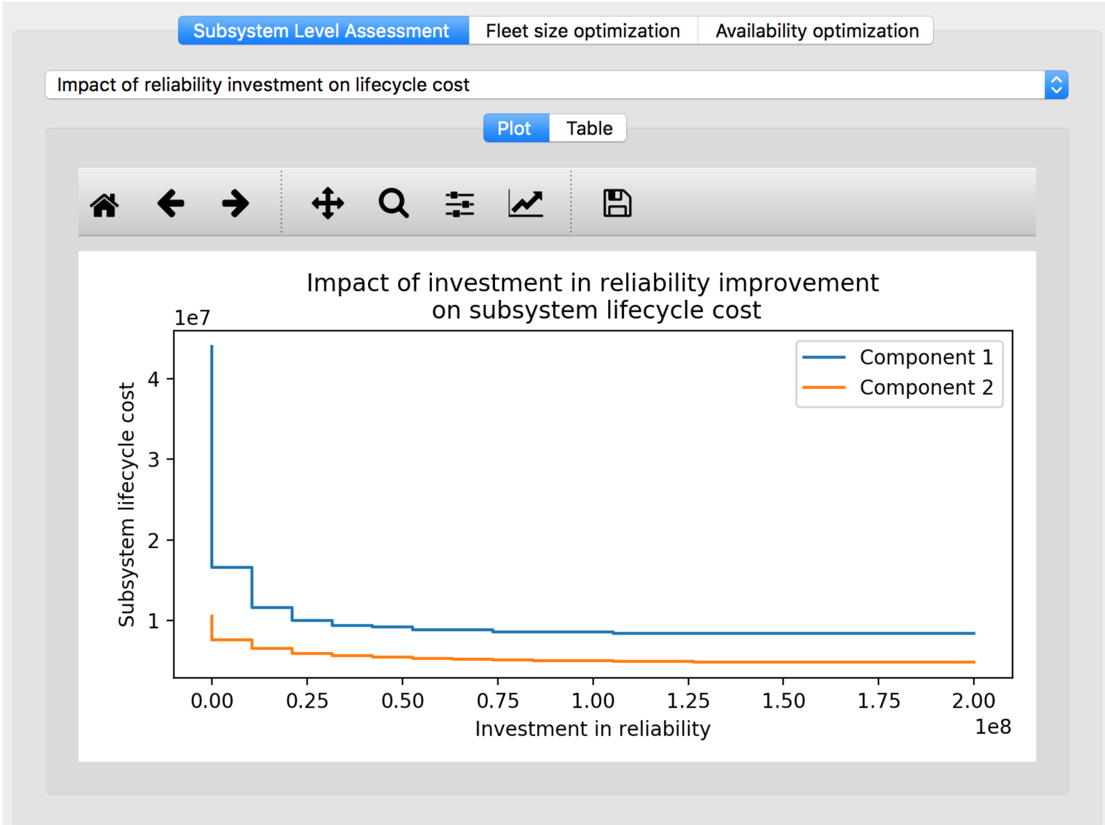


Fig. 5: Initial view of the TsERE output window

D. Tab1: Subsystem Level Assessment

Tab1 enables subsystem level assessment to show the impact of subsystem investment on lifecycle cost, fleet size, and availability. Tab1 has three different plot selection drop-down menu options. These drop-down menu options can be further used for a detailed tradespace exploration and perform sensitivity analysis for various sub-system. The following are the plots the drop-down menu option provides:

1) Impact of reliability investment on lifecycle cost
2) Impact of reliability investment on availability
3) Marginal utility of reliability investments

The above options can be seen on the tool as shown in Figure 6 below

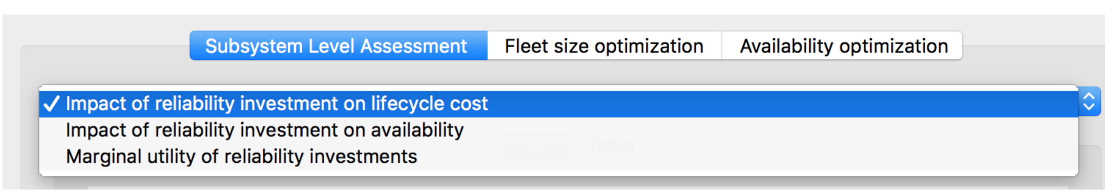


Fig. 6: Output options in Tab1

1) Impact of reliability investment on lifecycle cost: Figure 7 shows the impact of subsystem investment on subsystem lifecycle cost.

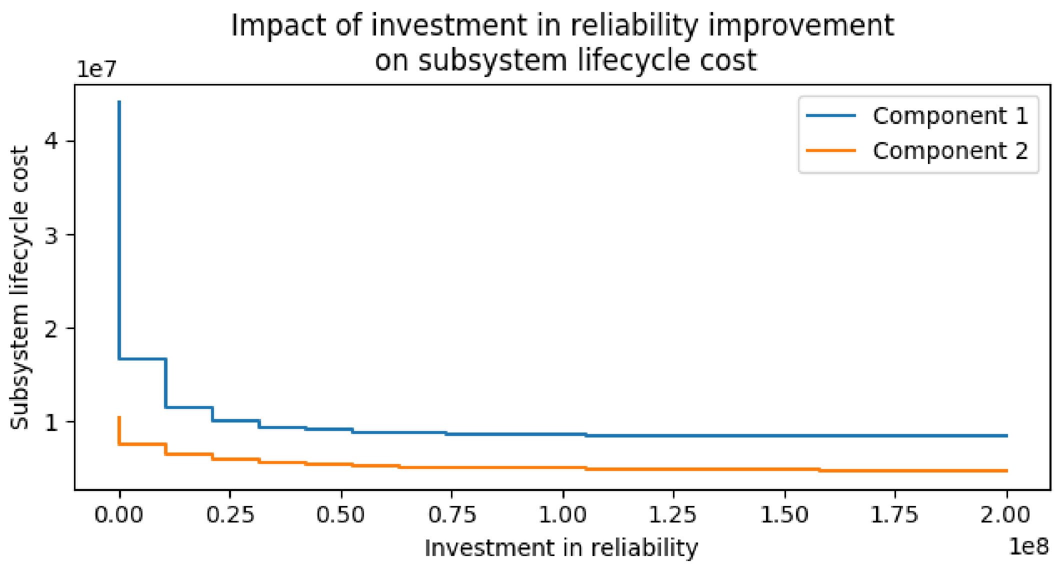
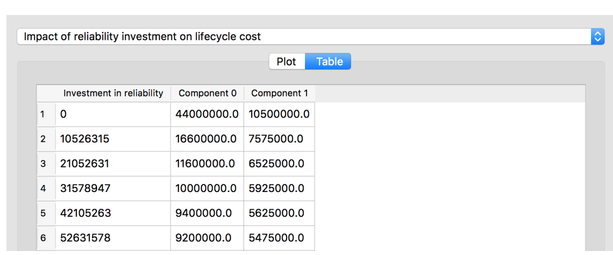


Fig. 7: Impact of investment in reliability improvement on subsystem lifecycle cost

The x-axis represents the various level of investments from \$0 to \$200,000,000 and the y-axis represents the subsystem lifecycle cost. Figure 7 indicates that investments to improve the reliability of component 1 could achieve significantly greater cost savings over the system lifecycle, whereas subsystem 2 is much less responsive to reliability improvement investments. These observations agree with intuition because subsystem 1 has a higher fix effectiveness factor and higher lifecycle cost. Despite these relative trends, it may still be reasonable to allocate some funds to lower the lifecycle cost of subsystem 2. These type of plots provide a insight to the designers about which subsystem is more sensitive to reliability improvement.

The tool also provides an option to view the result in a tabular plot for further analysis as shown in Figure 8, which is the tabular view of the result shown in Figure 7.



Impact of reliability investment on lifecycle cost

Plot Table

	Investment in reliability	Component 0	Component 1
1	0	44000000.0	10500000.0
2	10526315	16600000.0	7575000.0
3	21052631	11600000.0	6525000.0
4	31578947	10000000.0	5925000.0
5	42105263	9400000.0	5625000.0
6	52631578	9200000.0	5475000.0

Fig. 8: Tabular view of the impact of investment in reliability improvement on subsystem lifecycle cost

In Figure 8, the first column represents the computed optimal subsystem investment at each breakpoints. The second and third columns represents the achieved saving in the corresponding subsystem lifecycle cost corresponding to each subsystem.

2) Impact of reliability investment on availability: Figure 9 shows a plot of the marginal utility of investing nothing in the reliability improvement of one subsystem and anywhere from nothing to $200,000,000 (user defined) in the other subsystem.

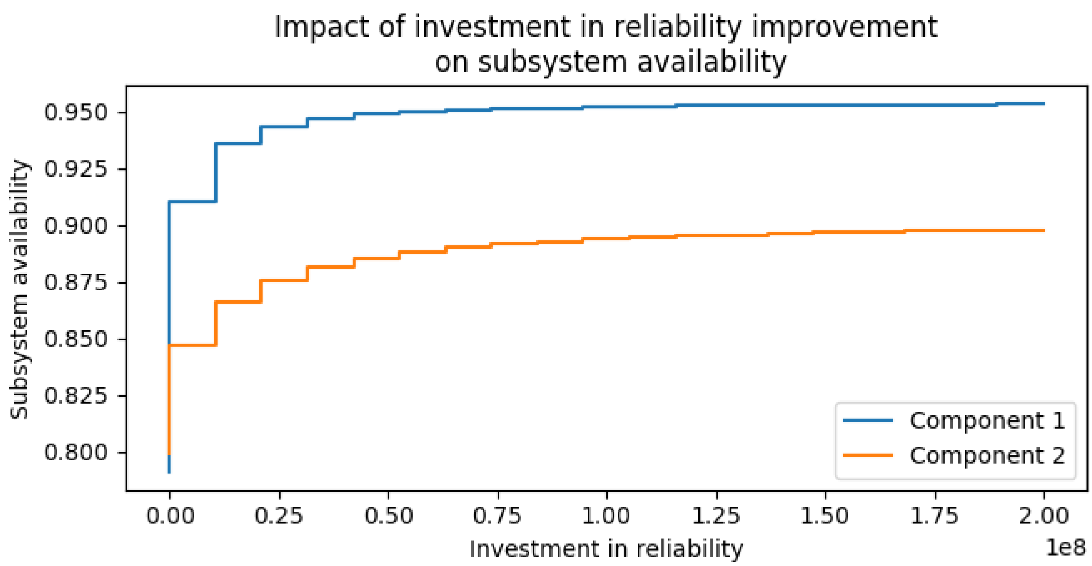


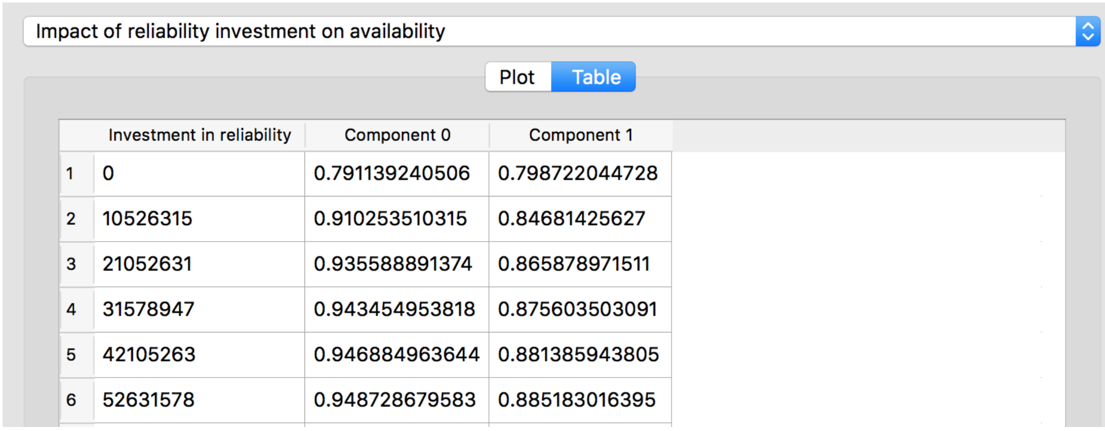
Fig. 9: Impact of investment in reliability improvement on subsystem availability

Figure 9 compares the availabilities of subsystem one and two. The x-axis corresponds to the investment in reliability improvement and the y-axis corresponds to the change in fleet availability w.r.t to the change in system's overall improvement in reliability. When no reliability investment is made, the availabilities are 0.7911 and 0.7987 respectively, while unrestricted investment in either of these two subsystems would lead to availabilities of 0.9541 and 0.9025 respectively. The maximum availability that can be achieved in subsystem one is greater than subsystem two since $MTTR_2 > MTTR_1$, $M_{A,1} > M_{A,2}$. Finally, $\mu_{d,1} > \mu_{d,2}$, which means that the fix effectiveness factor for B-mode failures in subsystem one is higher, enabling greater availability improvement despite the fact that the mean time between B-mode failures in subsystem two is larger $M_{B,1} < M_{B,2}$. Thus, investments in subsystem 1 will have a greater practical impact on reliability, availability, and cost of spares.

Figure 10 shows the tabular view of the Figure 9, which lists the numerical values of subsystem availability at each breakpoint within the subsystem investment range and the step size defined by the user which can be imported to another formats and further used for future evaluation.

3) Marginal utility of reliability investments: To confirm the relative efficiency of investments to improve the reliability of subsystem 1, Figure 11 shows a plot of the marginal utility of investing nothing on the reliability improvement of one subsystem and anywhere from zero to $200,000,000 in the other subsystem.

Figure 11 indicates that 18 systems can be supported when there is no investment in reliability improvement, whereas over $6,000,000$ would need to be spent on improving subsystem two to reduce the subsystem and system



Impact of reliability investment on availability

Plot Table

	Investment in reliability	Component 0	Component 1
1	0	0.791139240506	0.798722044728
2	10526315	0.910253510315	0.84681425627
3	21052631	0.935588891374	0.865878971511
4	31578947	0.943454953818	0.875603503091
5	42105263	0.946884963644	0.881385943805
6	52631578	0.948728679583	0.885183016395

Fig. 10: Tabular view of the impact of investment in reliability improvement on subsystem availability

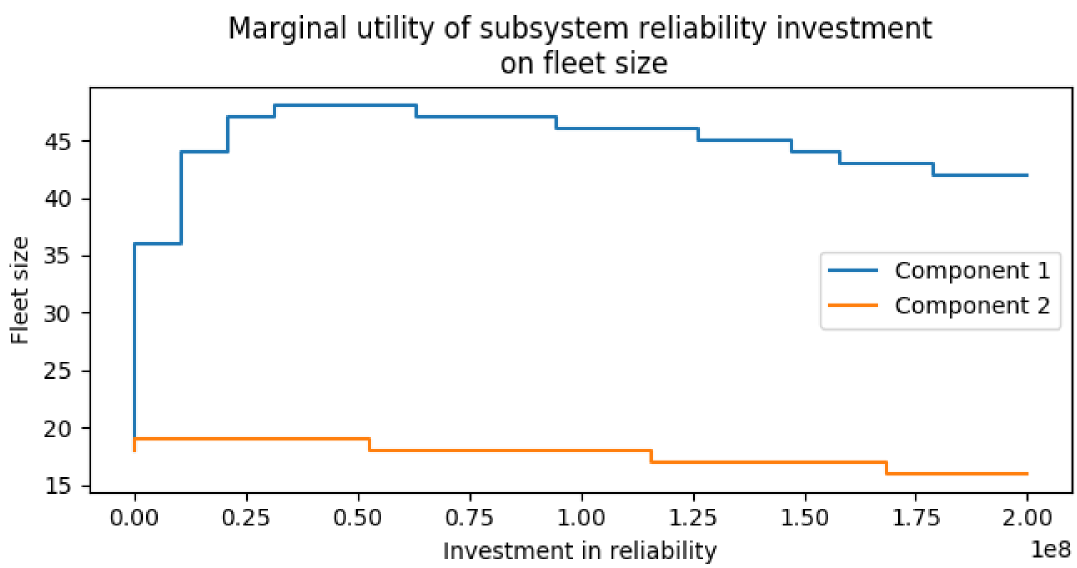


Fig. 11: Marginal utility of subsystem reliability investment on fleet size

lifecycle costs to the point where utmost 19 systems could be supported with the remainder of the budget. On the other hand, a much smaller investment in subsystem one is sufficient to achieve the same fleet size. Figure 11 shows that a maximum of fleet of 48 can be supported with an optimal investment of approximately 60M in subsystem one. If more investment is made beyond the optimal level, the fleet that can be supported decreases since budget is spent on unnecessary improvement in subsystem reliability thus decreasing the budget to support more fleet.

Figure 12 reports the tabular results of the assessment presented in Figure 11.

E. Tab2: Optimal subsystem investment to maximize fleet size

Tab2 reports the system parameters based on optimal subsystem investment identified by solving an optimization problem under given budget B. The results of the optimization are shown in form of a table as shown in Figure 13.

Marginal utility of reliability investments

Plot Table

	Investment in reliability	Component 0	Component 1
1	0	18.0	18.0
2	10526315	36.0	19.0
3	21052631	44.0	19.0
4	31578947	47.0	19.0
5	42105263	48.0	19.0
6	52631578	48.0	19.0

Fig. 12: Tabular view of the marginal utility of subsystem reliability investment on fleet size

Figure 13 compares the outcomes with and without reliability investment, listing subsystem MTBEFF (M_i), average number of part replacements over the system lifecycle (P_i), and the corresponding subsystem cost (c_i), the system cost (C_s), as well as the fleet size (η) and its total cost.

Subsystem Level Assessment | Fleet size optimization | Availability optimization

Outcomes under various scenarios

Table

			No Investment				Optimal Investment	
Fleet size	18.0				62.0			
Fleet Cost	981000000.0				892800000.0			
Unit Cost	54500000.0				14400000.0			
	C	P	M	γ	C	P	M	γ
Component 0	44000000.0	219.0	90.9090909091	0	9000000.0	44.0	444.788600547	53204989.0379
Component 1	10500000.0	139.0	142.857142857	0	5400000.0	71.0	277.986716872	53181499.3349

Fig. 13: Outcomes under various scenarios

Figure 13 indicates that investing in the reliability improvement of the subsystems increases their mean time between essential function failure, thereby lowering the number of times they need to be replaced over the system lifecycle and their associated contributions to subsystem and the overall system cost. The savings achieved enables spares for a larger fleet, whereas the cost of this larger fleet without reliability investment is $3,379,000,000(62 \times 54,500,000)$, which is far in excess of the original budget.

Note that all cost units are calculated in US Dollars ($). In Figure 13 component 0 and component 1 represents subsystem 1 and subsystem 2 respectively.

F. Tab3: Optimal subsystem investment to maximize availability

This tab shows the effect of using the optimal values of investments at each breakpoint values on fleet size, availability and lifecycle cost. There are three drop-down options associated with this tab.

1) Investment in reliability vs. Fleet size.

2) Investment in reliability vs. system availability.

3) System availability vs. fleet size.

Figure 14 shows the output options in **Tab3** which includes the plots of impact of subsystem reliability investment on fleet size and system availability as well as the trade off between the subsystems.

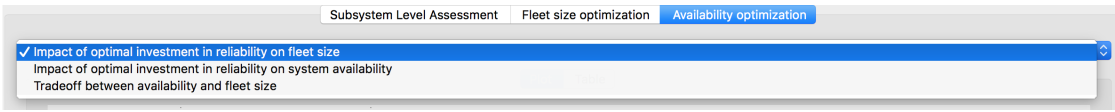


Fig. 14: Output options in Tab3

1) Investment in reliability vs. Fleet size: Figure 15 shows the fleet size when the optimal reliability investment strategy is implemented.

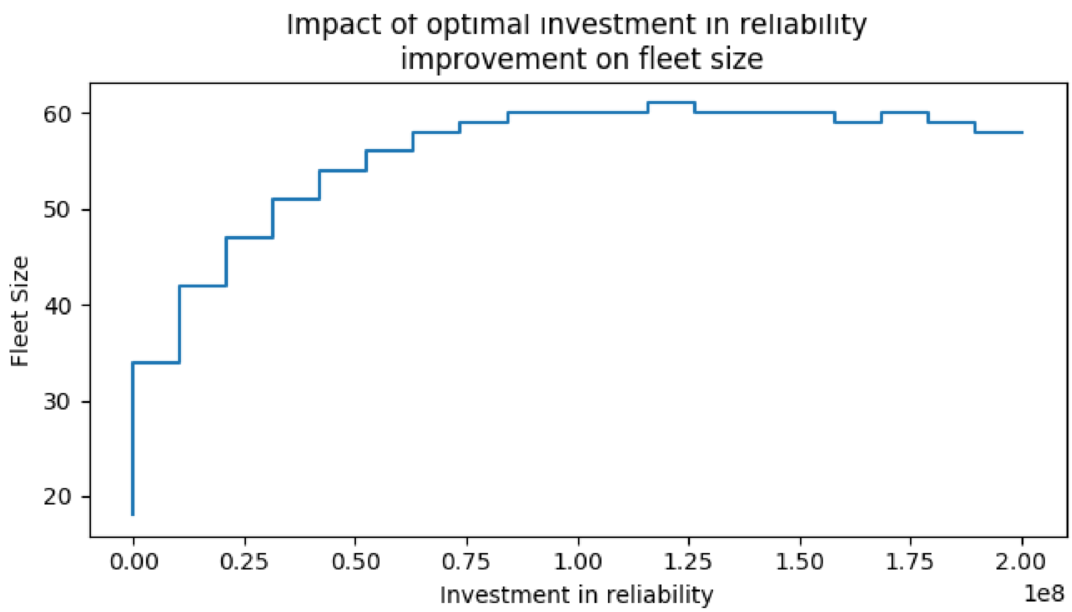


Fig. 15: Impact of optimal investment in reliability improvement on fleet size

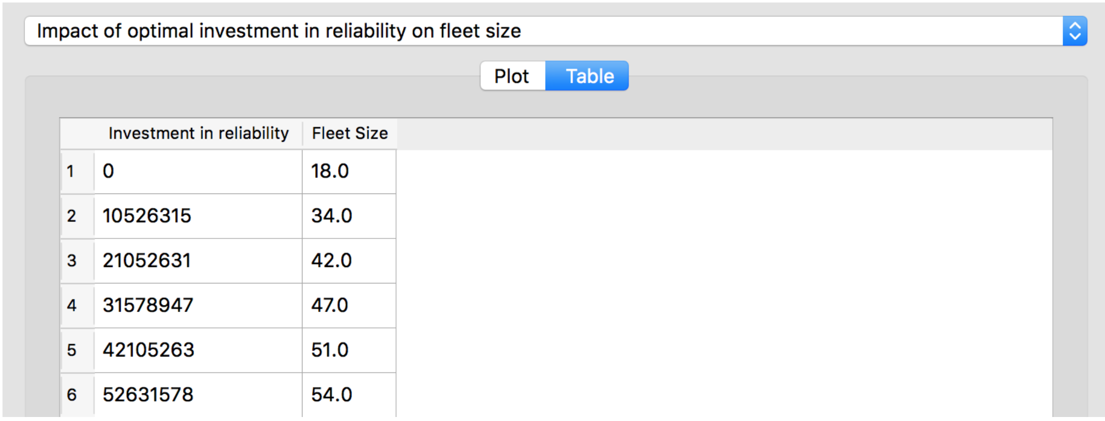
For small investments, Figure 15 exhibits monotonic increases in fleet size. However, the fleet size actually decreases around $60,000,000$. This non-monotonic trend occurs because additional investment does not improve reliability and cost significantly as marginal utility has decreased. Therefore, the additional investment does not improve affordability and fewer dollars remain, reducing the fleet size.

Figure 16 shows the corresponding numerical values in tabular format.

2) Investment in reliability vs. system availability: Figure 17 shows the optimal system availability with a overall subsystem investment between 0 and 200M.

Figure 17 indicates that reliability investment increases system availability monotonically from 0.631900 to 0.850787 when 200M for reliability improvement is distributed between optimal values of subsystems one and two.

Figure 18 shows the numerical values corresponding to the results shown in Figure 17.



Impact of optimal investment in reliability on fleet size

Plot | Table

	Investment in reliability	Fleet Size
1	0	18.0
2	10526315	34.0
3	21052631	42.0
4	31578947	47.0
5	42105263	51.0
6	52631578	54.0

Fig. 16: Tabular view of the impact of optimal investment in reliability improvement on fleet size

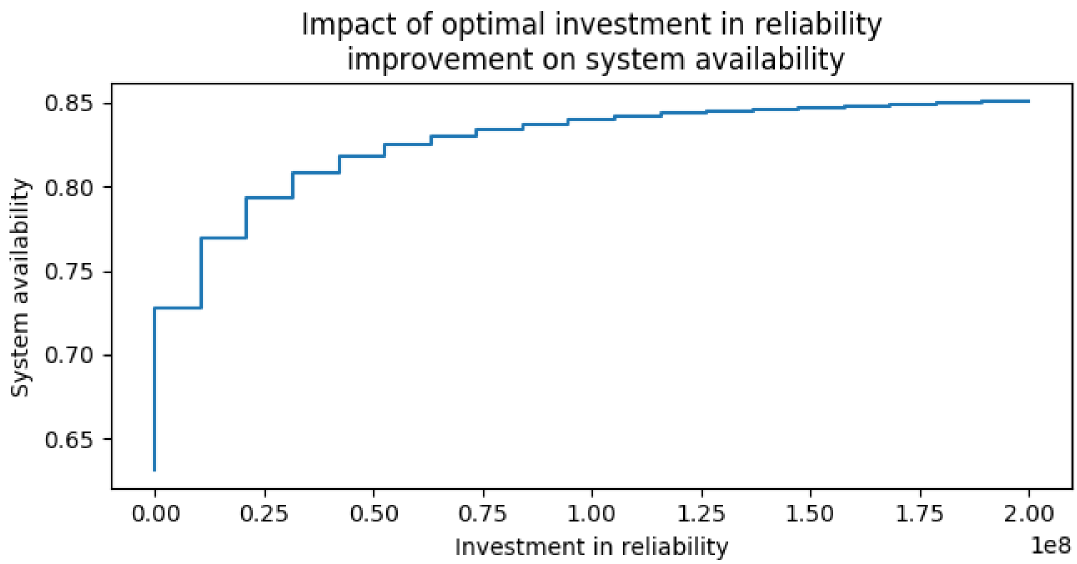
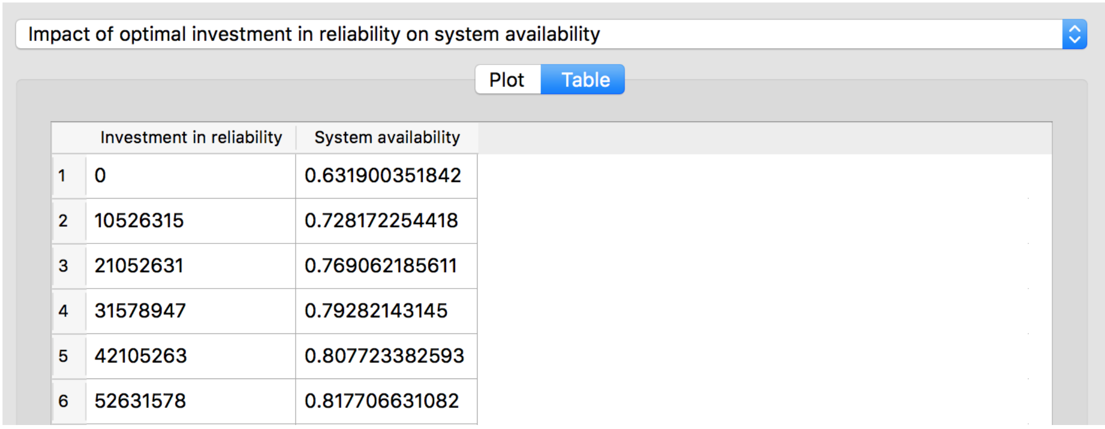


Fig. 17: Impact of optimal investment in reliability improvement on system availability

3) System availability vs. fleet size: Figure 19 tradeoff between optimal system availability and fleet size, plotting the y-values of Figure 17 and 15 as the x- and y-values respectively.

Figure 19 shows the explicit relationship between availability and fleet size. For most of the range of reliability investments increasing availability also increases fleet size, indicating that no compromise is required. However the cost to achieve a higher availability leaves a smaller fraction of the budget for a fleet. Thus, a compromise between availability and fleet size may only be encountered when both the target availability is close to the theoretical limit and the fleet size is close to the maximum achievable.



	Investment in reliability	System availability
1	0	0.631900351842
2	10526315	0.728172254418
3	21052631	0.769062185611
4	31578947	0.79282143145
5	42105263	0.807723382593
6	52631578	0.817706631082

Fig. 18: Tabular view of the impact of optimal investment in reliability improvement on system availability

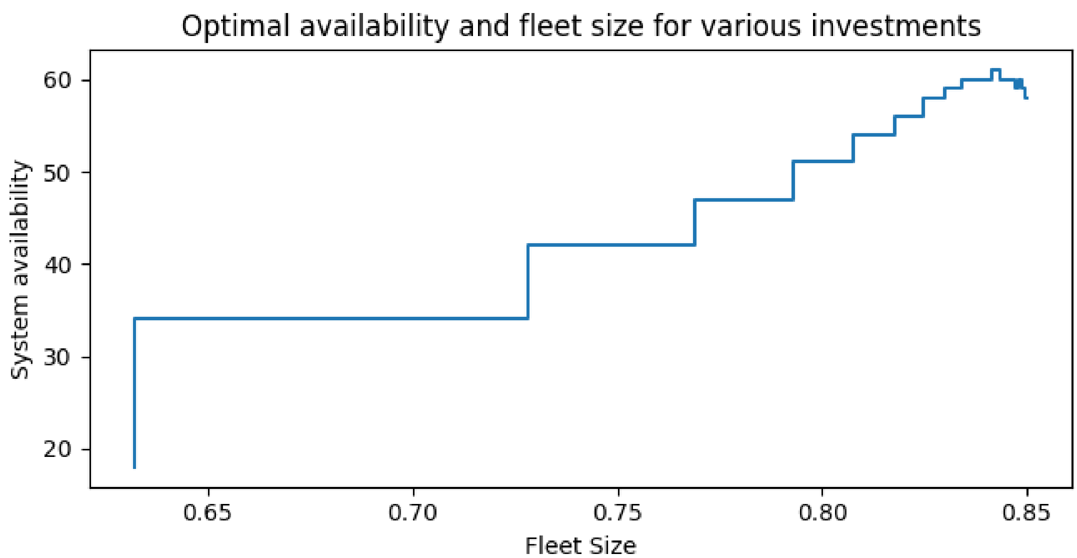


Fig. 19: Optimal availability and fleet size for various investments

G. Data saving and other control options

TsERE tool has data saving options associated with each mode. The tables can be saved in .csv format, whereas the plots can be saved in .png, .pdf, and other formats.

Figure 20 shows more options associated with each mode. In Figure 20, is associated with eight options to modify

Fig. 20: TsERE - Data saving options

or save the figure. The options include:

- **Home button**: Restores the original figure if the user has made some modifications.
- **Backward and Forward arrows**: Allows the user to navigate one step to the previous or next modifications that they might have done on the figure.
- **Pan/Zoom**: This allows the user to pan axes by clicking left mouse button and zooming the area pointed with the cursor by clicking the right mouse button.
- **Zoom**: Allows the user to zoom in selected the area. To restore the figure, the user can either use the home button or forward/backward arrows.
- **Configure Subplots**: Allows the user to set the figure layout, define the borders as well as spacing as shown in Figure 21 below:

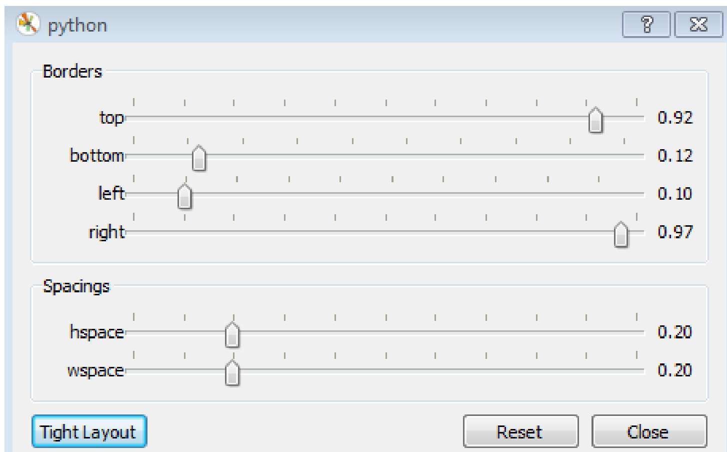


Fig. 21: Data saving - Configure subplot

- **Figure Options**: This enables defining the axes range, changing the title and axes label, curves label, legends, line, and marker styles as shown in Figure 22 below:
- **Save the Figure**: Allows the user to save the data plot in the desired format including .png, .pdf, and .eps
- On the right corner after all these options, the x- and y-co-ordinates are displayed based on the cursor.

REFERENCES

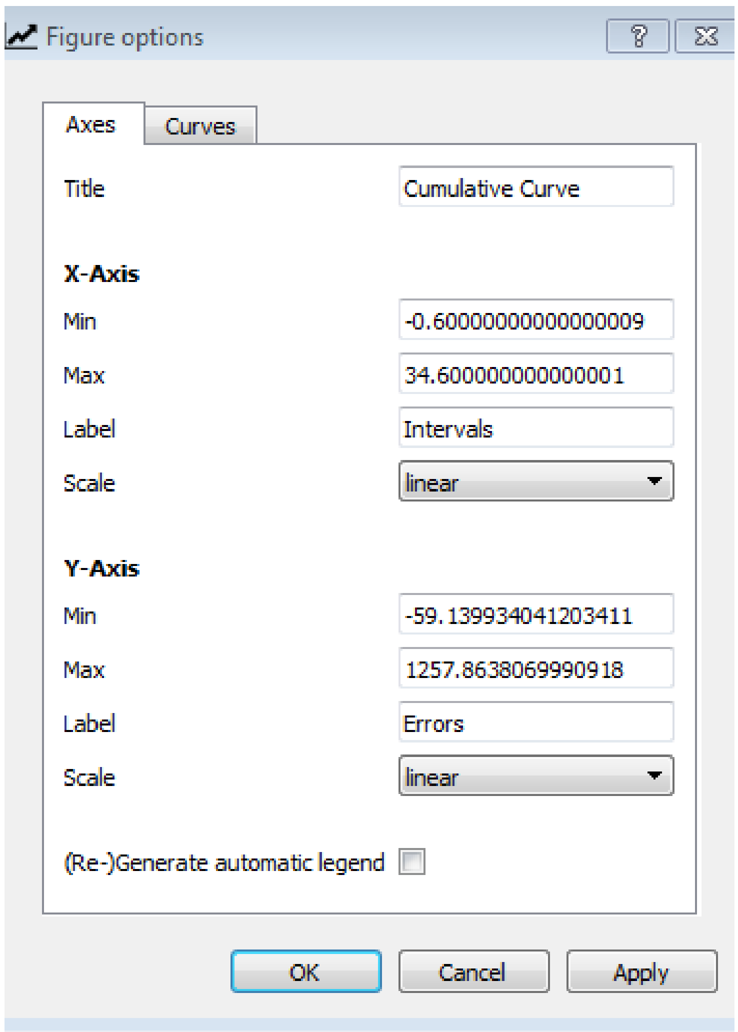


Fig. 22: Data saving - Figure Options