

Development of a Manufacturing Applet's User Interface to Enhance its Properties as a Teaching Tool

by

Michael Dobson

Submitted to the

Department of Mechanical Engineering

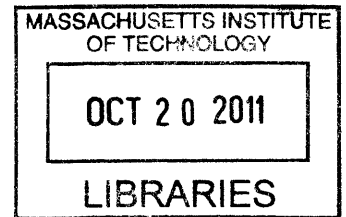
In Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the Massachusetts Institute of Technology

June 2011

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ABSTRACT

A manufacturing system's design and operation plays a critical part in the cost, rate and quality of any product. As a result optimization techniques and cost benefit analysis are common practices in any industry involving manufacturing lines. Due to the prevalence of this field of engineering, Dr. Stanley Gershwin has developed a java applet to serve as a learning tool in teaching students about the processes that occur within manufacturing systems. Since these manufacturing systems are often large complex networks of machines and buffers, it can be difficult to identify a critical component of the line and predict how changes in a component could affect the line as a whole. This thesis develops the framework for four different feedback systems which effectively teaches students how to approach problems commonly seen in industry. The 'Constant Buffer Size Tool' aids students in understanding how to optimally reallocate available space between buffers. The 'Buffer Sensitivity Tool' is able to identify which buffer capacity variances have the highest impact upon the line's production rate. The 'Machine Sensitivity Tool' can be used to help students locate bottlenecks throughout a line. Lastly, the 'Buffer Profit Tool' teaches students the relationship between the revenue of a production line and the costs linked to buffer capacity and hold inventory.

Thesis Supervisor: Stanley Gershwin

Title: Senior Research Scientist

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I would like to thank Professor Stanley Gershwin for his continued support throughout the past year. He has constantly provided me with opportunities to further my learning in manufacturing system development and has served as a valuable resource in educating me in this particular field. He has taught me areas in this field which receive constant attention in industry and methods to most effectively incorporate these areas into the java applet.

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Background

The Manufacturing Line Java Applet was developed Dr. Stanley Gershwin of the MIT Course 2 Department. The purpose of this applet is to give mechanical engineering students a better understanding and intuitive feel for how manufacturing lines operate. Since many manufacturing lines involve multiple machines all which have different characteristics as well as many buffers of different sizes, the effect which one of these components has upon the entire line's production can be very difficult to predict in complex line situations. This applet was created to serve as a tool for students to be able to change certain variables of their choice and observe the overall impact on the line. Currently, a prior version of the applet is used in Dr. Gershwin's class, 2.852 (also 2.853/2.854) Manufacturing Systems Analysis.

Applet Functionality

The applet is equipped with five different computational programs (referred to as 'tools') and is able to solve manufacturing lines with many different characteristics. These characteristics include the basic tandem line, assembly/disassembly lines, loops and lines with profits that are linear combinations of production rate and average inventories. The five different computational programs which the applet is comprised of include the following:

1. Production Line Simulator (PLS) – This tool calls a simulation program. It deals with serial lines, assembly/disassembly lines, loops and evaluates linear combinations.
2. HiMIT Tandem Line and Assembly/Disassembly Systems
 - a. Tandem Line Performance Evaluation (TL-PE) and Tandem Line Buffer Allocation (TL-BA)

- i. These evaluate serial lines (lines without any tree structure, loops or linear combinations)
 - b. Assembly/Disassembly Performance Evaluation (AD-PE) and Assembly/Disassembly Buffer Allocation (AD-BA)
 - i. These evaluate serial lines and tree structures (assembly/disassembly systems) without any loops or linear combinations
- 3. Multiple Loop System – Deterministic
 - a. This tool evaluates serial lines, assembly/disassembly structures and loops. It does not address linear combinations.
- 4. Multiple Loop System – Exponential
 - a. This tool evaluates serial lines, assembly/disassembly structures and loops. It does not address linear combinations.
- 5. Multiple Loop System – Continuous
 - a. This tool evaluates serial lines, assembly/disassembly structures and loops. It does not address linear combinations.

The program is able to use these tools to evaluate many different types of manufacturing systems and return many different forms of information to the user. This data feedback can consist of the line's production rate and total average inventory. It can also calculate each machine's average production rate, percent blockage and percent starvation. It can also include the average inventory and production rate for each buffer.

Objective

The applet has several different tools which help the user evaluate customized manufacturing systems of their choice. However, there are certain limitations in the user interface and well as insufficiencies in the program's feedback systems. As previously stated, the main forms of feedback the user receives are the average production rate for a line and average inventory size and volatility for each buffer. These are displayed to the user in a text format. While these are very important in describing the operation of a line, there are three shortfalls with the program.

1. It does not convey the information in a very engaging format. The text files in use are fairly cluttered and can prove difficult to for the user to locate the desired information.
2. There is other information which can give great insight into the line's functionality and operations which is not currently available to the user. The program does not calculate it.
3. Since the purpose of the applet is to be used as a learning tool for students, it is expected that the users will be using the results from a line's evaluation to make changes to the line and observe what impact those changes have upon the line's functionality. Thus it is necessary for the user to be able to quickly change parameters and the line layout of their manufacturing system. This means a fluid quick user interface is needed to facilitate easy operation of the program. This will ensure the students are not spending time struggling with the program to remodel their line and instead are able to focus on understanding the results the program and how to apply those results to make beneficial changes to the line.

These areas of improvement will be address by the multiple feedback designs developed in this paper.

GUI Input

The objective of this paper is aimed at furthering the teaching capabilities of the program. While most of this paper will focus of different feedback methods designed to give students a better understanding of manufacturing systems, different forms of input methods to designate the parameters of the machines and buffers in the manufacturing line where also considered.

The initial input method is shown below. Once the line of machines (represented by squares) and buffers (represented by circles) is created, the user must enter the parameters for each of these line components via the input box at the bottom of the screen. Both machines and buffers require the input of multiple parameters from the user. This method of input tends to be time consuming when the user wants to quickly modify a parameter for a component and also leads to occasional input mistakes.

Simplistic Line Displayed on Applet

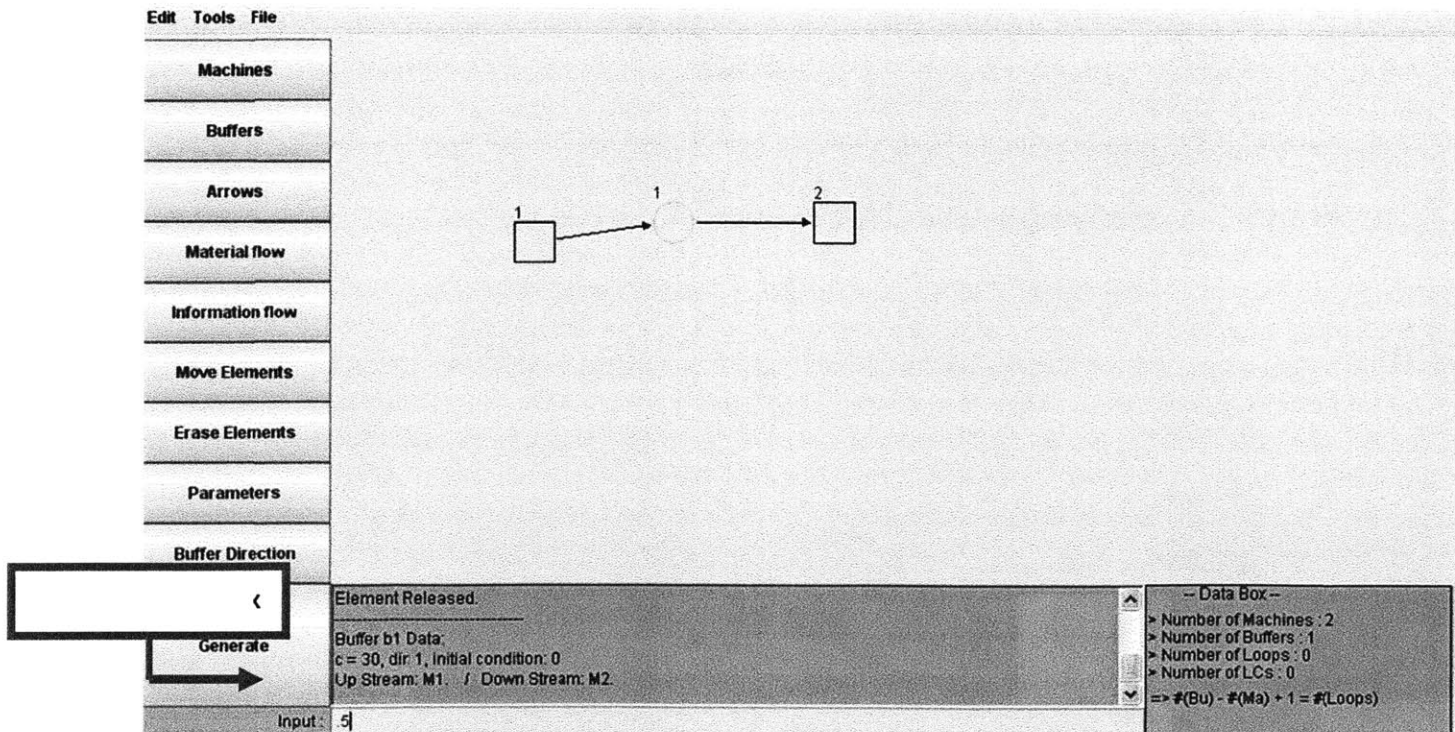


Figure 1: Outdated line component input style. Parameters must be typed one after another into the orange input box at the bottom of the applet. The input requests in the gray box above the input box are also difficult to read.

To improve the user input interface, a dialog box input style was implemented. Now when the user wishes to enter or change the parameters for a particular line component, a dialog box opens. The dialog box contains a list of all the parameter's and their current values immediately visible to the user. This way the user can see the previous values of the component and has easy access to quickly modify any of them.

Applet's Updated Input Method for Machines

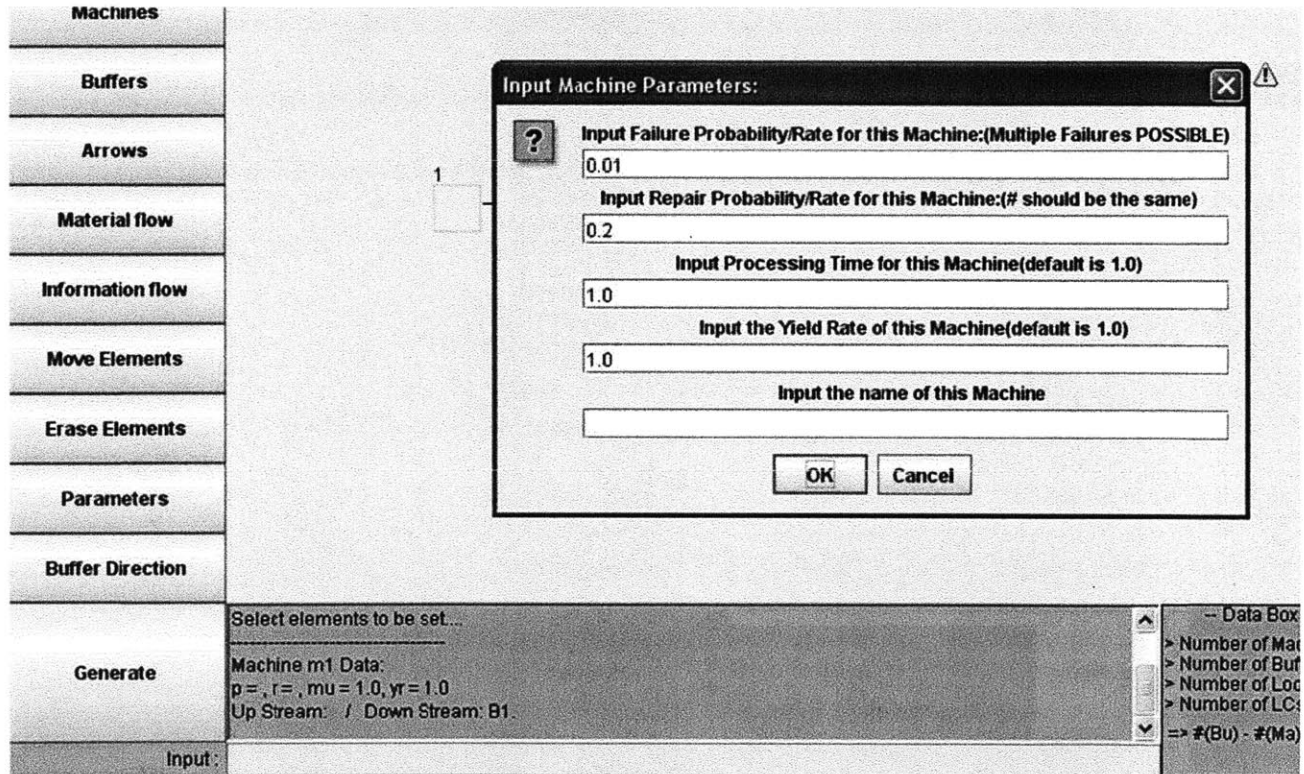


Figure 2: Updated machine component input style. This approach uses a dialog box so all parameters can be viewed by user at once. Also user can choose which parameters he desires to modify without redefining all of them as in the outdated case.

Applet's Updated Input Method for Buffers

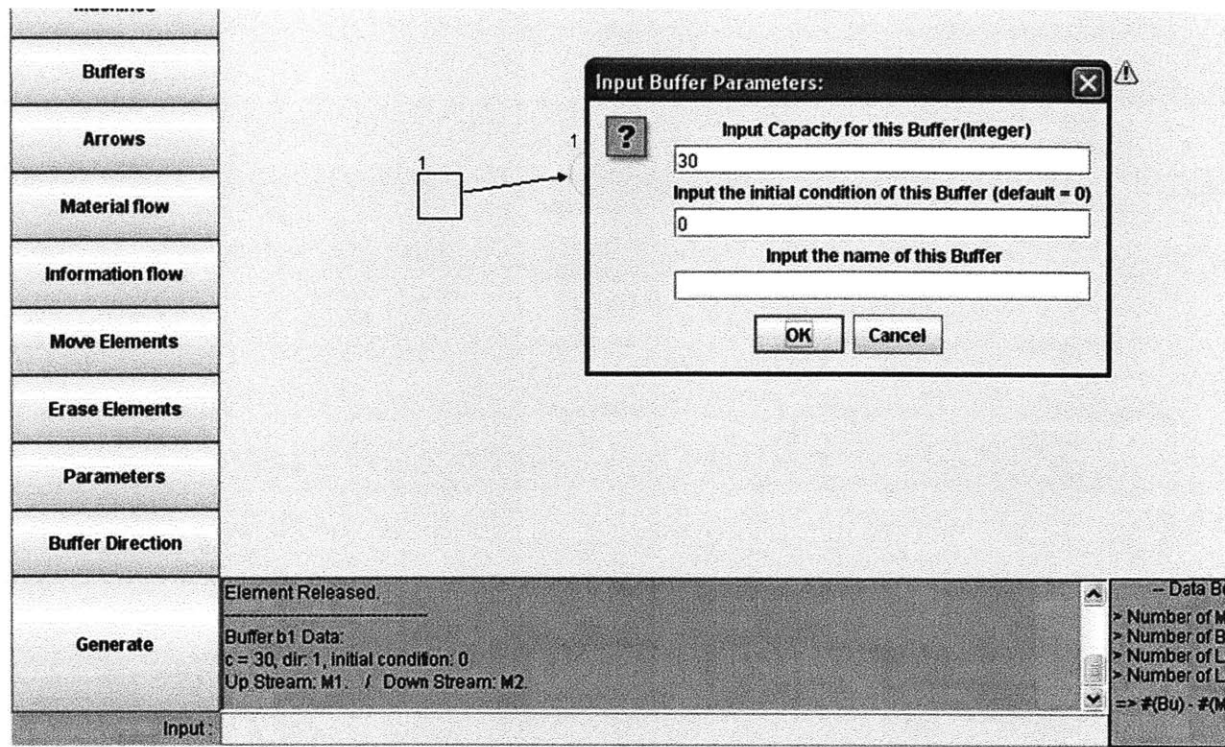


Figure 3: Updated buffer component input style.

Available Line Data

The goal of this program is to serve as a teaching tool to help mechanical engineers develop a better understanding for how manufacturing lines function and how different parts of the line affect the whole line. There is a large amount of data that can be gathered from a line which describes its overall efficiency and performance. With the purpose of instructing students how to optimize a manufacturing line, potentially valuable feedback information has been identified and explained in the section below. Once the relevant information has been identified, it will be applied to the user feedback methods in the following section.

Manufacturing lines can consist of many different machines and buffers which can be connected in a wide range of ways. Since the order in which machines are placed in a line is

usually determined by the product being developed, there is not very much freedom or flexibility in changing the order of machines in a line. Two areas that are under the decision of the engineer are buffer placement as well as the types of machines purchased. The information gathered will be grouped in four categories including buffers, machines, lines, and profit.

Buffers

Buffers are an extremely important part of manufacturing systems and received a huge amount of attention from line owners when trying to determine their optimal sizes. Since the machines in manufacturing lines often have different individual efficiencies, probabilities of failure and probabilities of repair, buffers are a holding area where products in the middle of production are kept when transitioning from one machine to the next in a line. Buffers help prevent starvation throughout the line during times of machine failure and help the line flow smoothly by minimizing interruptions.

While introducing buffer areas into lines is very helpful and a practiced used in all manufacturing systems, it is often difficult to predict the appropriate amount of space to distribute to each buffer once the line becomes more complex. The following is data that would be helpful in teaching students efficient buffer allocation.

- **Buffer Size** – the amount of space in a buffer which dictates the number a parts the buffer can hold.
- **Average Buffer Inventory** – during a line’s steady state, the average amount of inventory found in a buffer.
- **Buffer Fluctuation/Variance** – a measure of the frequency and magnitude in which the inventory inside a buffer increases and decreases about the average buffer size.

- Empty Buffer (Machine Starvation) – the amount of time a machine does not receive parts because there are no parts in the buffer in front of it
- Full Buffer – during a line’s steady state, the cumulative amount of time a buffer is filled with its maximum amount of inventory. A full buffer hurts the production of a line because it shuts down the production of the upstream machine since there is no longer a place for that machine to place its finished parts.

Provided with this data, students would have a better understanding of the operation of the line which they are evaluating. This would help the user learn to efficiently allocate their available buffer resources and understand which buffer in a particular line has the highest influence over the line’s total production rate.

Machines

When creating a manufacturing line, the owner has the option to purchase different types of machines for the same function. These different machines come with different characteristics all of which have the potential to significantly impact the overall line’s production rate.

- Mean Time to Fail – the average time until a machine or one of its components experiences a failure causing the machine to be non functional.
- Mean Time to Repair – the average time necessary to repair a failed machine. It is used as a method of measuring the maintainability of machines on a line.
- Multiple Failure Modes – some machines have many different sources of failure which may occur for different reasons. Each of these types of failure has a mean time to fail and mean time to repair associated with it.

- Efficiency – the percentage of time the machine is functioning properly versus the total amount of time it would be ideally running

$$Efficiency = \frac{MTTF}{MTTF + MTTR}$$

- Operation Time – the time it takes for a machine to process a part (sec/part)
- Production Rate – the number of parts a machine outputs per unit of time when it is up
- Average Production Rate (for a machine) – the average number of parts a machine can output per unit of time when it should be running

$$Production Rate = \frac{Efficiency}{Operation Time}$$

- Set Up Change – a source of interruption when a machine cannot be used due to tool changes or reconfigurations
- Operator Absence – a source of interruption when a machine is down due to no operator present to run the machine

In practice the line manager does not have as much power over changing these properties once the machines are bought as he has over the properties of the buffer distribution. However, there still are actions that can be taken in manufacturing plants which can adjust these values.

Lines

There are some characteristics that are useful in describing different manufacturing lines as a whole. These characteristics help describe the efficiency of the line as well as its weak points which can be improved upon.

- Average Production Rate – the number of parts a manufacturing line can output per unit of time
- Bottleneck – The machine (or parallel group of machines) in a manufacturing line that is the limiting factor for an increase in production rate. The bottleneck can be located by ranking each machine's effective production rates.
- Cycle Time – the average time from release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing. This is calculated through Little's Law

$$L = \lambda w$$

where L is the average inventory, λ is average production rate and w is average cycle time.

Profit

The previous data can be used to optimize lines to help them run faster and increase their production rate. However, the goal of managing any manufacturing line is not necessarily to achieve the highest production rate but to achieve the highest profit. Here are some variables that can significantly affect the profit of a line.

- Buffer Size Costs – cost per amount of space in a buffer
- Inventory Costs – cost for housing one unit of inventory.
- Cost of Lost Inventory Value – during a product's time in inventory there are a number of events which could occur that would devalue the stored goods. Some examples being the goods become damaged, spoiled, obsolete on the market, out of date, devalued from demand changes or the possibility of finding a design/manufacturing error in the product.

All of these possibilities of devaluation are risks of keeping high inventory and need to be account for as potential costs.

- Price of Finished Product – monetary value of a finished part
- Capital Cost – cost of purchasing equipment (such as machines and warehouses) when building a manufacturing system

Without any buffers, there would be constant interruptions and blockages in a line. If there were no failures, the line would be restricted to run at the slowest machine's production rate. Taking into account all the line's failure possibilities, the production rate would actually end up much slower and extremely inefficient. By increasing the buffer sizes throughout a line, the line's production rate increases. However, it can also bring about high costs due to large buffer sizes and inventory sizes. At some point, these costs are enough to match or overcome the gained revenue from increasing production rate. Therefore some optimal middle ground for buffer size is needed. The equation below determines a manufacturing line's profit and can help address this question.

$$Profit Rate = AP - \sum b_i N_i - \sum c_i n_i - \sum d_j C_j$$

where A = price coefficient, P = production rate, b_i = cost coefficient for unit of space, N_i = buffer size of buffer i, c_i = cost coefficient for holding inventory, n_i = average inventory of buffer i, d_j = coefficient representing rate of depreciation, C_j = capital cost of machine j.

GUI Feedback Implementation

The information presented above is helpful in giving students an intuitive understanding of how manufacturing lines run. However, to be an effective teaching tool, the applet must present the data to the student in ways that are impactful and designed for student interaction. This paper will now propose four separate feedback methodologies and a detailed description of their functionalities, benefit to the user and a graphical walkthrough of the user interface.

Constant Buffer Size Tool

This tool will be used when the user wishes to mimic a manufacturing line which has a restricted space on the total available buffer capacity. In the case the optimal allocation of all the available buffer space to the various buffers throughout the line is unclear. The goal of this feedback tool will be to teach the user how much space to allocate to each buffer when only a limited amount of space is available. This tool is applicable to almost all manufacturing lines because it serves as a way of mimicking many practical situations where a manufacturing company's buffer capacity is limited by the size of the warehouse they have purchased.

This tool will run by varying two buffers chosen by the user while keeping the total buffer size of the line constant. For example, take a line that has four buffers where B_1 (buffer 1) has 4 units of space, B_2 has 3 units of space, B_3 has 7 units of space and B_4 has 1 unit of space. The user will be prompted to choose the two buffers they wish to vary. Say the user chooses B_1 and B_3 . The program will calculate the line's production rate for cases where $B_1 = 0$ and $B_3 = 11$, $B_1 = 1$ and $B_3 = 10$, $B_1 = 2$ and $B_3 = 9$ all the way to $B_1 = 11$ and $B_3 = 0$ with all the other buffer sizes remaining the values in which they were originally set. Then feedback will be presented to the user in the form of B_1 versus the production rate. From this graph the user would be able to

quickly see if it is optimal to redistribute the buffer space between B_1 and B_3 . This is directly applicable to many situations manufacturing companies attempt to solve, and is a visual way to effectively show the user the large impact strategic buffer allocation can have on a manufacturing line's production rate.

The graphical user interface for this tool's input sequence can be found in the appendix. Also, it would be possible to extend the power of this feedback tool to evaluate three buffers simultaneously. If the computing power of the program was not of concern, the line's production rate could be calculated for all possible combinations of buffer sizes for the three selected buffers and presented to the user in the form of a 3D topological graph. One axis (x axis) would represent one buffer size, one axis (y axis) would represent another buffer size and the third axis (z axis) would represent the line's production rate. From the values of the first two first, the value of the third buffer could determined at each point on the graph.

Buffer Sensitivity Tool

The purpose of this tool is to give students an idea which buffers have the largest impact on the line's overall production rate. This tool would be used to mimic a situation where the overall buffer capacity of the line under evaluation can be changed. It would be applicable to practical scenarios in determining which buffers to purchase more space for (increase in size) or sell/reallocate space (decrease in size).

When choosing to evaluate a manufacturing system with this tool, the user will be prompted with the option of choosing to evaluate an individual buffer or the entire system of buffers. An individual evaluation of one buffer allows the user to input a capacity range for that buffer. The program will then compute the line's production rate for all the discrete buffer size

values within the range specified and display the information graphically in terms of buffer size vs the line's manufacturing rate. All other buffer sizes in the manufacturing line will be held constant in this instance of the 'Buffer Sensitivity Tool'.

The other option is to evaluate and then compare all the buffers in the line simultaneously. This will allow the user to see how large an impact a change in each buffer's size has on the entire line's production rate and compare which buffers are most significant. While the program is computing the line's production rates over a range for one buffer, all other buffers in the line will be held at the initial values they were set at when first created. The step by step logic of the program's operation is based on the following steps.

User chooses individual buffer evaluation.

1. User selects a buffer to analyze.
2. User specifies the selected buffer's capacity range for evaluation. A default range of 90% to 110% of its initially set capacity can be used if nothing is entered.
3. User enters the increment step size for the program to perform calculations across the selected buffer's specified range.
4. Each calculated buffer size within the specified range is plotted against the line's production rate.

User chooses total buffer system evaluation.

1. User enters the percentage of the line's total buffer size which will be used as the size range for every buffer's calculation. This size range will be denoted as Q. If nothing is entered, some small value for Q will be set.

2. Varies 1st buffer size by Q amount around buffer 1's original value while keeping all other buffer sizes constant. Thus if buffer 1's size was S_1 , calculations would be performed with buffer 1's size at $S_1 - Q/2$ to up to buffer 1's size at $S_1 + Q/2$.
3. Records the line's production rate for each discrete value within this range.
4. After all the production rates have been calculated for each discrete value, the total difference between the production rate at $S_1 + Q/2$ and the production rate at $S_1 - Q/2$ will be recorded for that buffer.
5. This process will be repeated for every buffer in the line.
6. A bar chart is made of the Production Rate Difference (PR at $S_1 + Q/2 - PR$ at $S_1 - Q/2$) vs the Buffer Number.

The graphical user interface for this tool's input sequence can be found in the appendix.

Machine Sensitivity Tool

The purpose of this tool is to give students an idea which machines have the greatest effect on the production rate of a line. By looking at how the production rate of a line is effected by varying the parameters of an individual machine (such the mean time to failure, mean time to repair and the processing time) and holding all other machines in the line constant, it is easy to identify which machines the entire line's production rate is most sensitive towards. This is useful information because it can help locate bottlenecks in the line and suggest machines where improvements (MTTF, MTTR and processing time) would have the greatest success in increasing the line's production rate.

Since the MTTF, MTTR and processing time of an individual machine are typically not easily changeable like a buffer's capacity, this tool is not as applicable when dealing with a line

already in operation. However, this tool could be applicable to a case involved in determining which machines to purchase when initially building a manufacturing line. An example that fits this case would be a manufacturing company who must replace a particular machine in their line which has broken. Currently on the market are three different machines all of which have different values for individual MTTF, MTTR and processing time. While none of these machines is necessarily individually superior when compared to the others, one will be the optimal choice when connected to the particular line under consideration. This tool would allow students to see which parameters of each machine are important to their specific line's production rate.

Also, while the parameters of machines are not as easily changeable as the buffer parameters, there are some efforts that can be taken to slightly adjust a machine's MTTF, MTTR and processing time. Thus it is still useful for students to understand and recognize cases where a slight change in any of the parameters of a machine can have a significant impact on the line's production rate.

Similar to the 'Buffer Sensitivity Tool', this tool will also have the option for the user to choose to evaluate an individual machine or evaluate and compare every machine in the line at once. An individual evaluation of one machine allows the user to input a MTTF range, MTTR range or a processing time range for that machine. The program will then compute the lines production rate at some step interval for all MTTF, MTTR or processing time values within the range specified. Then the information will be displayed graphically in terms of the machine's MTTF, MTTR or processing time vs the line's manufacturing rate. All other machine parameters in the manufacturing line will be held constant in this instance of the 'Machine Sensitivity Tool'.

The other option the user has is to compare all the machines in the line to one another. Once this option is picked, the user then must also specify which parameter of these machines he

wishes to evaluate (MTTF, MTTR or processing time). This will allow the user to see how large an impact a change in each machine's MTTF, MTTR or processing time has on the entire line's production rate in comparison to the other machines. While the program is computing the line's production rates over a range of one machine's parameter, all other machines in the line will retain the initial values of the parameters they were given when first created.

The portion of the 'Machine Sensitivity Tool' which compares all the machines in the line to one another can be useful to teaching students how to predict bottleneck locations throughout a line.

The step by step logic of the program's operation is based on the following steps.

User chooses individual machine evaluation.

1. User selects a machine to analyze.
2. User selects the machine's parameter to analyze (MTTF, MTTR or processing time).
3. User specifies the selected machine's selected parameter range for evaluation. A default range of 90% to 110% of its initial value can be used if nothing is entered.
4. User enters the increment step size for the program to perform calculations to find the production rate for every value in the selected machine's specified parameter range.
5. Each machine parameter within the specified range is plotted against the resulting line's production rate.

User chooses total machine system evaluation.

1. User selects the machine parameter he wishes to analyze (MTTF, MTTR or processing time).
2. User enters the range to be used as the range for every machine's parameter during the calculations. This size range will be denoted as Q . If nothing is entered some small value for Q will be set.
3. Varies 1st machine parameter by Q amount around machine 1's original value while keeping other values of machine 1 and values of all other machines in the line constant. Thus if machine 1's parameter value was M_1 , calculations would be performed with machine 1's parameter at $M_1 - Q/2$ to up to machine 1's parameter at $M_1 + Q/2$.
4. Records the line's change in production rate for each discrete value within this range.
5. After all the production rates have been calculated for each discrete value with the specified range for the machine parameter, the total difference between the production rate at $M_1 + Q/2$ and the production rate at $M_1 - Q/2$ will be recorded for machine 1.
6. This process will be repeated for every machine in the line.
7. A bar chart is made of the Production Rate Difference (PR at $M_1 + Q/2 - PR$ at $M_1 - Q/2$) vs the Machine Number.

The graphical user interface for this tool's input sequence can be found in the appendix.

Buffer Profit Tool

The 'Buffer Sensitivity Tool' is useful in seeing increasing the size of which buffers are able to have highest beneficial impact on the line's production rate. However, eventually there will come a point where the cost of increasing the buffer size does not justify the resulting

benefits from the increased production rate. The 'Buffer Sensitivity Tool' is unable to provide insight into the topic. The goal of the 'Buffer Profit Tool' is to show the extent to which increasing a particular buffer is financially justifiable. This is important because in practice all decisions related to buffer allocation, expansion or reduction are made with the intension of maximizing profit.

The step by step logic of this program's operation is based on the following steps.

1. User selects the buffer to analyze
2. User selects costs of one buffer size unit
3. User selects cost for holding one unit of inventory in this buffer
4. User selects the price at which product is sold after being manufactured.
5. User specifies the selected buffer's capacity range for evaluation (default range of 90% to 100% of its capacity can be used if nothing is entered)
6. User enters the increment step size for the program to perform calculations across the selected buffer's specified range
7. The profit for the line is calculated for each incremented value of the selected buffer's capacity range.

$$Profit = AP - \sum b_i N_i - \sum c_i n_i$$

where A = price of a part, P = production rate, b_i = cost per unit of space, N_i = buffer size of buffer i, c_i = cost per unit of inventory, n_i = average inventory of buffer i. The fixed costs of the machines will not be included in this equation.

8. Each buffer capacity within the specified range is plotted against its corresponding line's profit

The graphical user interface for this tool's input sequence can be found in the appendix.

Conclusion

Manufacturing systems are a critical part of any product's development. Since these systems are made of many interconnected machines and buffers which depend on one another, it can prove difficult to understand how each component affects the entire line's production. The feedback frameworks developed in this paper utilize information available about the system and convey it to the user in ways that mimic practical scenarios and give insight regarding the impact each component has on the entire line.

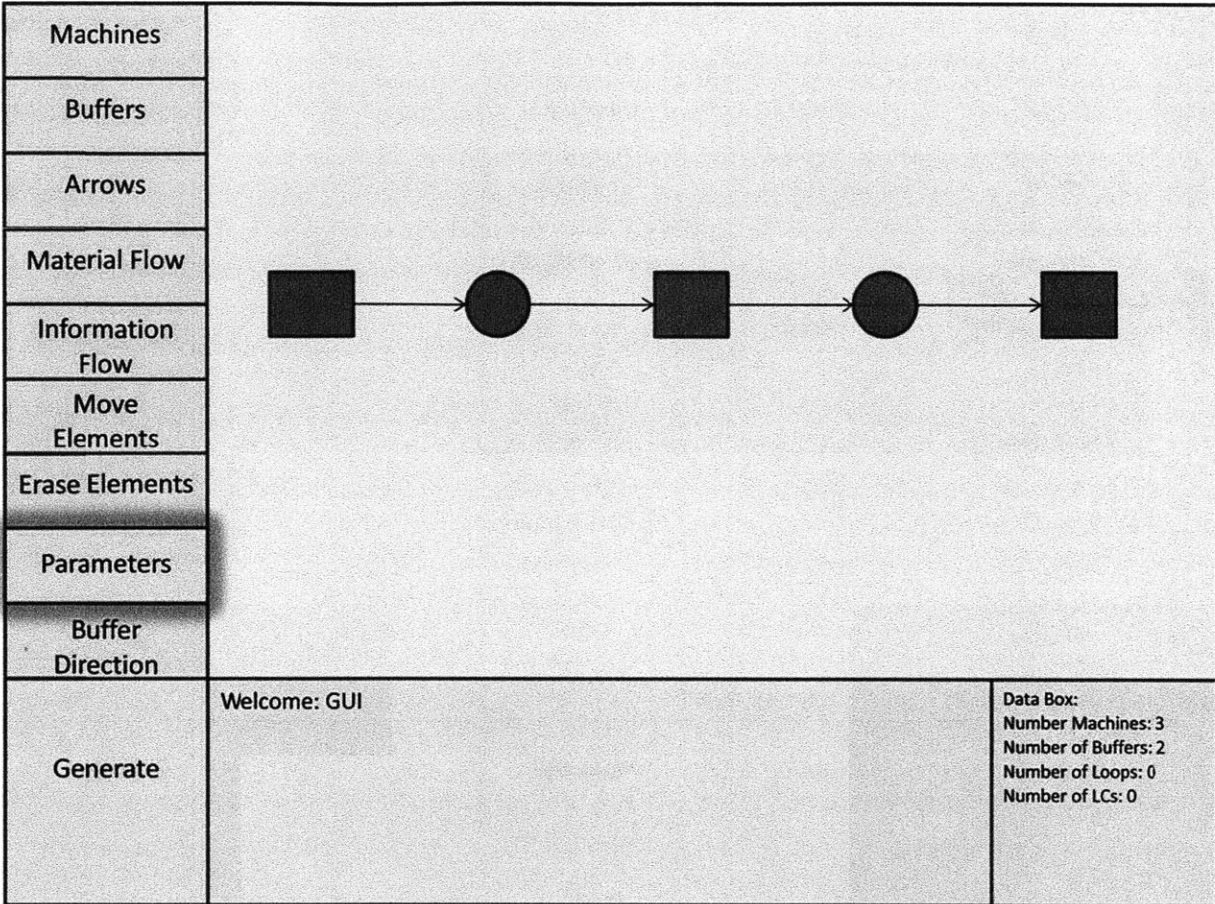
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Chun, Jung-Hoon. "Manufacturing Systems 2.008" PowerPoint presentation. Boston, MA. 2004.

Gershwin, Stanley B. "Manufacturing Systems: Single Part Type, Multiple Stage Systems." PowerPoint presentation. Boston, MA. 2003.

Appendix

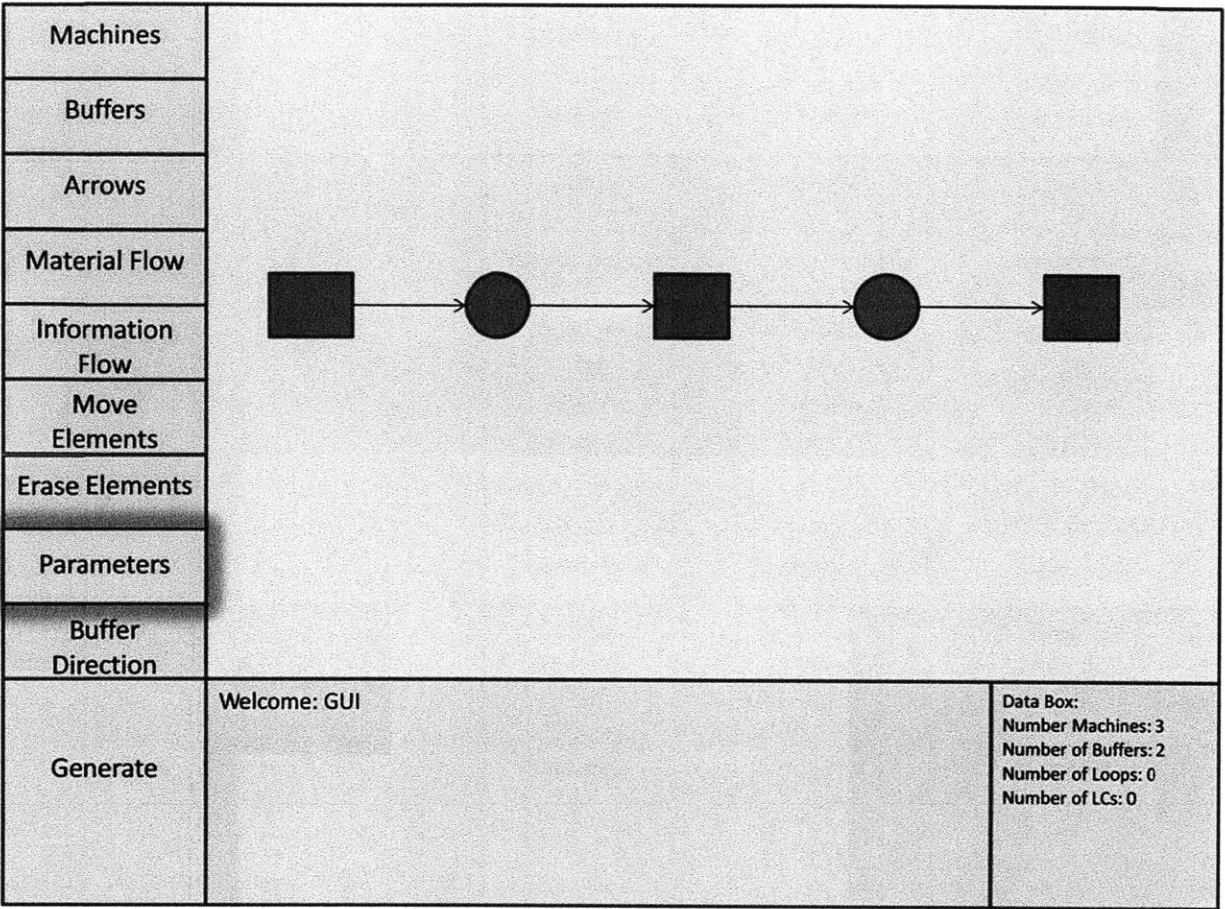
Creation of Example Line



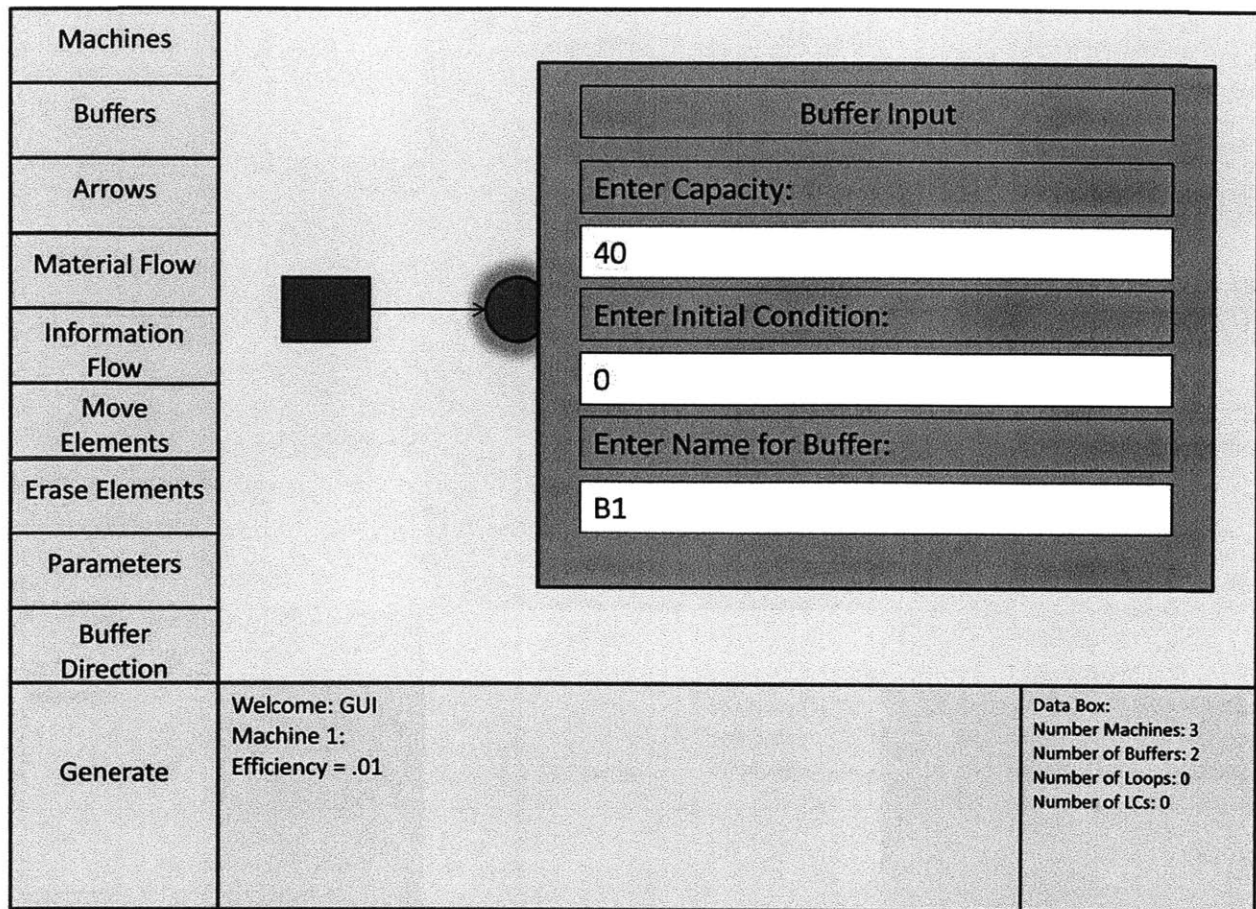
Appendix Figure 1: Here is a diagram of a sample tandem line. The squares represent the machines and the circles represent buffers.

Machines	<div style="border: 1px solid black; padding: 5px;"> <p style="text-align: center;">Input Box</p> <p>Enter Failure Probability Rate for Machine:</p> <input type="text" value=".01"/> <p>Enter Repair Probability Rate for Machine:</p> <input type="text" value=".2"/> <p>Enter Process Time:</p> <input type="text" value="1.0"/> <p>Enter Yield Rate:</p> <input type="text" value="1.0"/> <p>Enter Name for Machine:</p> <input type="text" value="Bob"/> </div>	
Buffers		
Arrows		
Material Flow		
Information Flow		
Move Elements		
Erase Elements		
Parameters		
Buffer Direction		
Generate		Welcor

Appendix Figure 2: Here is the dialog box requesting the parameters for the first machine.

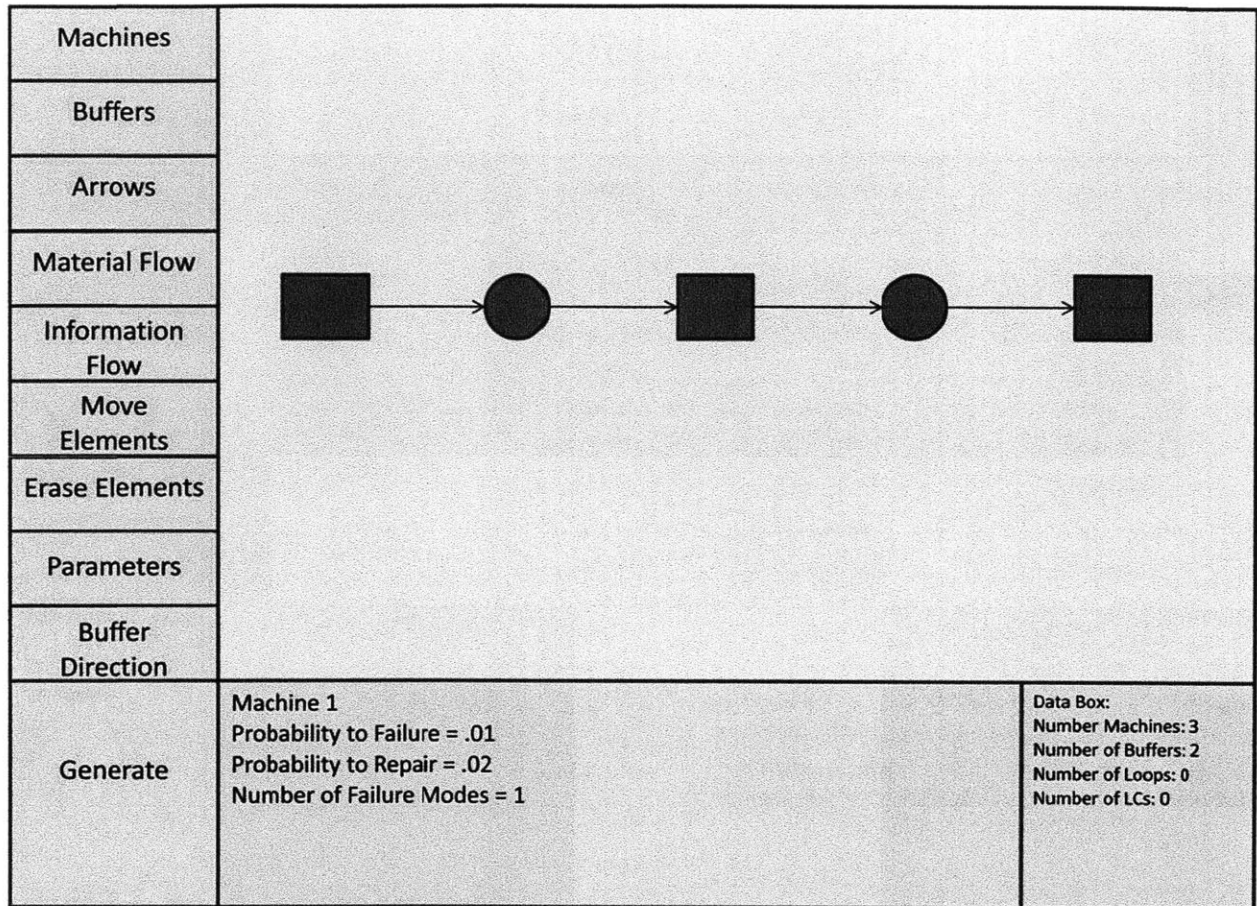


Appendix Figure 3: The parameters for the first machine have been entered. The applet return to the manufacturing line layout.

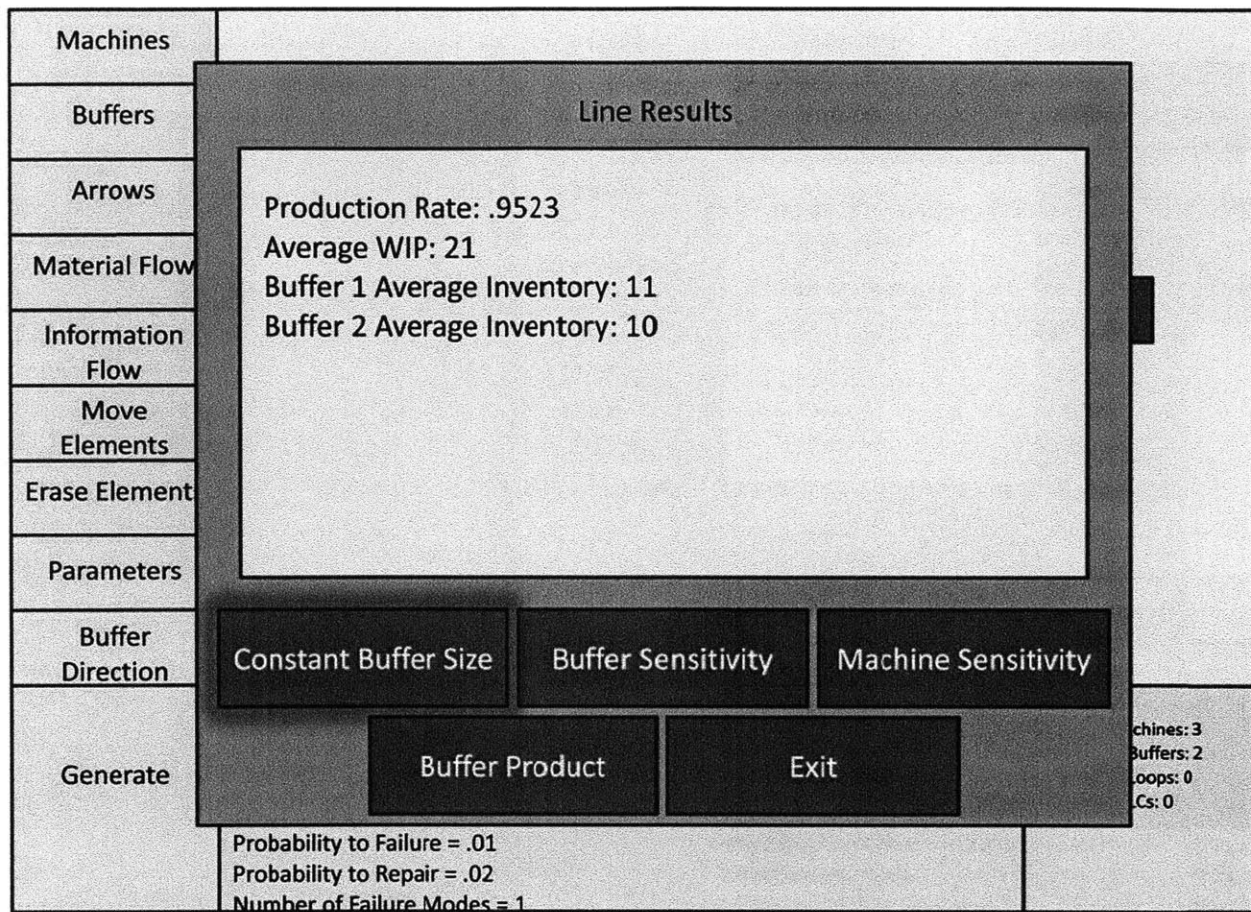


Appendix Figure 4: Here is the dialog box requesting the parameters for the first buffer. The input process for the remaining two machines and one buffer will not be shown but the process is the same as previously shown.

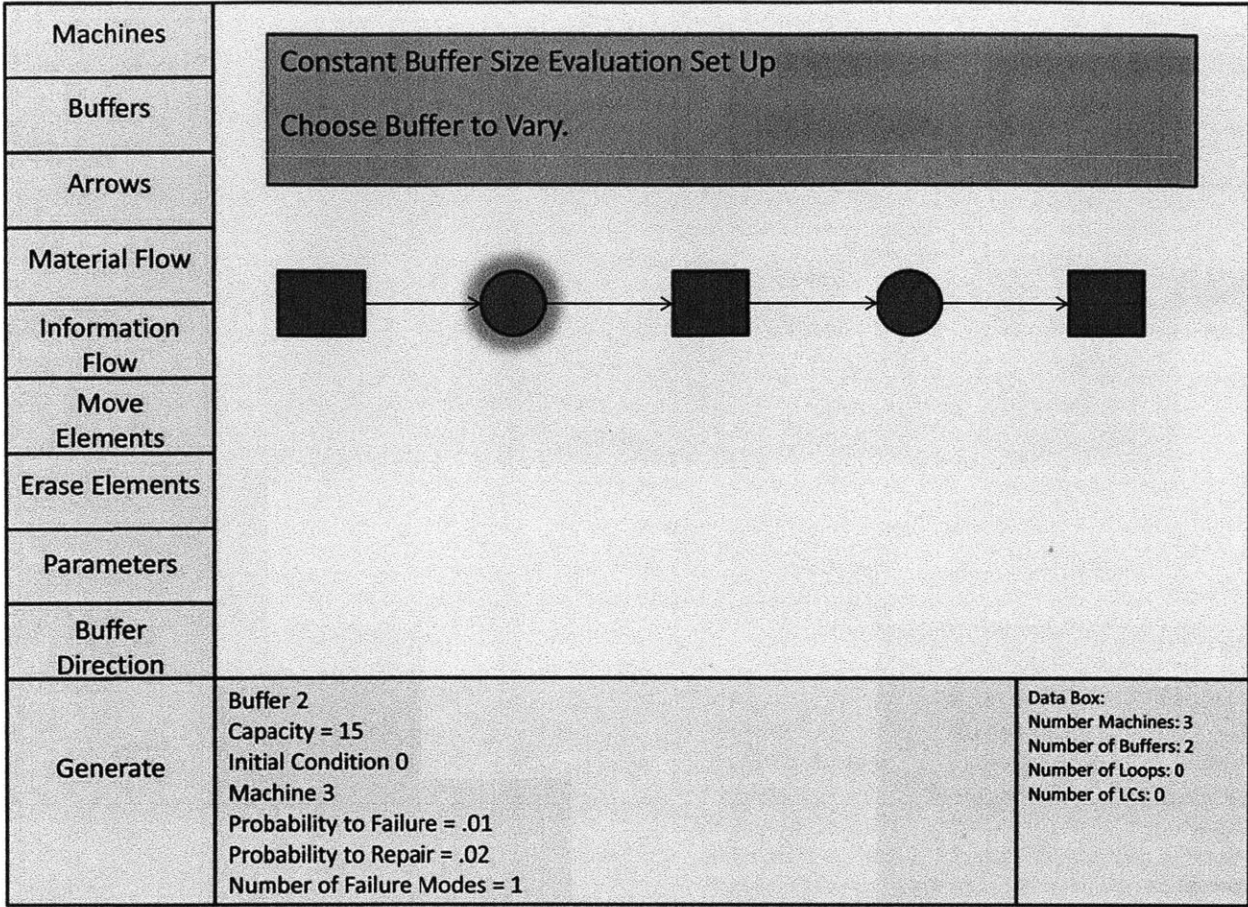
Steps demonstrating the use of the 'Constant Total Buffer Size Tool'



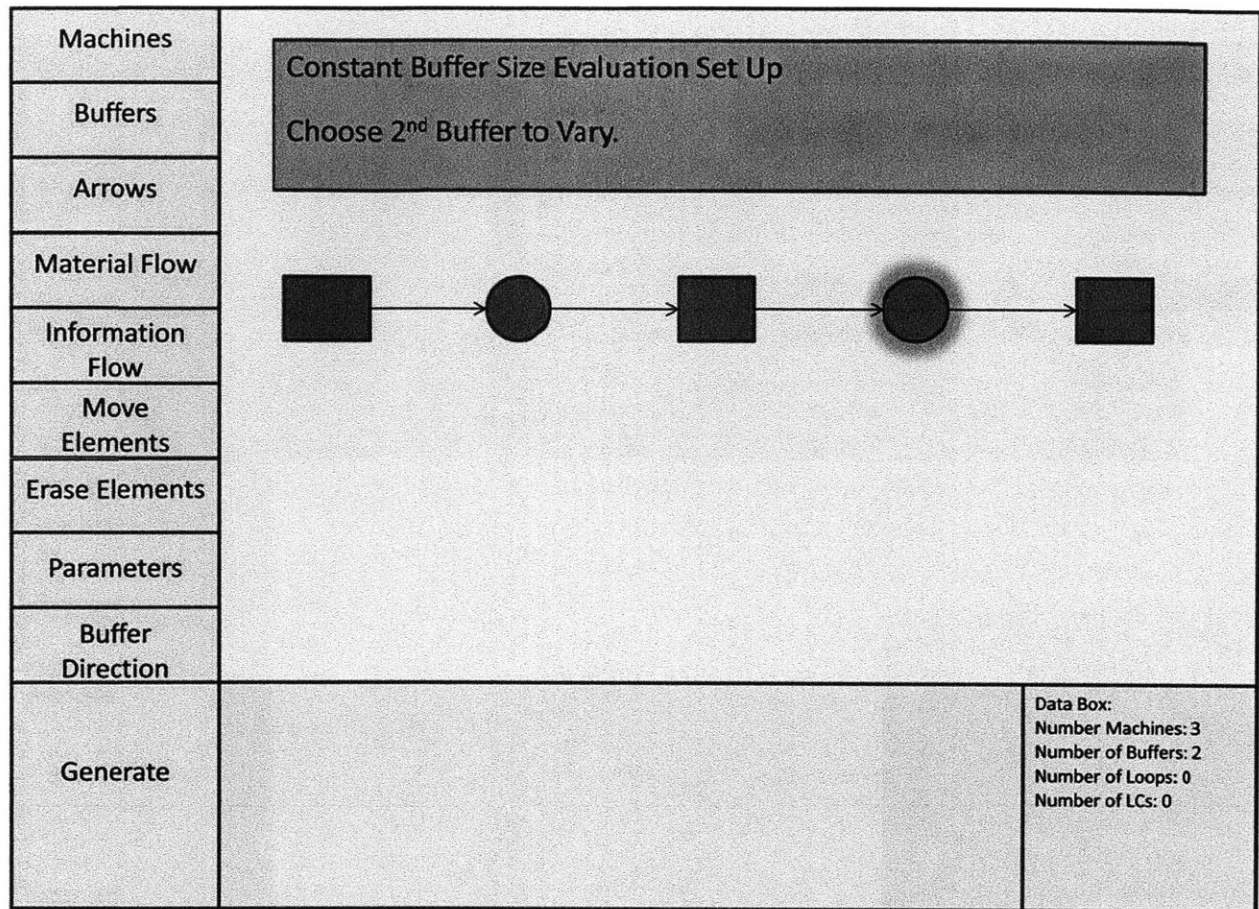
Appendix Figure 5: After the parameters for all components in the line have been entered, the applet returns to the line layout and is ready for the user to pick a form of evaluation.



Appendix Figure 6: Once the line is evaluated, an output file is returned to the user. The data returned in the output file depends on the type of line entered and which computational code the user chose to evaluate the line. This output file provides basic information in text format. At the bottom of the output file is where the user would have the option of choosing one of the feedback tools to further evaluate the line. In this case, the ‘Constant Buffer Size Tool’ is chosen.



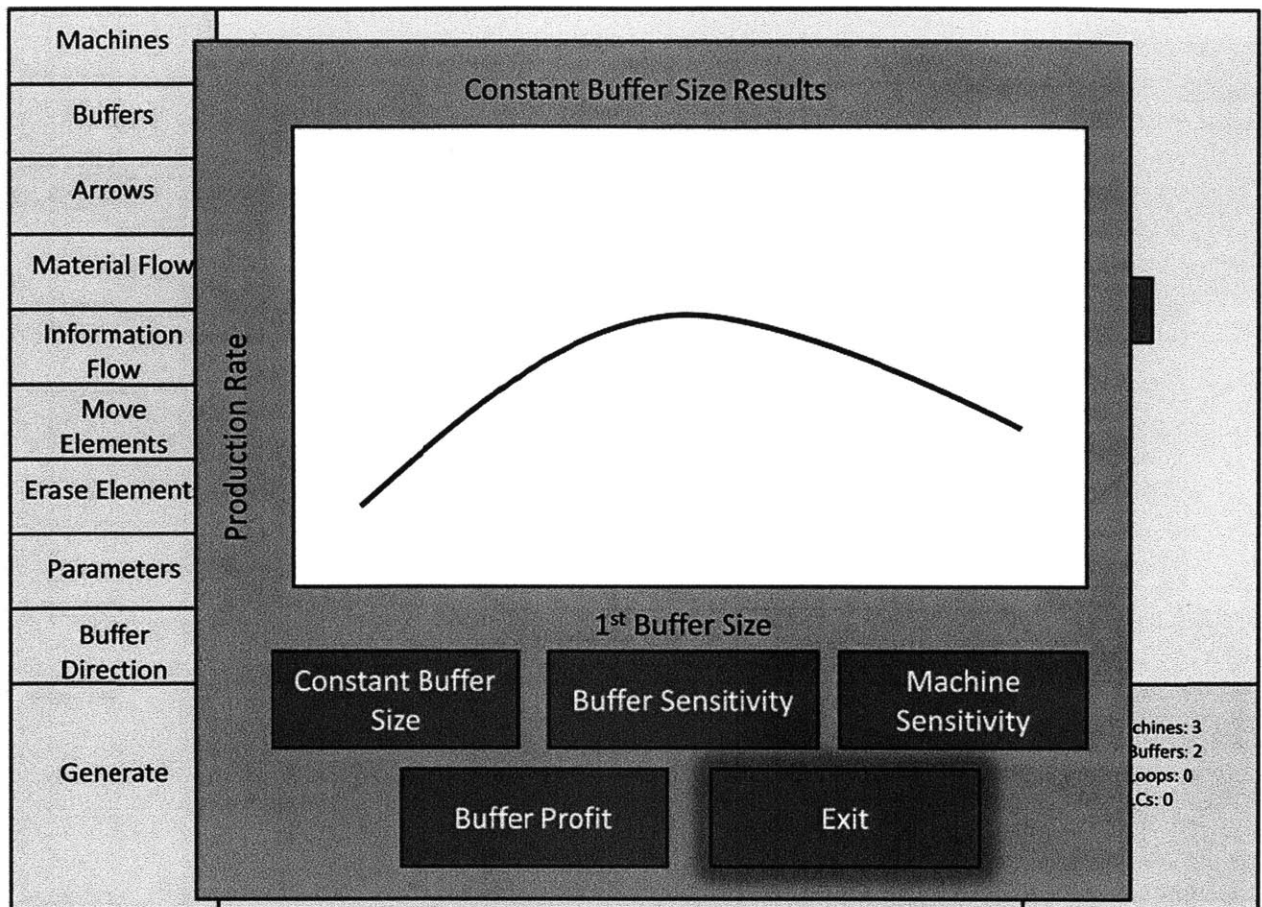
Appendix Figure 7: Now that the ‘Constant Buffer Size Tool’ has been chosen the program will run through the sequence of steps described in the GUI Feedback Implementation section under how the ‘Constant Buffer Size Tool’ operates. The user now chooses the first of the two buffers he desires to evaluate.



Appendix Figure 8: The user now chooses the second of the two buffers he desires to evaluate.

Machines		
Buffers		
Arrows		
Material Flow		
Information Flow		
Move Elements		
Erase Elements		
Parameters		
Buffer Direction		
Generate		

Appendix Figure 9: The user enters the incremental step sizes for the program's calculations.

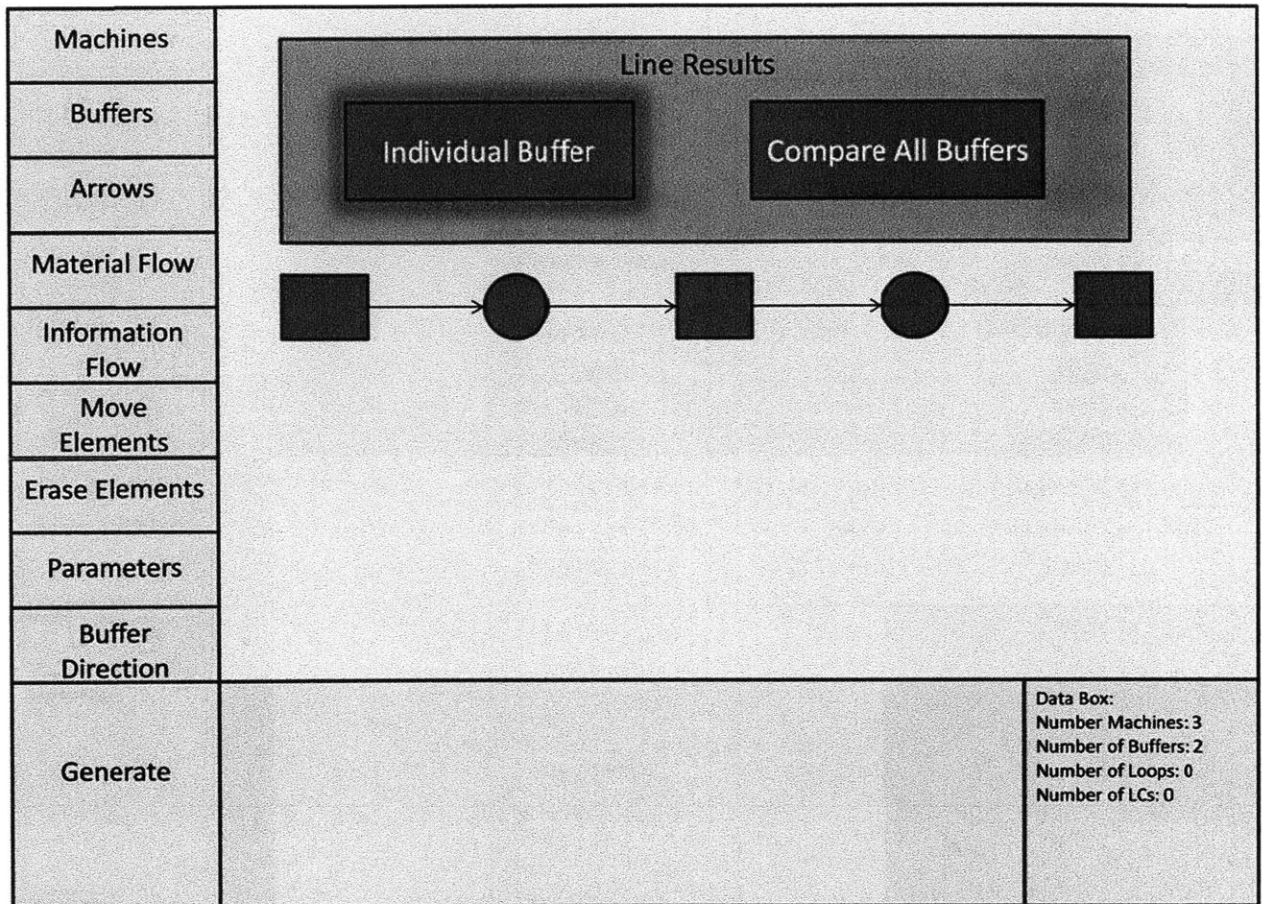


Appendix Figure 10: A graph is displayed with of all the different cases of buffer one's capacity (from which buffer two's capacity can be calculated) plotted against the production rate.

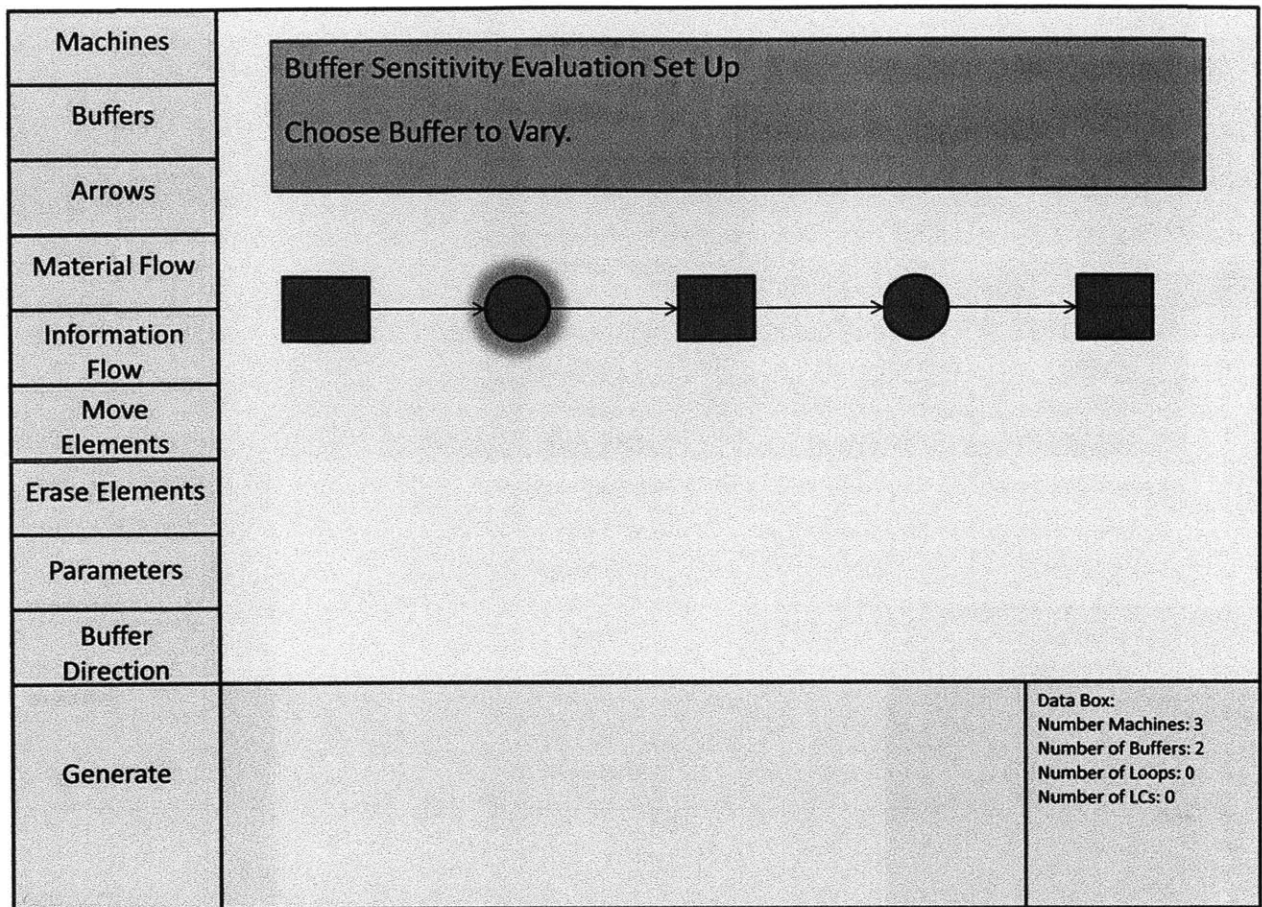
Steps demonstrating the use of the 'Buffer Sensitivity Tool'

Machines	<div style="border: 1px solid black; padding: 10px;"> <p style="text-align: center;">Line Results</p> <p>Production Rate: .9523 Average WIP: 21 Buffer 1 Average Inventory: 11 Buffer 2 Average Inventory: 10</p> <div style="display: flex; justify-content: space-around; margin-top: 10px;"> Constant Buffer Size Buffer Sensitivity Machine Sensitivity </div> <div style="display: flex; justify-content: space-around; margin-top: 10px;"> Buffer Product Exit </div> </div>		
Buffers			
Arrows			
Material Flow			
Information Flow			
Move Elements			
Erase Element			
Parameters			
Buffer Direction			
Generate			
			Machines: 3 Buffers: 2 Loops: 0 Cs: 0

Appendix Figure 11: After the user exits from the 'Constant Buffer Size Tool' the applet returns to the original evaluation output file. From here the user has the option of choosing the 'Buffer Sensitivity Tool'.



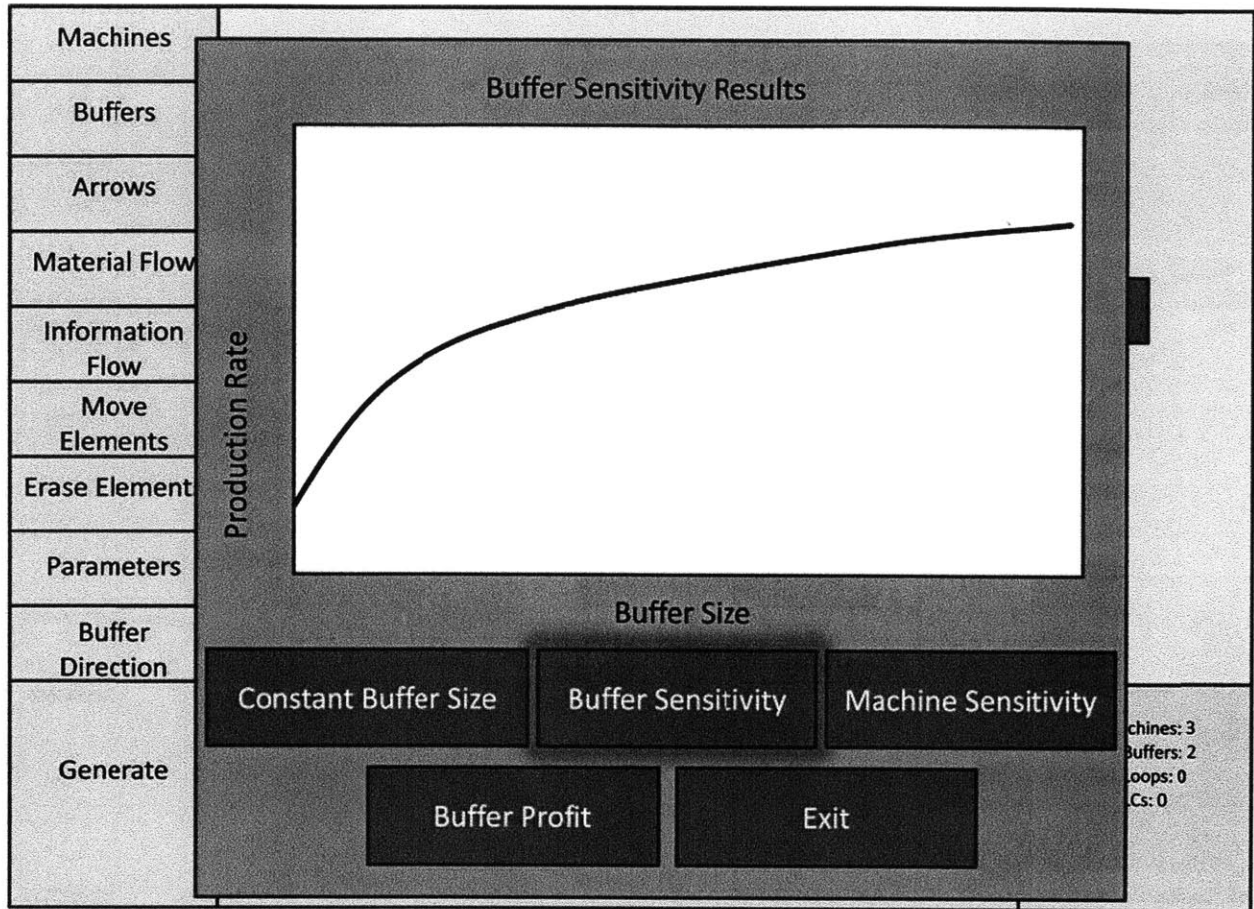
Appendix Figure 12: The user is then prompted with the choice to analyze one buffer individually or all of them simultaneously. Here the individual buffer choice is selected.



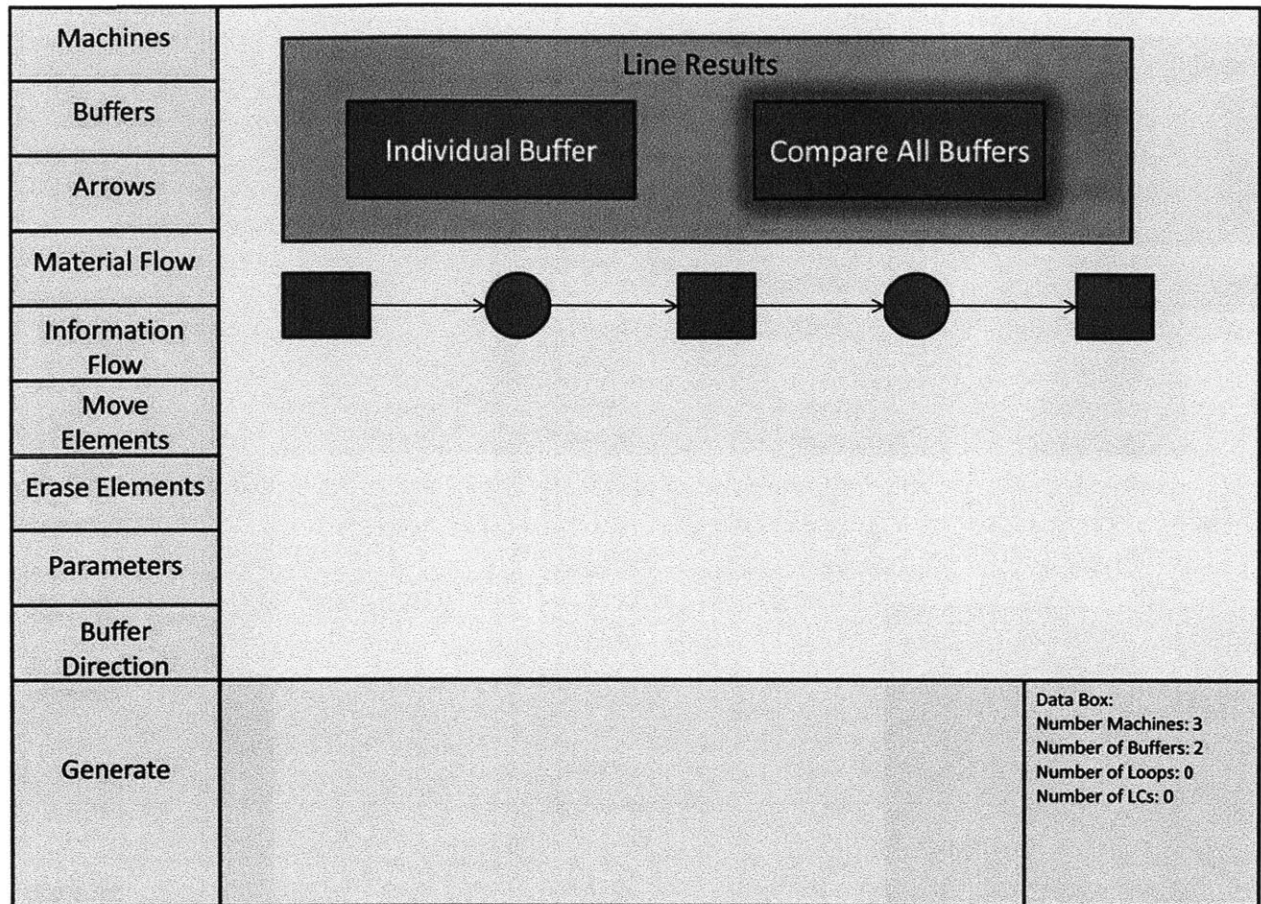
Appendix Figure 13: The user is then prompted with which buffer to choose.

Machines		
Buffers		
Arrows		
Material Flow		
Information Flow		
Move Elements		
Erase Elements		
Parameters		
Buffer Direction		
Generate		

Appendix Figure 14: The user is prompted with the capacity range and the incremental step size for the computations.



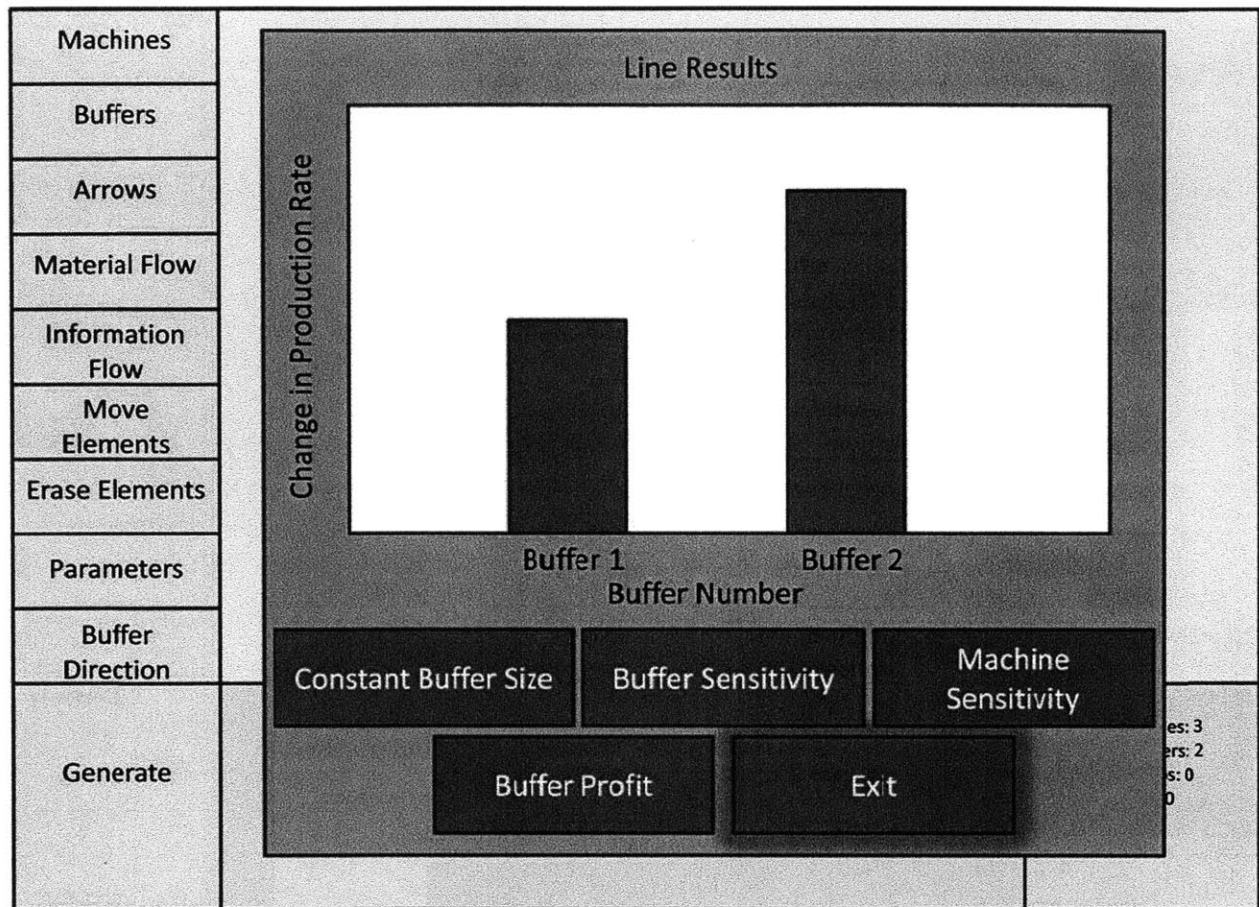
Appendix Figure 15: A graph is provided with production rate values for all the buffer capacity values throughout the specific range. The 'Buffer Sensitivity Tool' is then selected again.



Appendix Figure 16: The user is prompted to choose between evaluating an individual buffer or all the buffers simultaneously for comparison. In this case, the user decides to analyze all the buffers.

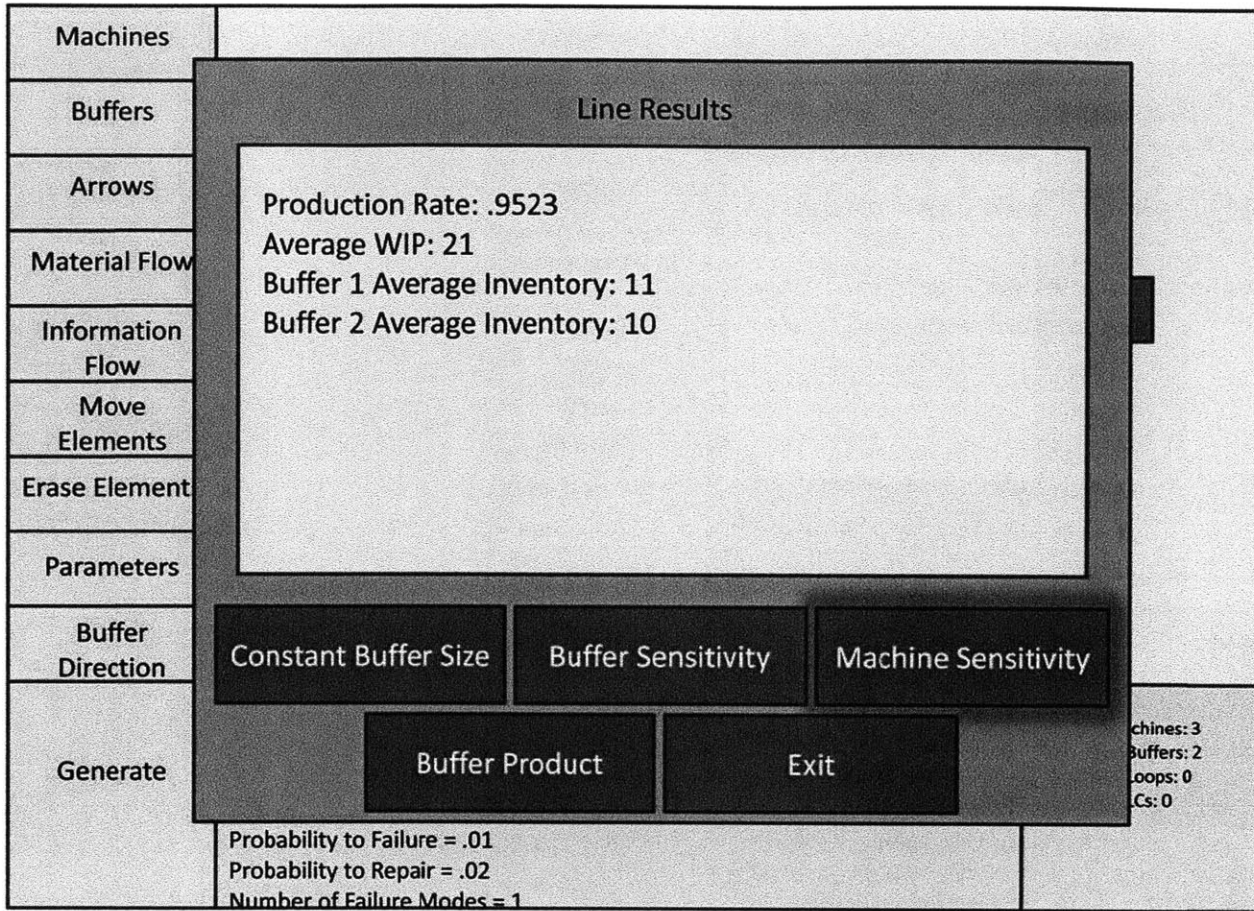
Machines		
Buffers		
Arrows		
Material Flow		
Information Flow		
Move Elements		
Erase Elements		
Parameters		
Buffer Direction		
Generate		

Appendix Figure 17: The user is prompted with the capacity range and the incremental step size for the computations.

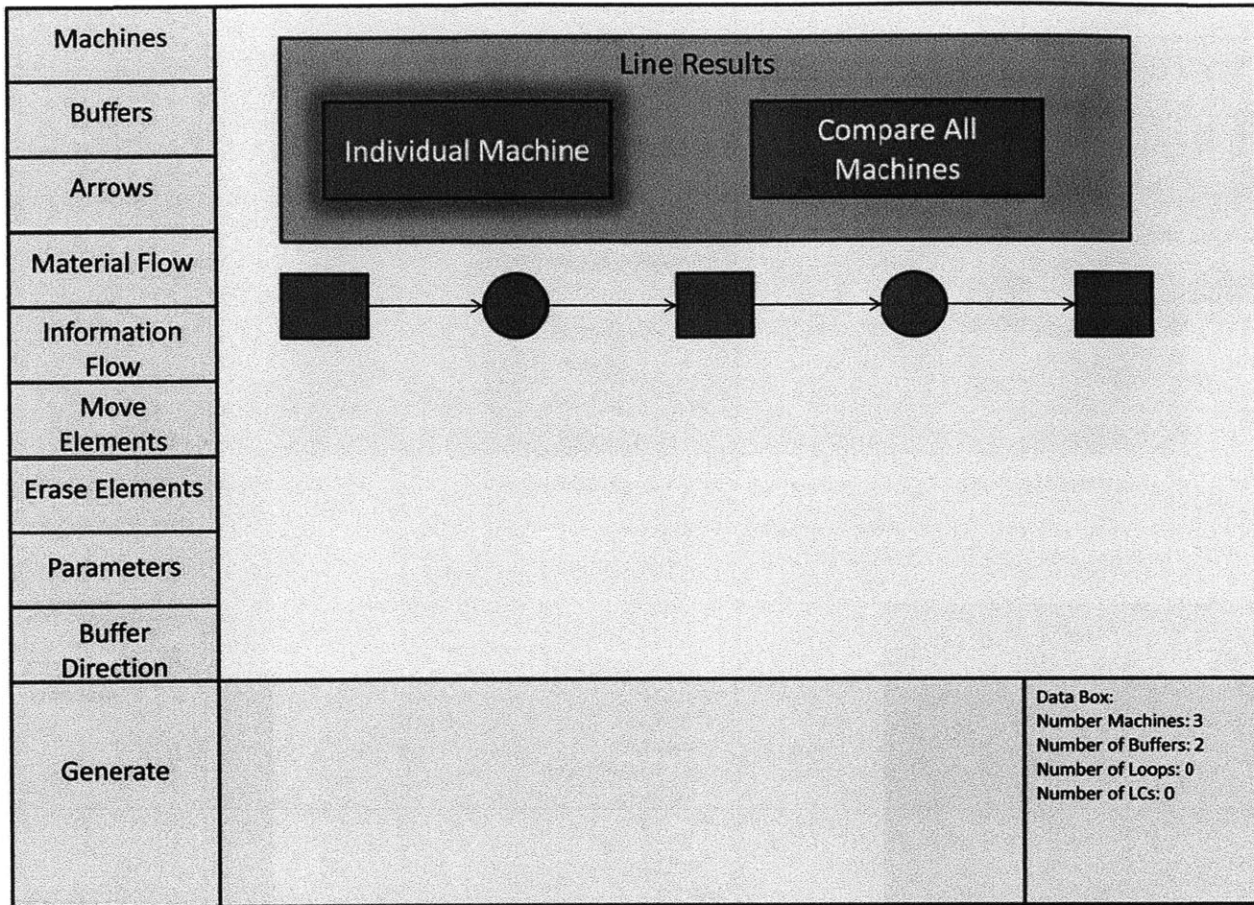


Appendix Figure 18: A bar graph is displayed for the user which shows the change in production rate across for the capacity range for each buffer in the line.

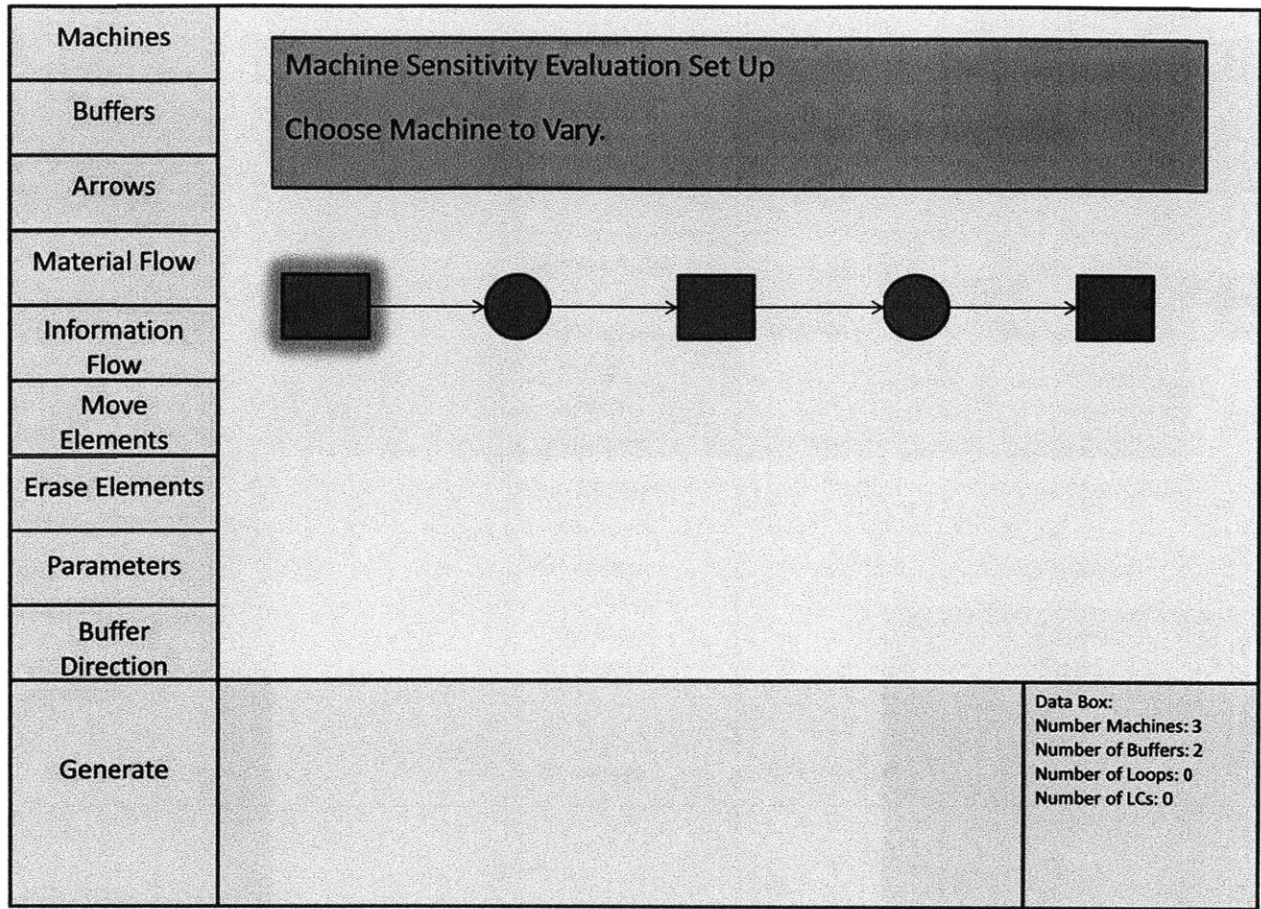
Steps demonstrating the use of the 'Machine Sensitivity Tool'



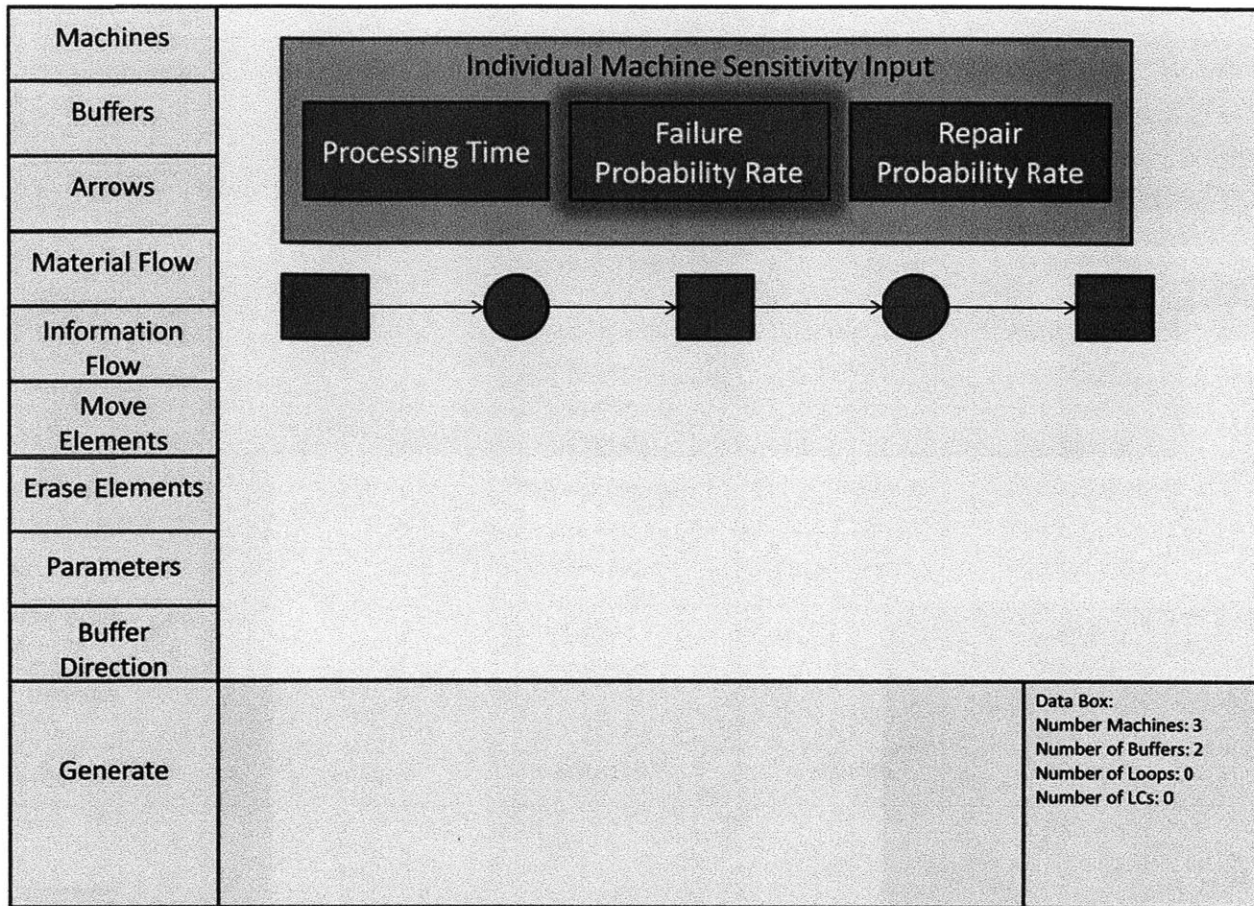
Appendix Figure 19: After the user exits from the 'Buffer Sensitivity Tool' the applet returns to the original evaluation output file. From here the user chooses the 'Machines Sensitivity Tool'.



Appendix Figure 20: The user is prompted to choose between evaluating an individual machine or all the machines simultaneously for comparison. In this case, the user decides to analyze an individual machine.



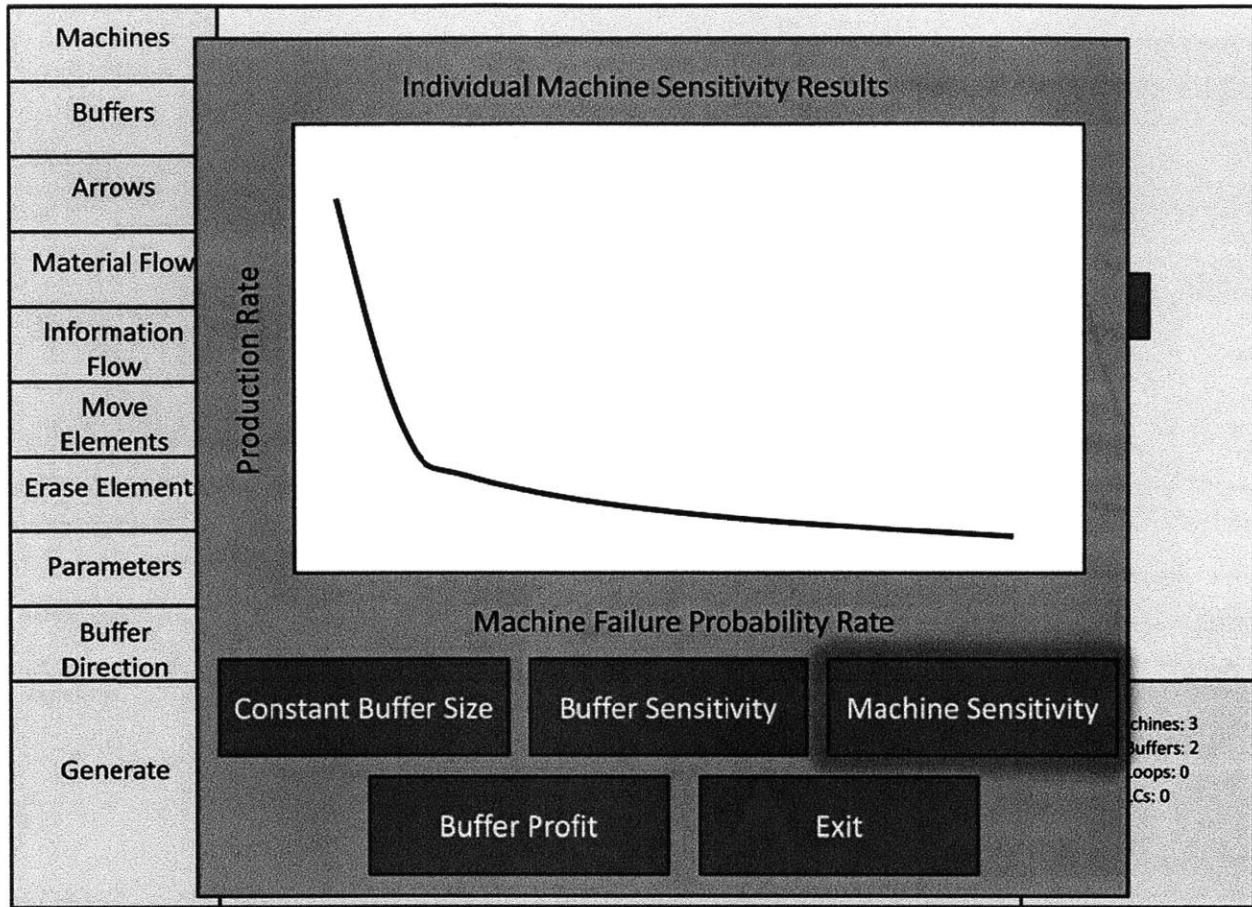
Appendix Figure 21: The user chooses which machine to analyze.



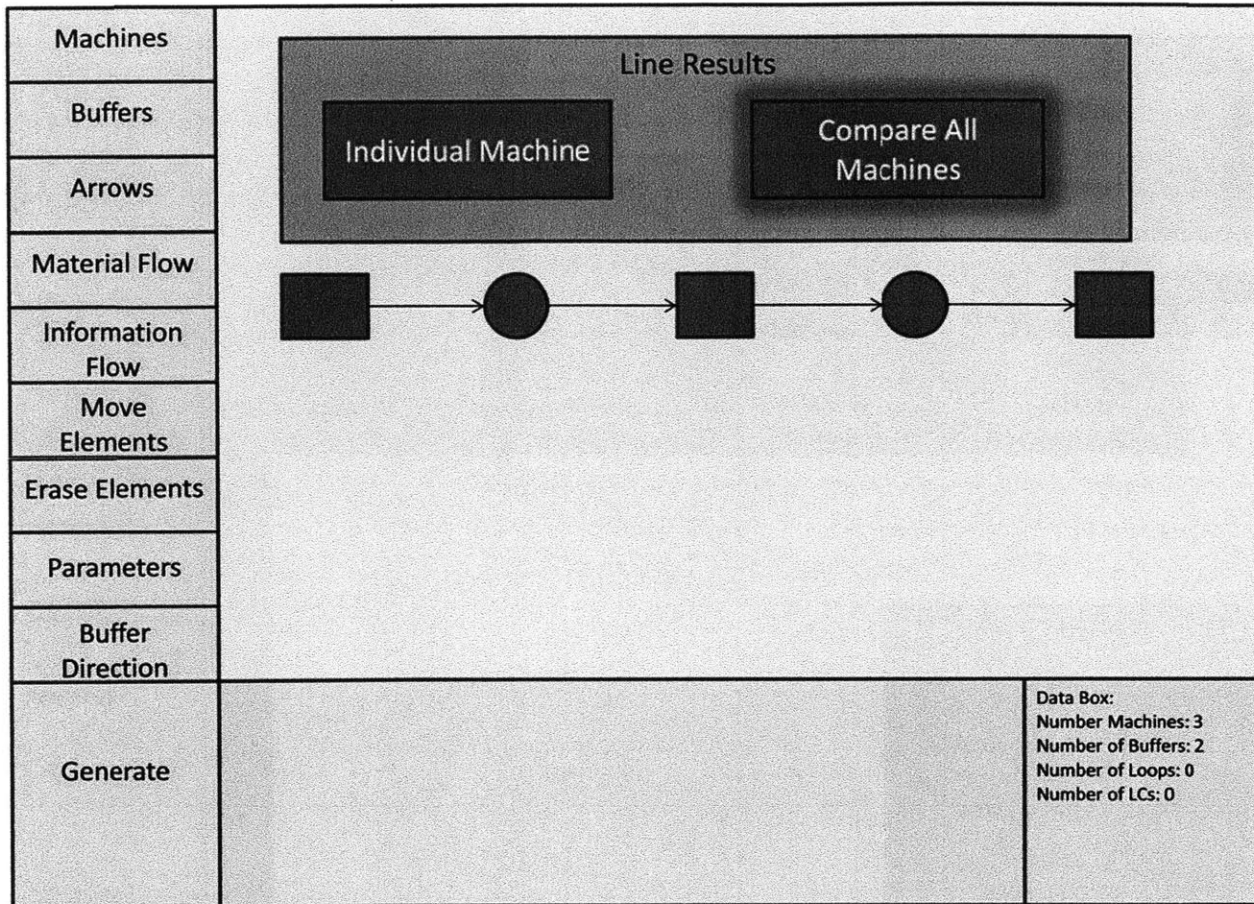
Appendix Figure 22: The user must choose which parameter of the machine to vary. The options consist of the machine’s processing time, failure probability rate and repair probability rate. In this case, the user chooses the failure probability rate. The following steps will be the same regardless of which parameter is chosen.

Machines		
Buffers		
Arrows		
Material Flow		
Information Flow		
Move Elements		
Erase Elements		
Parameters		
Buffer Direction		
Generate		

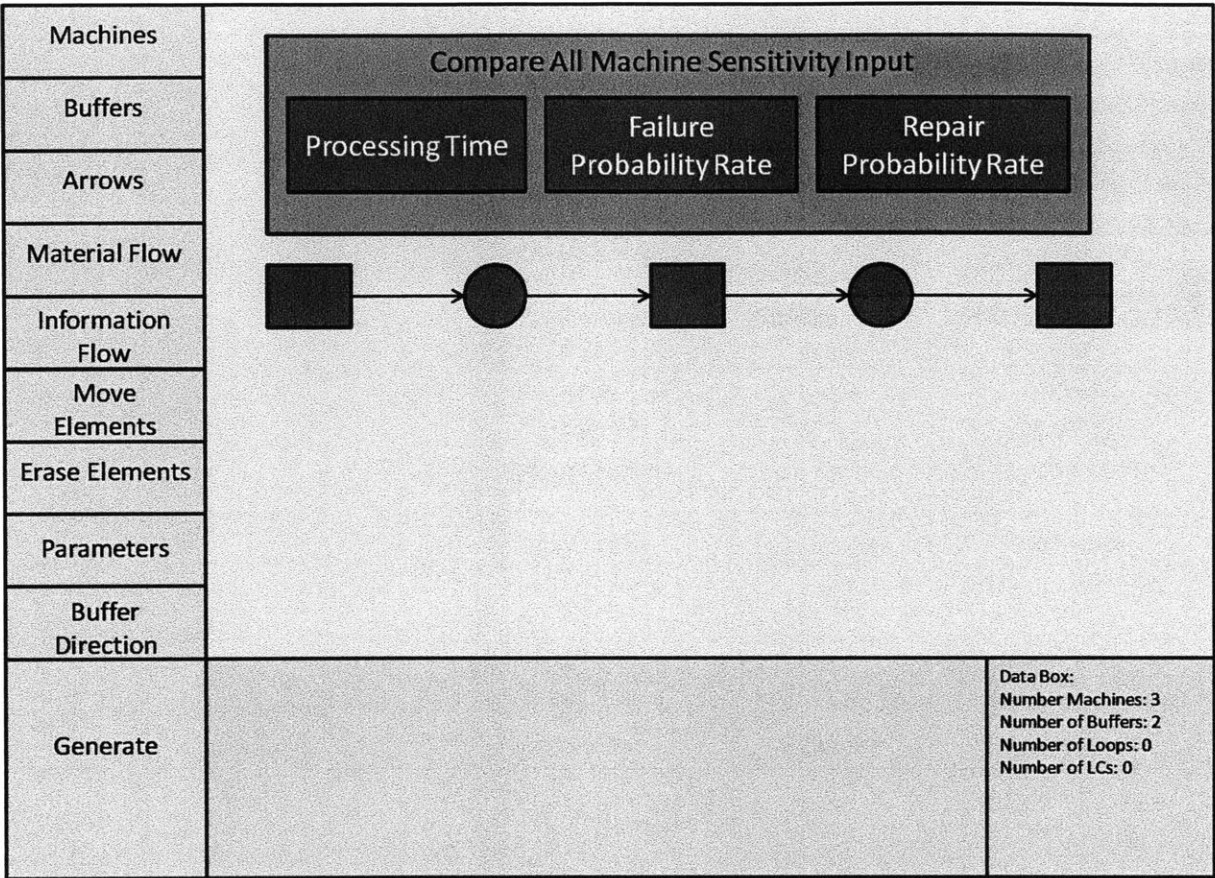
Appendix Figure 23: The user is prompted with the parameter range and the incremental step size for which to compute the production rate.



Appendix Figure 24: A graph is displayed which plots all the calculated production rates against all the failure probability rates within the specified range. The 'Machine Sensitivity Tool' is then reselected.



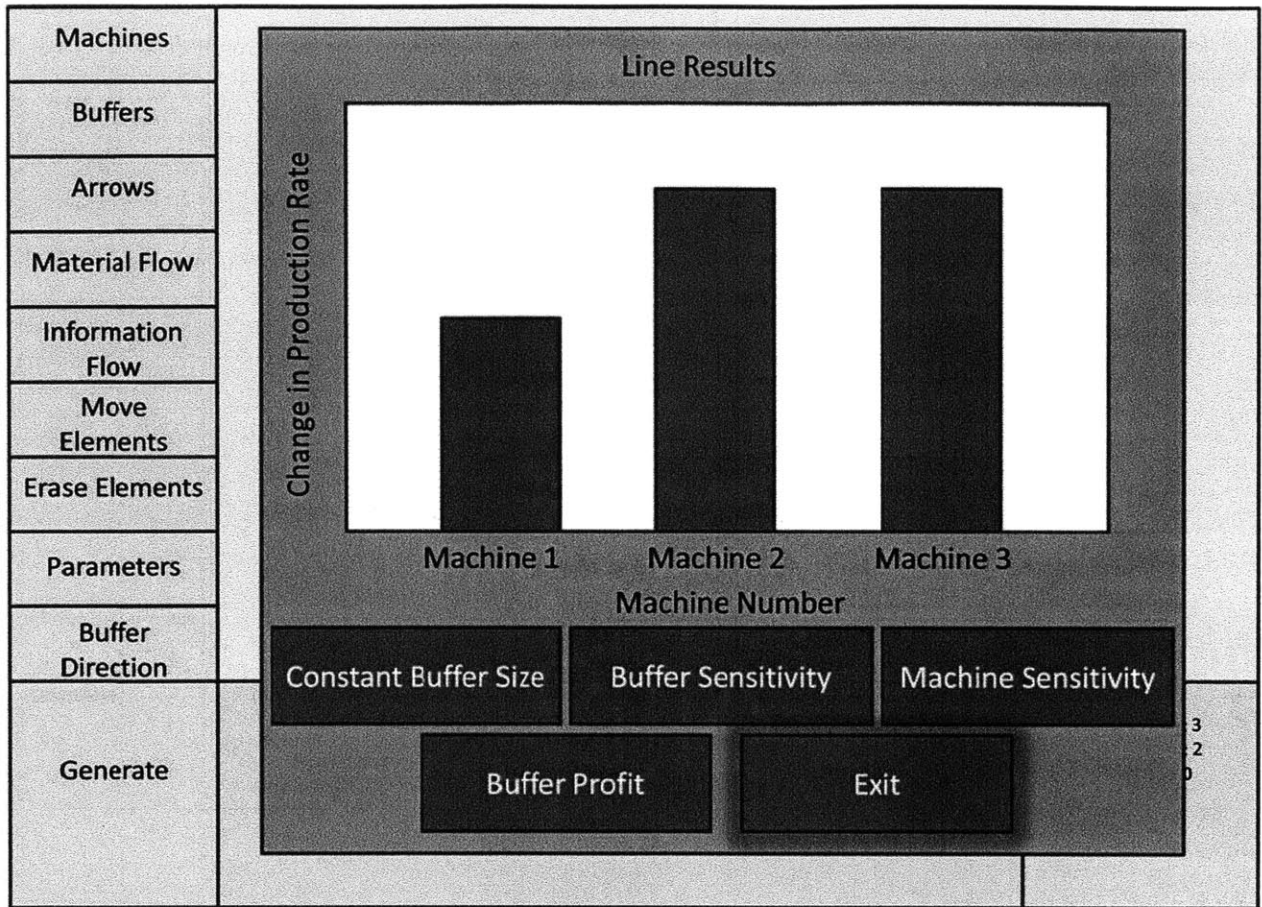
Appendix Figure 25: The user is prompted to choose between evaluating an individual machine or all the machines simultaneously for comparison. In this case, the user decides to compare all the machines.



Appendix Figure 26: The user must choose which parameter of the machine to vary. The options consist of the machine’s processing time, failure probability rate and repair probability rate. In this case, the user chooses the failure probability rate. The following steps will be the same regardless of which parameter is chosen.

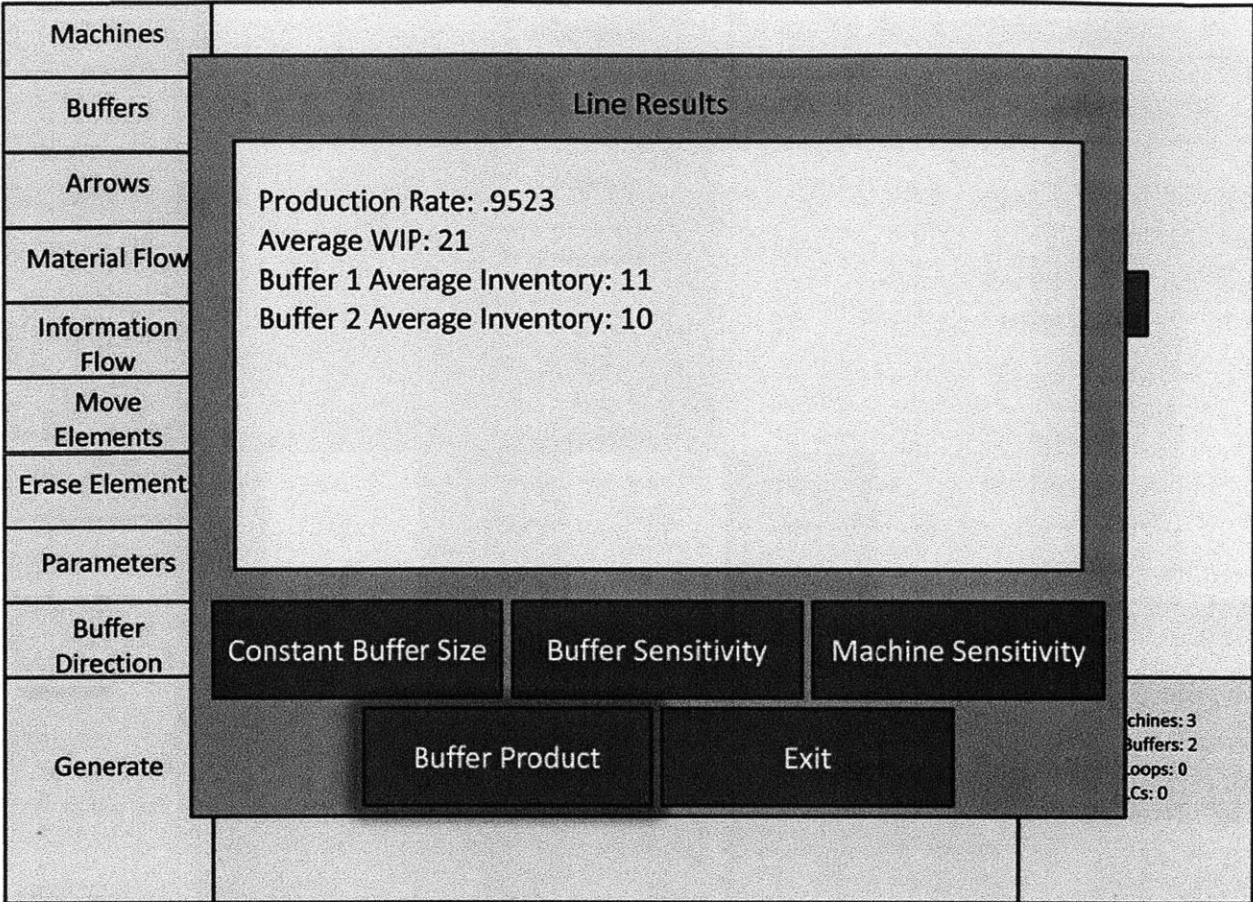
Machines		
Buffers		
Arrows		
Material Flow		
Information Flow		
Move Elements		
Erase Elements		
Parameters		
Buffer Direction		
Generate		

Appendix Figure 27: The user is prompted with the parameter range and the incremental step size for which to compute the production rate.

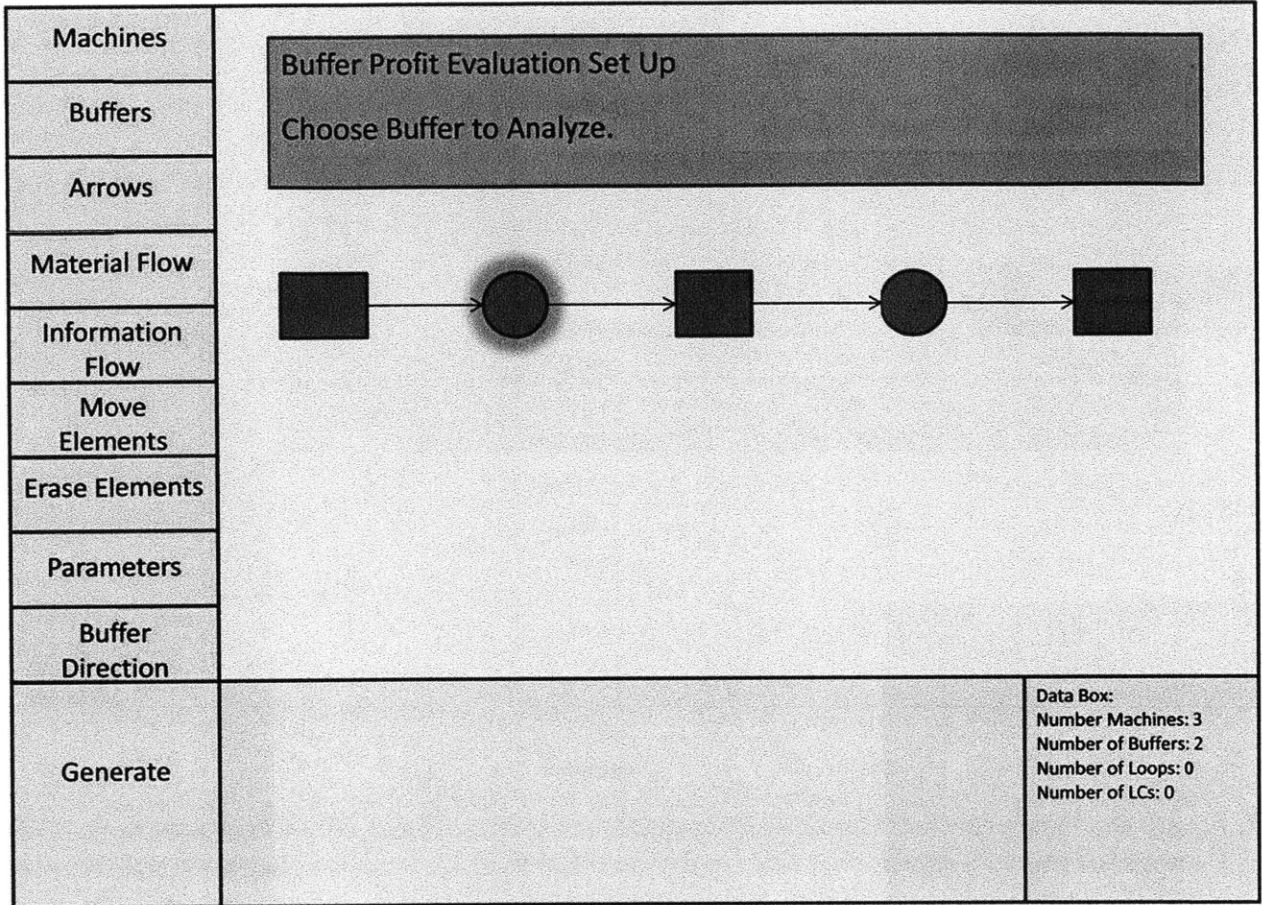


Appendix Figure 28: A bar graph is displayed for the user which shows the change in production rate across for the parameter range for each machine in the line.

Steps demonstrating the use of the 'Buffer Profit Tool'



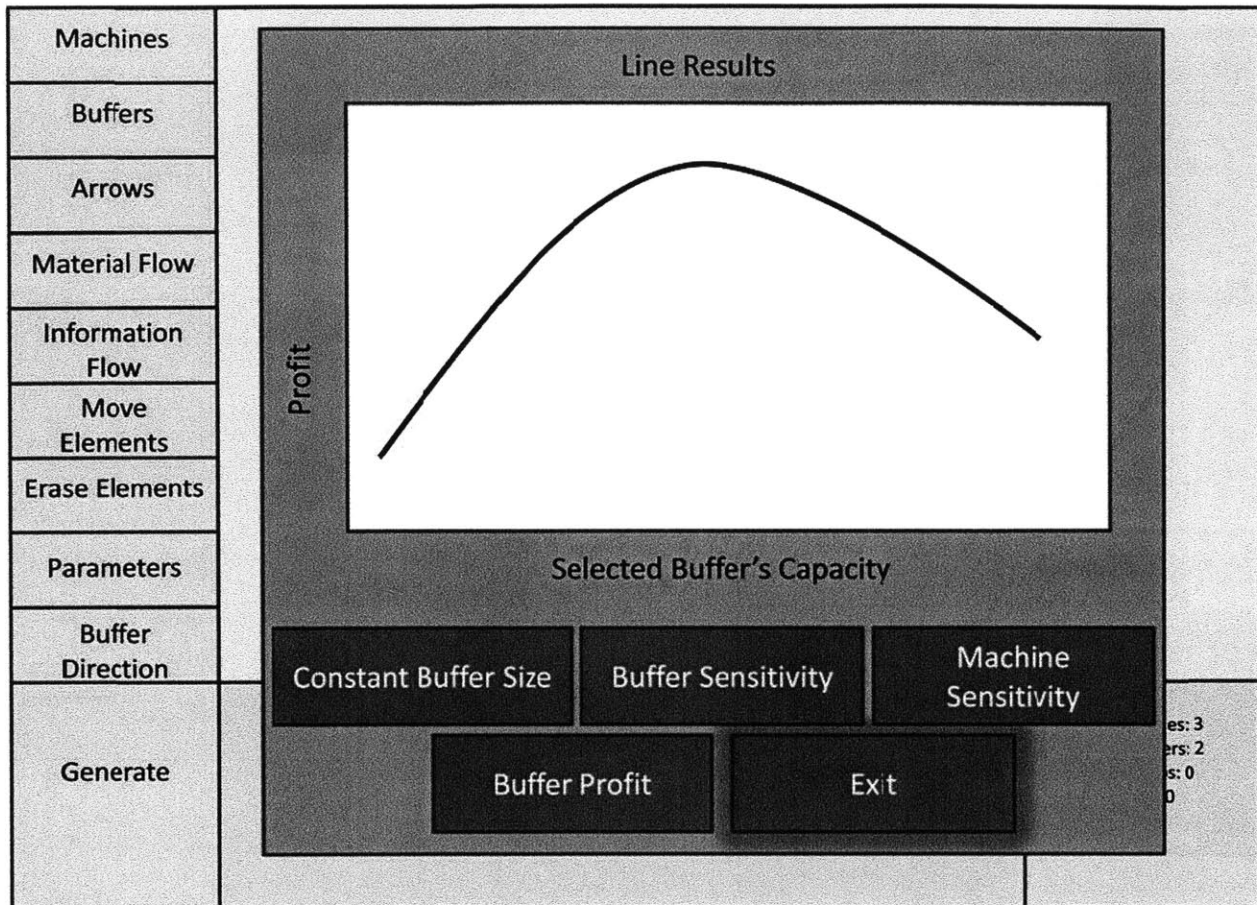
Appendix Figure 29: After the user exits from the 'Machine Sensitivity Tool' the applet returns to the original evaluation output file. From here the user chooses the 'Buffer Profit Tool'.



Appendix Figure 30: The user selects the buffer to analyze.

Machines	<div style="border: 2px solid black; padding: 10px;"> <p style="text-align: center; background-color: #cccccc;">Profit Analysis Input</p> <p>Enter Unit Cost of Buffer Size:</p> <input style="width: 100%;" type="text" value="1.50"/> <p>Enter Unit Cost for Holding Inventory:</p> <input style="width: 100%;" type="text" value="2.25"/> <p>Enter Price of Product:</p> <input style="width: 100%;" type="text" value="10"/> <p>Enter Buffer Capacity Range:</p> <input style="width: 100%;" type="text" value="20"/> <p>Enter Incremental Step Size for Computations:</p> <input style="width: 100%;" type="text" value="2"/> </div>	
Buffers		
Arrows		
Material Flow		
Information Flow		
Move Elements		
Erase Elements		
Parameters		
Buffer Direction		
Generate		<p>Welcome Machine Efficiency</p>

Appendix Figure 31: The user enters input values for the parameters of the line as shown in the figure above. These values go into setting variables which determine the revenue and cost of operating the line.



Appendix Figure 32: A graph is displayed which plots the selected buffer's capacities that are within the capacity range specified by the user against all the calculated profits that correspond with each of these capacities.