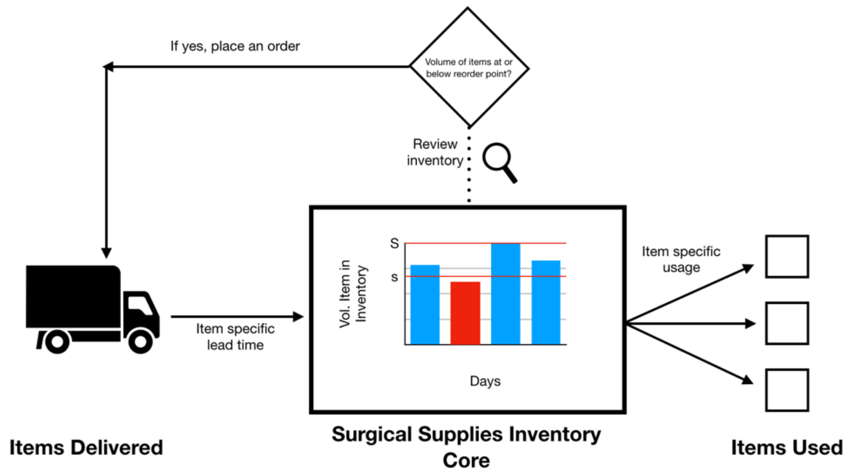
1. Introduction to Item Level Inventory Control Policy Performance Evaluation Software

This software is made for logistics and inventory managers to help them evaluate the performance of inventory control policies on disposable surgical supplies. It is intended to help managers set reorder points, order up to points, and review frequencies that will provide the right disposable surgical item at the right time in the desired quantity to enable a high-quality of care for surgery patients while lowering inventory costs. It is intended to provide performance evaluation for business-as-usual scenarios. The software simulates the disposable surgical supplies inventory core where disposable surgical supplies arrive to the inventory core, wait in inventory to be used, and are used when required in surgery. Items are ordered when a review is conducted and the level of inventory for an item is at or below its reorder point:

Figure 1: Depiction of How Disposable Surgical Items are Simulated in the Software.



The software evaluates the performance of a single item independent of other items. For more details on the policy modeled, the assumptions made, and the logic of the software, please see Appendix 1.

2. Description of Inputs and Outputs of the Software

Inputs

The software requires two types of inputs: the first are descriptive of the item's usage and lead time characteristics and the second can be varied at the user's discretion to test different scenarios.

Type 1: Descriptive Inputs

Descriptive inputs for usage should derive from an analysis of historical usage data, if available, to answer the following questions. If historical data is not available, an expert familiar with the flow of items in and out of the inventory core should be consulted.

1. **Weekday Usage:** What is the minimum, most frequent, and maximum number of items used on a typical weekday?
2. **Weekend Usage:** What is the minimum, most frequent, and maximum number of items used on a typical Saturday or Sunday? Weekend usage values are inputted separately from the weekday usage values to allow for a reduction in surgery that generally occur on weekends. However, if the usage of an item is consistent across all days of the week, the weekend usage values should equal the weekday values.

3. **Leadtime:** What is the minimum, most frequent, and maximum number of business days between when an order is placed and the order arrives and is unpacked into the inventory core? The model assumes that orders are not placed or delivered on weekends. The software also assumes the minimum allowable lead time is 1 day, instantaneous delivery is not accounted for.

The software will accept scenarios in which the minimum is less than or equal to the most frequent and the most frequent is less than or equal to the maximum but will not accept the maximum to be less than the minimum. If the maximum is equal to the minimum, the most frequent value is assumed to also be equal to the maximum and minimum.

4. **Current Inventory Level:** How many items are currently in the inventory core?
5. **Unit of Measure:** If an item can only be ordered in a certain unit, such as a case or box, the how many single items are there in that unit of order?

Type 2: User Specified Inputs

1. **Frequency of Review:** How many business days are there between each review of the inventory level? This parameter can be toggled to test different frequencies of review, while the default value is 1 day (representing review every business day).
2. **Reorder Point:** After a review of the inventory is conducted, the inventory level is compared to the reorder point. If the inventory level in the core drops down to at or below the reorder point, then an order is placed. The reorder point is sometimes referred to as the PAR level in hospital settings. The reorder point is generally set to achieve a safety stock of a given days of inventory.
3. **Order Up to Point:** After it is determined that an order must be placed, the amount of inventory to be ordered has to be determined. A common way that hospitals determine the order quantity is by using an order up to point to represent the number of items the hospital should have on hand and on route (items that are still being delivered). A high order up to point paired with low item usage may promote large volumes of inventory kept on hand, while a low order up to point with high usage, while may be feasible in scenarios with constant lead time, may promote stockouts.
4. **Forecast Horizon:** How many days into the future should the inventory policy be simulated for?

<u>Outputs</u>

After running the software with specified inputs, the software will output summary metrics that evaluate the performance the inventory control policy on the item. The outputs are divided between inventory level metrics and service level metrics.

Type 1: Inventory Level Metrics

1. **Inventory Level Graph:** the graph is present to depict the expected inventory level at the beginning of each day in the forecast horizon.
    a. **Average Inventory Level:** on each day of the forecast horizon, what is the expected inventory level at the beginning of that day? The red error bars represent the 95% confidence interval on each days' calculated estimate.
    b. **5th Percentile:** On each day of the forecast horizon, what is the expected bottom 5th percentile of the inventory level at the beginning of that day?

c. **95th Percentile:** On each day of the forecast horizon, what is the expected bottom 95th percentile of the inventory level at the beginning of that day?

2. **Expected Daily Inventory*:** The expected inventory level at the beginning of any given day of the forecast horizon.
3. **Expected Lowest Daily Inventory*:** The expected lowest inventory level at the beginning of any given day of the forecast horizon.
4. **Expected Highest Daily Inventory*:** The expected highest inventory level at the beginning of any given day of the forecast horizon.

Type 2: Service Level Metrics

1. **Expected Fill Rate*:** The expected proportion of item demand that will be satisfied from on hand inventory. Demand is assumed to be lost if an item is not immediately available. Item substitution is not accounted for in this software.
2. **Probability of a stockout*:** The probability that on any given day during the forecast horizon, a stockout will occur.

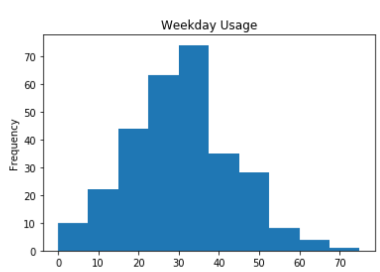
* bounded by a 95% confidence interval which represents, with 95% confidence, the range that the expected value can appear in.

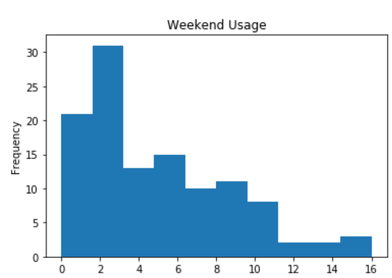
3. How to Get the Most out of this Software: What can it be used for?

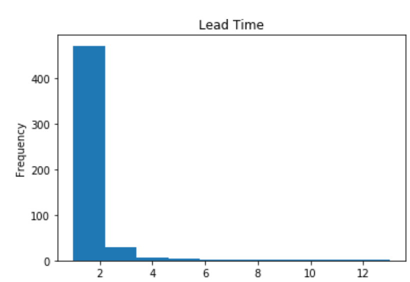
This performance evaluation software is intended to be used as a tool to aid the decision-making process of inventory managers by quantifying the effects on service and inventory levels when a change is made to a policy. It is intended to be generic enough so that managers from any hospital can use it, which means it also is not tailored to any hospital's unique procurement and usage practices. Additionally, the software has be designed to simulate business as usual scenarios: it does not accommodate emergency actions when a stockout occurs, will not handle outlier events in inventory arrival and usage unless those are included in the inputs. This software can be used to analyze questions like:

1. Inventory Level: What affect will lowering the order up to point have on the service and inventory level measures?
2. Safety Stock: What affect will decreasing the reorder point have on service level measures?
3. Frequency of Review: What affect will varying the frequency of review be on an inventory control policy?

To illustrate how the software can be used to answer the above questions, an example of a commonly used disposable surgical suture with the following usage and lead time characteristics is investigated:







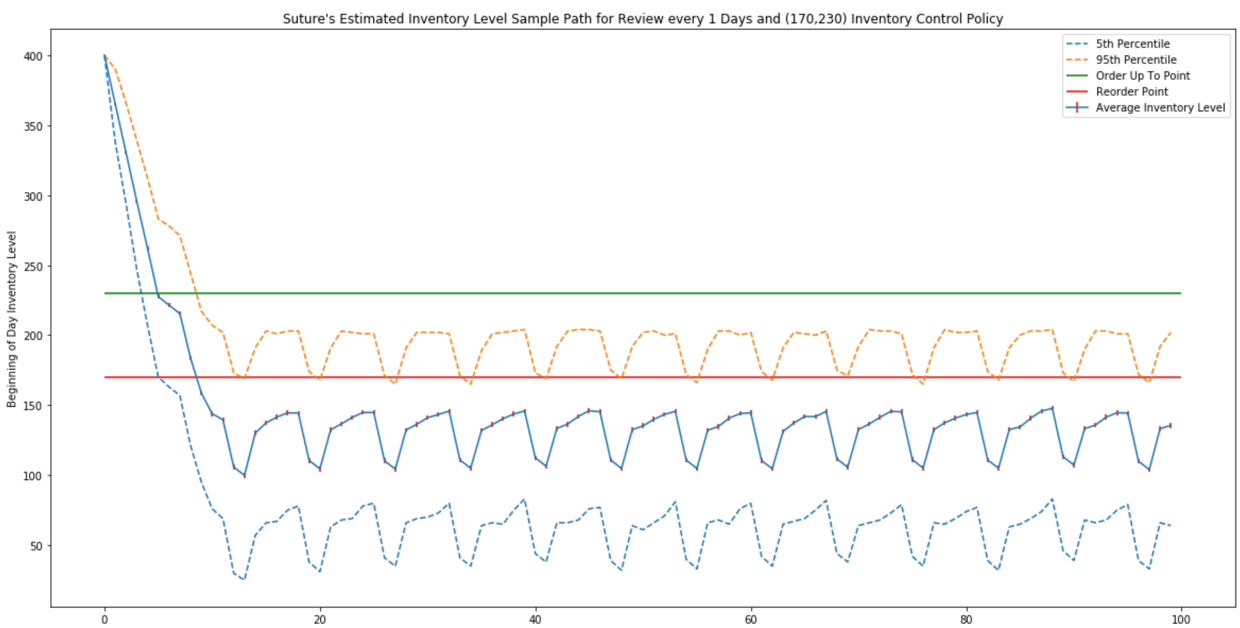
	Weekday Usage	Weekend Usage	Lead Time
Minimum Value	0	0	1
Most Frequent	28	2	2
Maximum Value	75	16	13

For this suture, the parameters for the lead time distribution are calculated by moment matching to be more representative of the mean of the data. The moment matching parameters are used in place of the minimum, most frequent, and maximum because the maximum of 13 days would drastically increase the simulated lead time when only a few instances of long lead times are present in the data. Using moment matching, the input parameters are calculated as (-0.351963435621957, 2.20966275938820, 4.77569798909364). However, because this simulation does not account for instantaneous lead time, which would occur if a lead time of 0 days in generated, whenever a lead time of 0 is generated it is replaced with a 1 day lead time.

Reorder point: 170, Order Up to point: 230, Frequency of Review: Every 1 day , Weekday usage: (0, 28, 75), Weekend usage: (0, 2, 16), and Current Inventory Level: 400 units. The software is run for a forecast horizon of 100 days and unit of measure of 1.

Question 1: Inventory Level

To investigate question 1 the software can be run with an initial inventory level significantly above order up to point to show the effect of lowering the inventory levels kept on hand.

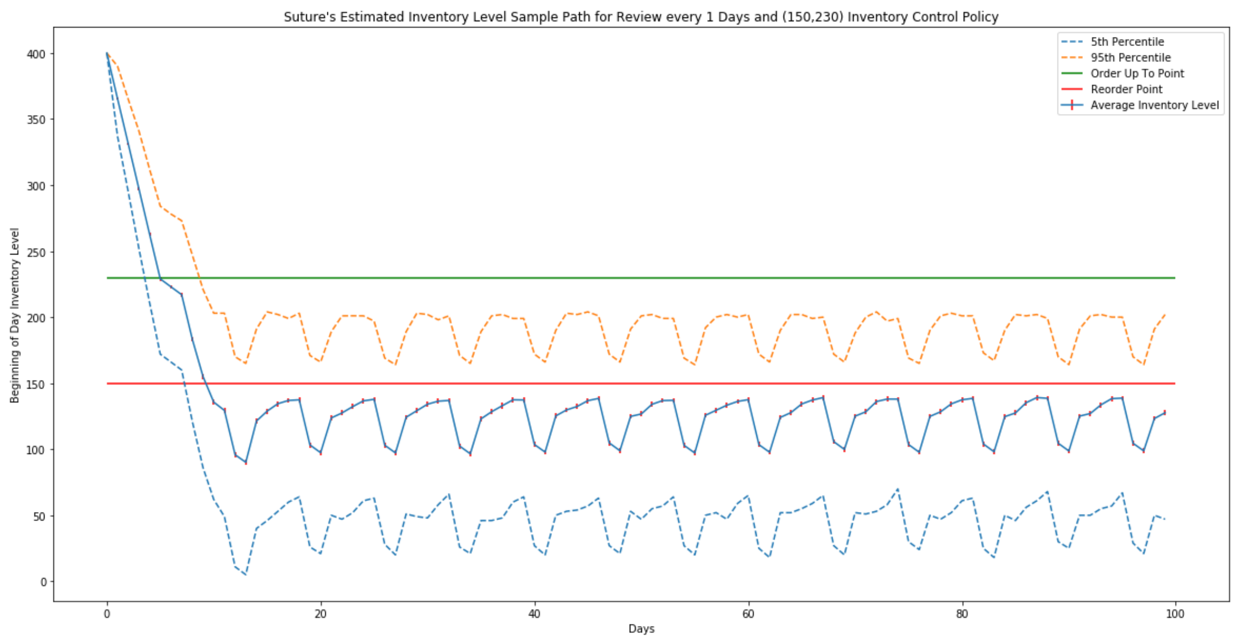


	Q1: Inventory Level
Exp. Fill Rate and 95% CI	0.9947155799218335, [0.9943215393925884, 0.9951096204510785]
Exp. Probability of Stockout and 95% CI	0.010280000000000001, [0.009691799135468668, 0.010868200864531333]
Exp. Daily Inventory & 95% CI	143.992775, [143.71464223638594, 144.27090776361405]
Exp. Min Daily Inventory & 95% CI	25.717, [24.900654164114066, 26.53334583588593]
Exp. Max Daily Inventory & 95% CI	400.0, [400.0, 400.0]

As is evident, the inventory level can be dropped from 400 to maintaining an order up to point of 230 and still maintain a fill rate of 99.4%. This promotes keeping less stock on hand, presumably reducing holding costs while providing a high quality of care for patients.

Question 2: Safety Stock

To investigate the effect of lowering the reorder point, which effectively represents lowering the amount of safety stock, the software is run with the same inputs as above, however this instance uses a reorder point of 150 as opposed to 170.

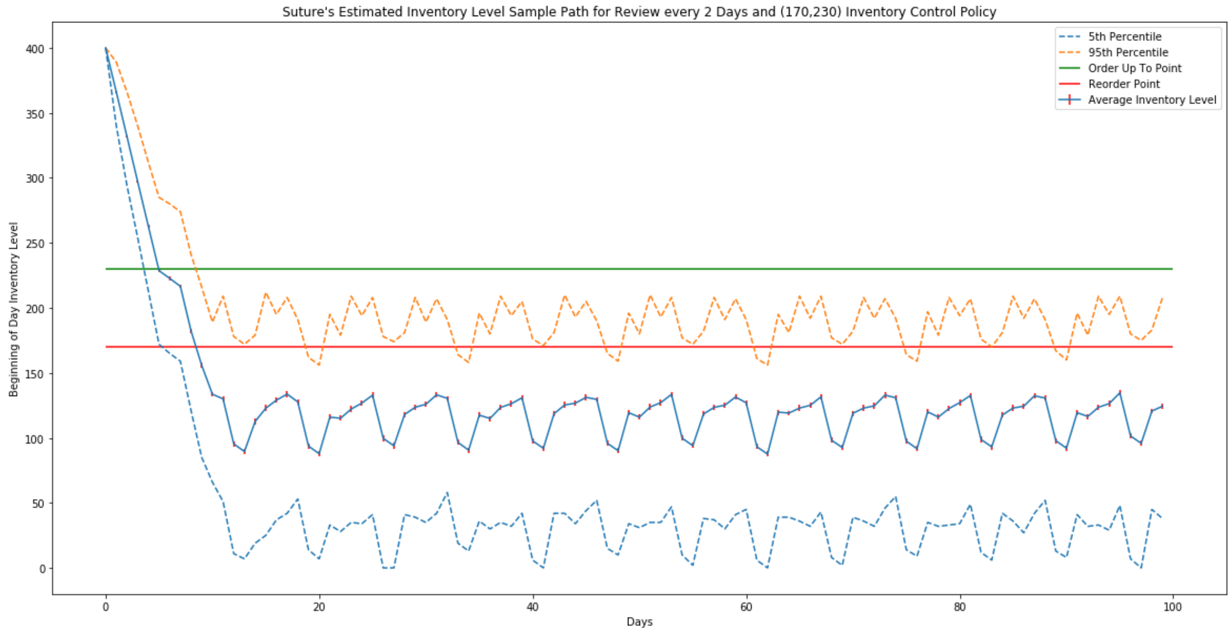


	Q2: Safety Stock
Exp. Fill Rate and 95% CI	0.9872486735834725, [0.9866260229699086, 0.9878713241970363]
Exp. Probability of Stockout and 95% CI	0.022815000000000002, [0.021932342042807505, 0.0236976579571925]
Exp. Daily Inventory & 95% CI	137.27856, [137.00705286635093, 137.55006713364907]
Exp. Min Daily Inventory & 95% CI	13.646, [12.99666440748436, 14.295335592515642]
Exp. Max Daily Inventory & 95% CI	400.0, [400.0, 400.0]

Evidently, the fill rate decreases by 0.7% from 99.4% to 98.7% while the expected daily inventory decreases from 144 to 137 units. While the difference in inventory level is not so significant, it can be depending on the value of the items unit cost. Nevertheless, this shows the use of the tool to evaluate the performance of various scenarios and be able to quantifiably compare them. We leave it to the decision maker to infer actions from the results of these scenarios.

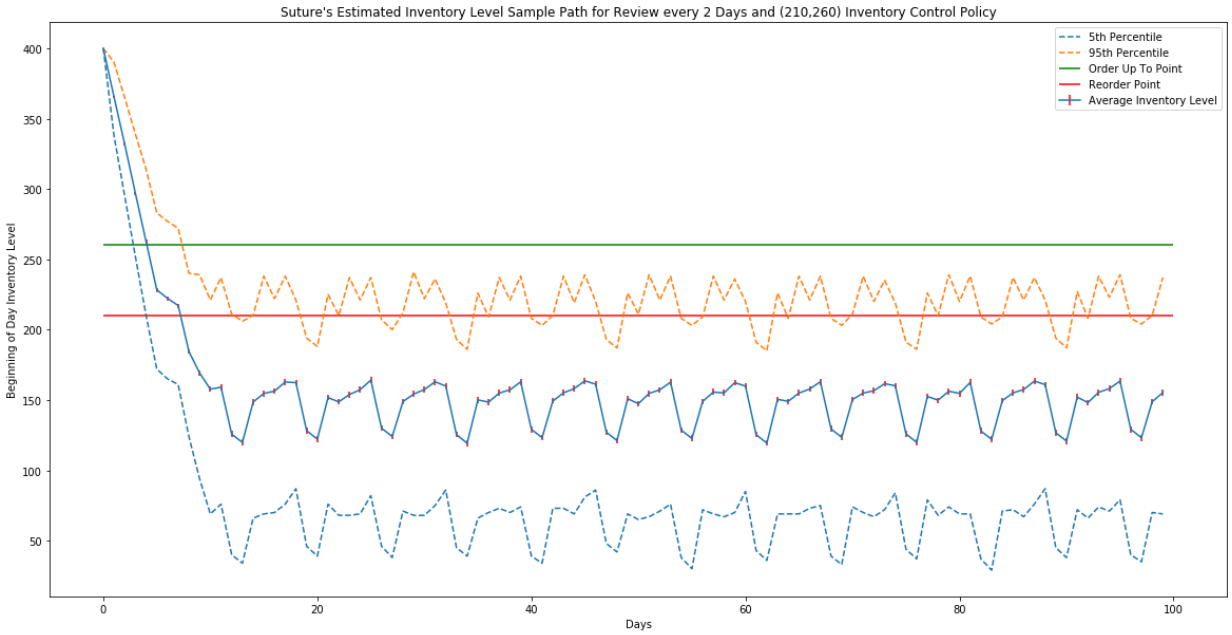
Question 3: Frequency of Review

Currently, the review period is set to once per day, however, it is possible that decreasing the frequency of review to once ever two days may results in decreased labor costs while maintaining high service level performance.



	Q3: Frequency or Review, Every 2 Days (170,230)
Exp. Fill Rate and 95% CI	0.9717218004727722, [0.9707666145845477, 0.9726769863609968]
Exp. Probability of Stockout and 95% CI	0.043995000000000006, [0.042771062803792344, 0.04521893719620767]
Exp. Daily Inventory & 95% CI	131.036755, [130.7116773510565, 131.3618326489435]
Exp. Min Daily Inventory & 95% CI	5.743, [5.274946014803565, 6.211053985196435]
Exp. Max Daily Inventory & 95% CI	400.0, [400.0, 400.0]

We can infer that decreasing the frequency of review does have an impact on this items service level performance, and so in order to maintain a high performance increased inventory would need to be held. The software could then be used to find an inventory control parameters that would achieve a fill rate of 99% and stockout probability around 1%. Using the software, we find the inventory control policy of reordering at 210 items and ordering up to 260 items with review every 2 days that will achieve equal service.



	Q3: Frequency or Review, Every 2 Days (210,260)
Exp. Fill Rate and 95% CI	0.9933802950470187, [0.9929055766107294, 0.9938550134833081]
Exp. Probability of Stockout and 95% CI	0.011415000000000002, [0.010758146072480664, 0.01207185392751934]
Exp. Daily Inventory & 95% CI	158.93891, [158.5823487615483, 159.29547123845168]
Exp. Min Daily Inventory & 95% CI	26.151, [25.233910702383028, 27.06808929761697]
Exp. Max Daily Inventory & 95% CI	400.0, [400.0, 400.0]

In using the software to gain insight on these three example questions, the user can leverage quantitative analysis to aid their decision-making process. The user is encouraged to explore a variety of inventory control policies when investigating a question, as we began to do when investigating question 3. These are only three example questions that can be explored with the help of this software. Other examples include measuring the effect of changing the order up to point, or simulating a scenario with a deterministic lead time and recording the change in performance metrics to inform delivery contract negotiation discussions.

The user should also be aware of some of the limitations of the software. One of the main limitations is the sensitivity of the software to the usage and lead time inputs. Altering any of the descriptive inputs will have a measurable impact on the results of the model.

4. Sensitivity of the Software to Descriptive Inputs

The software is sensitive to changes in the descriptive inputs because those inputs are used to define parametric distributions to represent usage and lead time. For the suture used in the examples, the true maximum lead time is 13 days, which occurs once in the empirical order data, while 88% of lead time occurrences are 2 days. However, if 13 days were used as the maximum in the lead time input, the software would generate a high percentage of lead times that are greater than 2 days. Therefore, we chose to use moment matching on the empirical data to generate lead time inputs more centered around the mean value. Expert opinion can also be used when inputting the data to validate that the input values are representative of most occurrences of usage and lead time. One tradeoff with truncating the lead time distribution is while the lead times generated are centered more closely around the mean, rare occurrences are not being simulated. This is a limitation of the software that the user should keep in mind and account for when interpreting results.

The usage histograms for the suture show a greater variety of items used per day with a noticeable percentage of occurrences being different from the mean and mode. While the usage inputs are also used to build triangular distributions for the simulation, using the true minimum and maximum values is acceptable because of how the empirical data is spread.

If the user chooses to be conservative in their analysis, they would include rare occurrences when defining their inputs. If the user wants to simulate most occurrences, outliers and rare occurrences should be excluded from the inputs. Graphing empirical usage and order data is a helpful way to analyze what the inputs should be set to.

5. Appendix

Appendix 1: Policy Description, Program Assumptions, and Program Logic of Software

1.1 (s,S) Policy Description:

$$Let\ u\ be\ the\ inventory\ level\ at\ time\ of\ review, b\ be\ the\ sum\ of\ backordered\ items,$$

$$s\ the\ minimum\ level\ of\ inventory, and\ S\ the\ maximum\ level\ of\ inventory$$

$$During\ review, if\ \begin{cases} u \leq s : order\ S - u - b \\ u > s : do\ not\ order \end{cases}$$

1.2 Program Assumptions

- Orders are not delivered on weekends.
- Orders can not be placed on weekends.
- Orders are added to the inventory at the start of the day, and inventory is then drawn from the inventory core afterwards.
- If an order is placed, but a review happens before the order arrives, another order can be placed.
- Reviews are conducted every X days. If a review of inventory falls on a weekend, it is not conducted.
- Demand is lost (e.g. if there is a stockout, demand is not backlogged).
- Leadtime does not include weekends and is not instantaneous. The minimum lead time is 1 day.
- Initial inventory position is equal to initial inventory level (no orders are in the pipeline).

1.3 Program Logic:

The periodic review (s,S) policy is used because it is commonly used in hospital inventory cores (Volland, Fügener, Schoenfelder, & Brunner, 2017). A framework was used to model each policy with it's particular (s, S) parameters. The inventory level for each item is affected by the stochastic arrival and usage of items. The framework simulates the arrival, usage and inventory level of each day for the duration of the simulation. For each day simulated, first the items scheduled to arrive is checked, and if items do arrive, they are added to the inventory level. Then, the model checks if a review of inventory is scheduled to occur on that day, and if it does, then a review of the inventory level occurs. If the inventory level is below or at the designated reorder point, an order is placed to bring the inventory position back to the reorder point. The amount of inventory ordered is defined by $S - u - b$. When an order is placed, the lead time is generated from the triangular lead time distribution for the specific item where only weekdays are counted. Orders are not placed or received on weekends. In section 2 of this document an analysis is done where there is no usage on weekends, while section 3 includes usage on weekends. A schedule of the order arrivals is kept. This framework allows for multiple orders to arrive on the same day and order crossing. Then, the item usage for that day is generated, also according to the item and day of week specific triangular usage distribution. If not enough items are available to meet the usage demand, a stockout occurs and the lost demand is recorded. The service rate is calculated as the fraction of demand satisfied from items in inventory (Bijvank & Vis, 2012) each day. Finally, at the end of each day, the end of day inventory level is calculated, and is defined by:

$$I_D = I_{arrived} + I_{D-1} - I_{used}$$

$$Where\ I_D\ is\ the\ inventory\ level\ at\ the\ end\ of\ day\ D, I_{arrived}\ is\ the\ volume\ of\ items\ that\ arrived\ on\ that\ day, and\ I_{Used}\ is\ the\ volume\ of\ items\ used\ that\ day$$

Each policy is considered a steady state simulation. Each policy is run for 2,000 replications, each with a user inputted run length equal to the prediction horizon. The number of replications is intended to reduce the variance amongst the estimated values. After each replication, the average mean, maximum, and minimum inventory level as well as fill rate are recorded. The sample means and 95% confidence intervals of these values are calculated across all replications. A sample path of the inventory level is generated by averaging each day's inventory level across all replications, and the confidence intervals are also included on the sample path. The 5^{th} and 95^{th} percentile of volume of items in inventory are also included on the sample path graph.

6.References

1.Bijvank, M., & Vis, I. (2012). Inventory control for point-of-use locations in hospitals. *The Journal of the Operational Research Society*, *63*(4), 497–510.

2.Volland, J., Fügener, A., Schoenfelder, J., & Brunner, J. O. (2017). Material logistics in hospitals: A literature review. *Omega (United Kingdom)*, *69*, 82–101. https://doi.org/10.1016/j.omega.2016.08.004