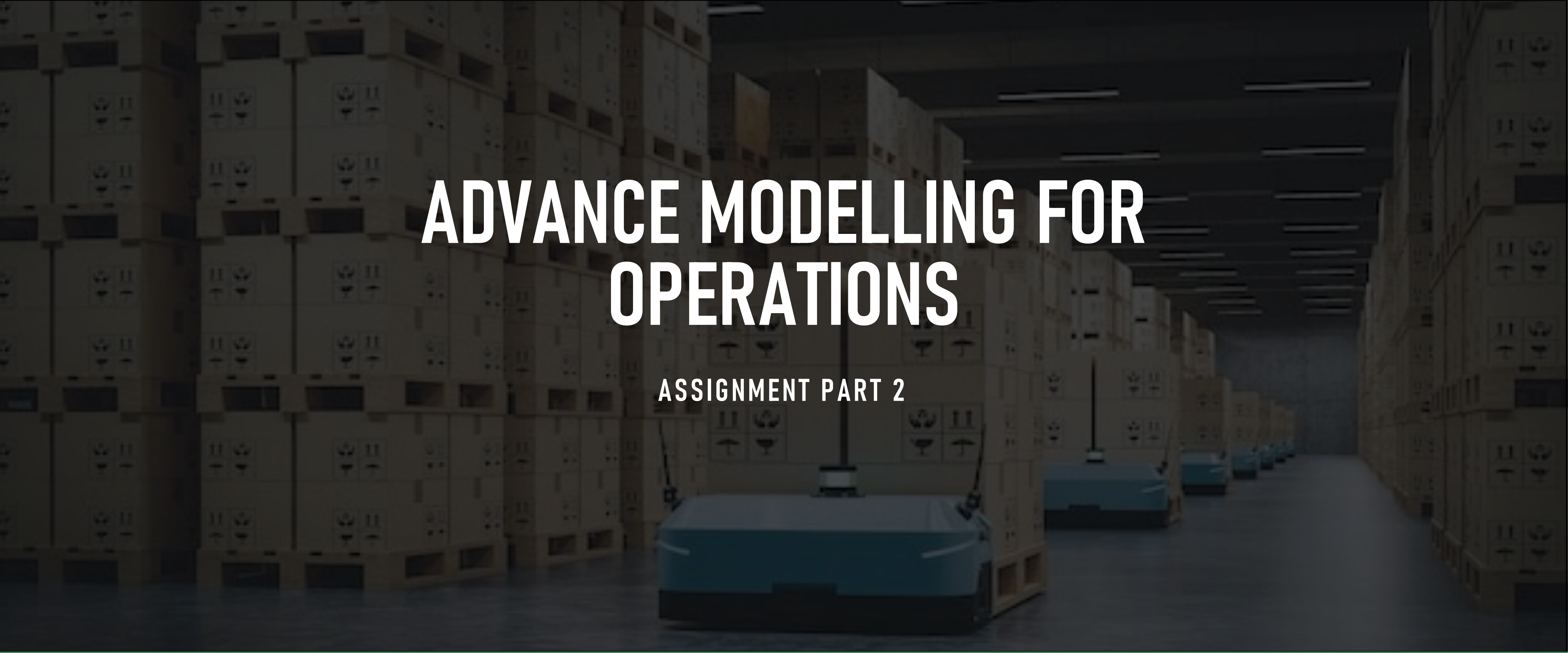

ADVANCE MODELLING FOR OPERATIONS

ASSIGNMENT PART 2

TEAM 1

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FACTORIAL ANALYSIS

1a

System performance measure of interest

Idle times of the production lines.

1b

Right number of runs

The number of simulations required to get the desired accuracy.

2a

Possible factors to investigate

All the idle time-dependent hyperparameters have been listed, discussed and among them two selected.

2b

The choice

The two varying factors of our simulation model.

3a

Set of experiments: Buffers

Every combination of hyperparameters has been tested by our model.

3b

Set of experiments: Charging Stations

Every combination of hyperparameters has been tested by our model.

4

Experiments results

A thorough analysis on our models' outputs.

A

Appendix

How to collect data.

1a

System performance measure of interest

Average Idle Time per Day

In this project's part we will investigate the effects that other factors, such as the buffers or charging stations have on the performance of the system. Based on the previous analysis' results, our studies will be carried out by setting the number of tugger trains to 6. In fact, after having noticed that the increase of an extra tugger from that number onwards on the average idle time is marginal, the investment for additional tugger train would not be justified. Understanding how other factors can increase our performances will allow us to have a wider range of solutions (with respect to simply considering the tugger trains as variables) and possibly find an economically better, if not optimal, solution.

To remain thus consistent, we chose to keep as system performance measure of interest the average idle time per day:

$$\frac{\sum_{i=0}^{4} idle\_time(i,7.5*2*3600)}{5}$$ i being the id of the production line.

Finite-horizon simulation

Having defined the performance measure as the average idle time per day, with the day composed of 2 shifts, the system will have a specific starting and ending point, namely the begin and the end of the working day. Moreover, our assumption consists of the system being brought every single day back to the initial condition, thus with empty lines' buffers and the tugger trains at the warehouse. The only condition that we kept variable regards the level of charge in the battery since we have assumed, on the contrary of what might be reasonable, that the tugger trains do not recharge at the end of the day, but rather return to the warehouse with the battery level reached at the 15th hour of the day.

Given the system's conditions and our objectives, the most appropriate type of simulation is, thus, the finite-horizon simulation with a period length of one day.

1b

Number of runs

Defining the right number of runs:

After having defined the performance measure it is necessary to identify the minimum number of runs that can provide an average value of the idle time with arbitrary precision. To do so we adopted a fixed-sample-size procedure, which depends on the assumption that the random variable is normally distributed, or N is “sufficiently large”.

The main drawback of this procedure is that we do not have much control over the confidence interval that, for a fixed N, depends on the variance of the random variable. To solve this issue, we opted for an iterative process in which, assumed the mean of X different from 0, we defined the relative error γ as:

$$\frac{|\bar{X}-\mu|}{|\mu|} = \gamma$$

We then computed the confidence-interval half-length for a given n and divided it by the absolute value of the sample mean, compared it with the adjusted relative error (γ/(γ+1)) and if lower, selected the given N as the optimal one to be used for the factors’ analysis, otherwise N had to be increased and the procedure to be repeated. Such procedure has been conducted considering the previously defined value of 6 tuggers train (over which the size of the fleet was not influential anymore) . The N obtained 801 with a relative error (γ) of 0,10.

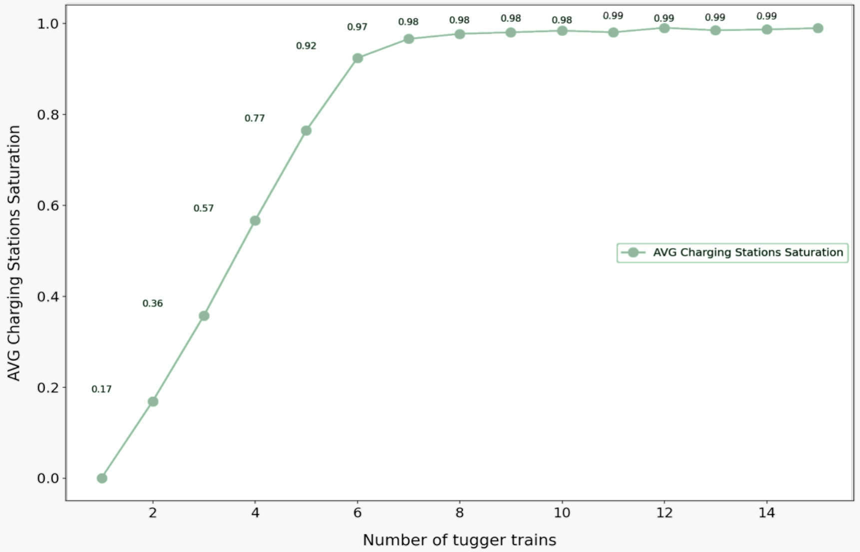
The high number of runs needed to get a sufficiently small confidence interval indicates that the model is quite variable. The relative error was increased mainly to computational constraints, with lower γ the number of runs needed increased too much and than it would not be possible for us testing different levels of factors.

2a Possible factors to investigate

Coherently with the assumption of using idle time as a performance measure, we have identified four main factors potentially to be investigated: number of tugger trains, capacity of lines' buffer, number of charging stations, and tuggers' train capacity.

Tugger trains. The number of tugger trains may vary from 1 to a large but still realistic amount, compliant with the plant layout's spatial constraints. As we had already seen in part 1 of the project, by adopting the *elbow method,* we have noticed that our model's idle time did not vary considerably with a number of tugger trains higher than 6. Therefore, we have opted to set the number of tuggers to that value for the rest of the simulation. Anyhow, it would be interesting to analyse how the optimal number of tuggers changes due to the variation of the other factors' levels in order to find a local optimum.

Lines buffers' capacity. The as-is model considers the lines buffers' capacity fixed to 3 unit-loads. Despite this, it must be highlighted that it is possible to reduce idle time considering an increasing number of buffers' pallets location.



Charging stations. In part 1 emerged that charging stations might represent the main system's bottleneck as the number of tuggers increases as depicted also in the graph reported on the left, therefore preventing to reach a standstill time of less than 5 minutes. So, it is possible to investigate the behaviour of the system when the number of charging stations varies.

Tuggers' train capacity. A further aspect that could have been investigated consists of the tuggers' loading capacity, both in terms of weight and length, in order to analyse how our system's performance would have changed by shuffling such parameters.

2b

The choice

In the following lines we will describe why we have opted to choose some variables above the rest.

First of all, we have decided to discard the tugger trains as a factor of interest because noticed that there was no point in having a number of tuggers larger than 6 due to the aforementioned reasons (see previous slides). Moreover, despite not having any economic constraints, the tugger trains represent, by far, the costlier item we might purchase among the ones scrutinized.

For what concerns the tuggers' capacity, the reasons for refusal are multiple. First, we strongly believed that by varying this aspect would have implied only a marginal impact on our model's performance. Second of all, enlarging the tugger's size could have represented also a problem from a technical point of view, e.g. considering the tuggers' movements agility within the warehouse's restricted space.

On the other hand, the decision about the charging stations seemed unavoidable, as the implied factor may result to be the bottleneck. Evaluating the increase in the number of charging stations is, therefore, necessary to provide a complete analysis of this simulation.

Concerning the decision about lines' buffers capacity, we have considered it as an interesting aspect for several reasons. First, due to its direct effects on the idle time and, secondly, due to its restrained economic impact: increasing the buffer capacity on the lines is believed to be cheaper than buying a new tugger train, along with their respective maintenance and operational costs. Lastly, an excessive number of tuggers could create congestion and increase safety issues, two aspects that have not be considered in our model since out of scope, but still negatively impacting the idle-time. Conversely, an increase in buffers' size, despite resulting in a decrease in the saturation, will likely improve the system's idle time.

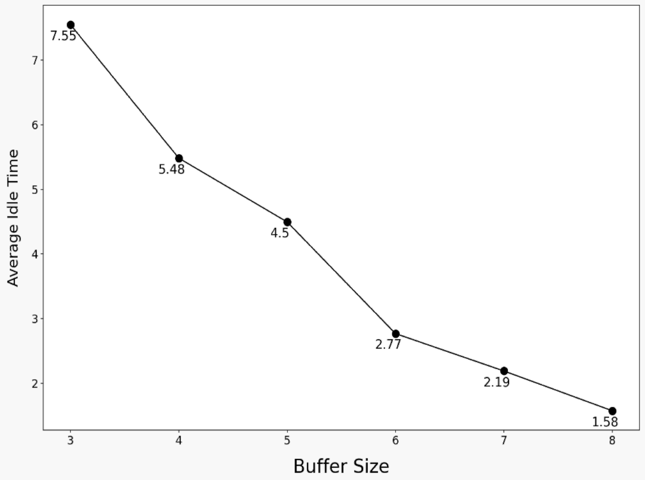
3a

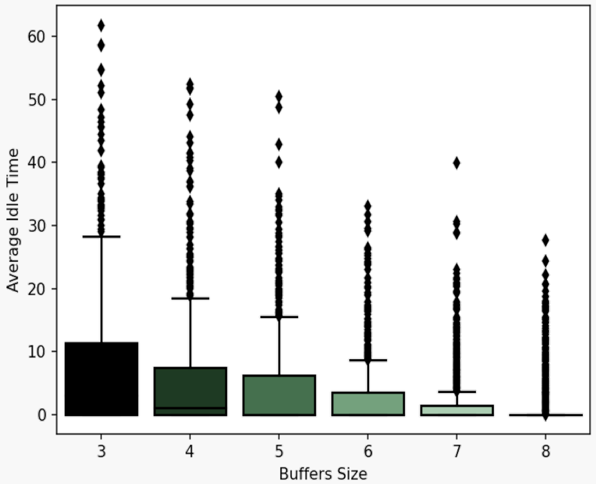
Set of experiments: Buffers

We have analyzed the behavior of the model by keeping the number of charging stations fixed at 2, as in the base case, and varying the size of the buffers of the five lines between 3 and 8. For each of the buffer sizes we conducted up to N (801) simulations, subsequently calculating the desired statistics on the chosen performance measure, i.e., the idle time of the production lines, including: the maximum and minimum values, the mean, the variance, and the median.

Focusing on the statistic we are most interested in, the results obtained from the N simulations for each of the six values assumed by the buffers, shown in the graph on the left, confirm what we already expected from the theory. As the buffer capacity increases, the lines’ idle time decreases remarkably. Already with buffers' capacity of 5 the overall idle time falls below the stated target threshold of 5 minutes considering the whole production lines, reaching a value of just over 4.5 minutes. Moreover, it must be highlighted that the rate at which the performance measure improves as the buffers' size increases is marginally decreasing.

Furthermore, as shown in the box-plot the results’ variability is falling as the buffer's capacity rises. Similar behavior is observable with the width of the idle times' range. This since, whereas the minimum has no room to decrease being 0 in all cases, the maximum has instead considerable “opportunities” to diminish. Anyhow, it appears that increasing the buffer size reveals to be a very effective method to avoid the lines idling significantly.



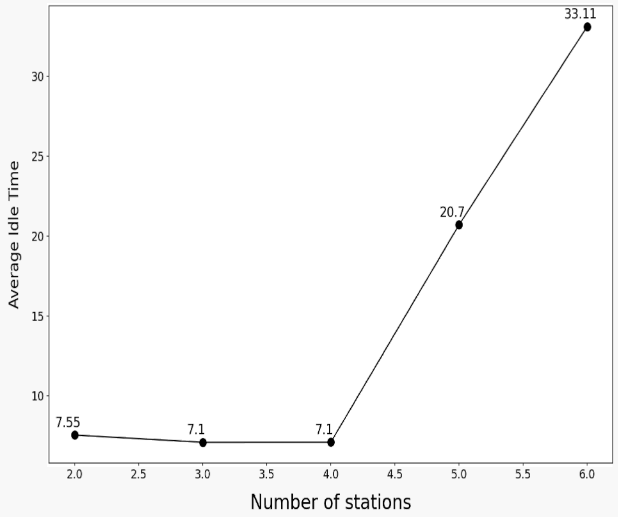


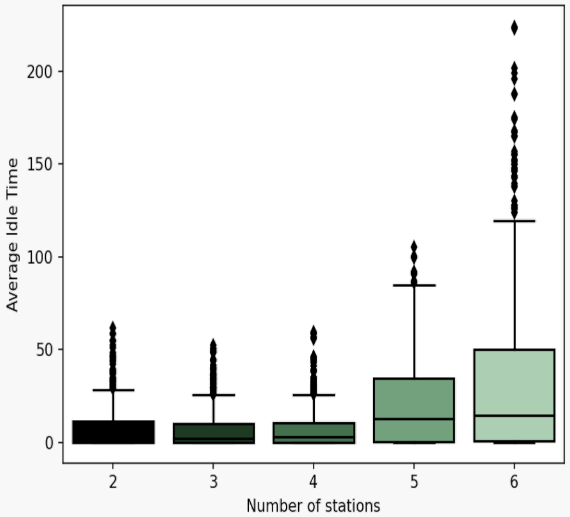
3b

Set of experiments: Charging Stations

After having analysed the impact of one factor, namely the buffers, we switched to the other-of-our-interest factor: the charging stations. Again, in order to obtain the results we are showcasing, 801 runs have been simulated with a configuration consisting of: 6 tugger trains, 3 buffers per line and a varying number of charging station, from 2 to 6.

The output looks everything but intuitive. In fact, by simply staring at the graphs depicted below, it seems that the more charging stations we place in the factory, the higher the systems' average idle time along with its variability. Thus, with the current configuration, it appears that the optimal number of stations would be either 3 or 4 (tie) but probably not justifying the cost of purchase with respect to keeping the as-is level, namely at 2, accepting a 30 seconds (ca.) penalty.





Cont…

3b

Set of experiments: Charging Stations cont.

Despite being counterintuitive, the reason is the following: since we have assumed that our tuggers' battery capacity may be with an equal probability between 0.05 and 0.98 percent due to the already explained reasons, having 2 charging stations is not so detrimental to our system despite all the problems related to the charging time length and the number of tuggers, because of the non-negligible probability to have the "right amount of tuggers" running throughout the factory while the remaining are charging. Indeed, a lower number of stations allows the system to maintain the **phase displacement** in terms of the tugger trains' charging level which is inherited from the very beginning of the simulation due to the assumption on the battery's initial levels. Forcing the tuggers to queue for charging purposes nudges the system to keep such displacement and diminishes the probability that the trains start to behave symmetrically at a given point in time during the simulation.

Therefore, the queue in the charging stations helps keeping steady the proportion of charging/working tuggers more or less balanced throughout the whole simulation time, conversely to what we have been expecting. Indeed, it can be noticed from the graphs reported in the previous slide that by adding few charging stations this equilibrium would be indented: by "removing" the queue, more than a small probability that the tuggers act synchronized is created, thus resulting with high likelihood in 6 tuggers running "hand by hand" (metaphorically speaking) through the factory trying to pick few buffers simultaneously (wasting energy as well), finalizing the work that maybe just 1 or 2 (exaggeration) tuggers might have performed.

This reason, of course, holds true due to the fact that our simulation model does not take into consideration the "Forecasts" update we would have wanted to integrate. In that case, the scenario would have become more "intuitive".

4

Conclusions

After having conducted all the analyses, we would have liked to understand which the optimal solution would have been. Obviously, in order to be able to do this we would have needed more information about the entire system. From the information gathered through numerous simulations, though, we can still affirm that under the conditions we have scrutinized, increasing the size of the buffers seems to be the best way to improve performances.

AVG Idle time (min)

As-Is 6 Tuggers	Buffers	Charging stations
7,45	5,48	7,09

Such strategy could reveal to be cheaper than adding a charging station. Anyhow, the costs comparison should be done considering the marginal benefits that either one or the other factor brings to the system. For instance, in our precise case (6 tuggers, 2 charging stations, and 3 buffers per line), ceteris paribus, adding one buffer per line could generate a marginal benefit 4 times (ca.) larger than adding one charging station as shown in the table on the left. Despite not having found clear information neither about the costs of adding one single buffer per line nor about the charging station, we might assume that the former solution might be cheaper than the latter proportionally to the marginal effects it brings to the table.

Certainly, the buffers' size could be limited by some factors such as:

- **The available space**. Every new spot for the buffer would measure about 1,4 m * 1 m (it would be the dimension of an Europallet with 10 cm per side to be able to manage it)
- **Line automation.** If the line is completely automated, the reach of the palletizing robot.

Similarly, the number of charging stations might be limited by other factors, such as the length of the aisle.

Cont…

4

Conclusions cont.

Thus, keeping what has been said so far, we reached the conclusion that the best solution in our case would be: 6 tuggers trains, 2 charging stations, and buffers that can contain 5 pallets, allowing the system to reach the desired performance measure's level.

Matter for reflection: If a more detailed knowledge about the costs was available, we believe that it would be possible to find an even better solution by simply running the simulation several times and allowing the number of tuggers trains to vary as well along with the possibility to have non identical buffers.

Regarding the second aspect, we noticed that in the various simulation runs, the idle time was not distributed evenly among the production lines. Therefore, having larger buffers for the last two lines and reducing the size for the first ones could further reduce the idle time by still maintaining, or even reducing, the overall required buffers' capacity.

In fact, the aforementioned solution has been dictated by the constraint of keeping the buffer size identical for all the lines. Indeed, if we relaxed this assumption, we have empirically tested that an even better solution in terms of both idle time and costs could been obtained through a configuration consisting of 6 tuggers, 2 charging stations, and buffers as follows: 3, 3, 4, 5, 5 for station 1, 2, 3, 4, 5, respectively. Without any doubt, this solution outmatches all the others found so far.

Note: This represents our local optimum since we have not been able, due to computational heaviness, to iterate through every single possible combination of parameters.

Cont...

4

Conclusions cont.

Furthermore, we have noticed that there was some room for maneuver for reaching the objective by keeping steady the amount of charging stations and by diminishing the number of tuggers, which represent by far the most expensive costs voice, to the detriment of the buffers' factors. Operating this way, we have obtained a solution represented by 5 tuggers, 6 buffers per line, and 2 charging stations. We believe that with respect to the solution explained in the previous paragraph where we opted to add 5 buffers overall, such solution might be even cheaper despite facing the costs related to 10 further buffers, since saving the ones related to 1 tugger.

Anyhow, we need to consider that this might be unfeasible in terms of physical space availability at the end of the line, as previously discussed in *The Choice*.

Note that such solution has been obtained assuming always the same number of runs, namely 801, despite each different configuration would have required an ad-hoc N. Thus, we need to keep in mind that this could have influenced slightly our results.

Cont…

4

Observations

Finally, we would like to highlight an interesting behavior of the simulated system.

As already mentioned in the results section, we noticed that the main driver for the improvement of the idle time does not depend much on the system's capacity in terms of load per cycle but more on the offset of the tugger trains active (not recharging) in the system.

We think that this is due to the high time needed to recharge the tugger trains (around 2 hours).
It is possible to estimate the number of active tuggers trains needed for a specific configuration just by running it without enabling the charging. Once the minimum number of active tugger trains is found (usually no more than 4), the other factors could be tuned to maximize the offset of the tugger trains and reach the desired target. First of all, by increasing the size of the buffer as much as possible, and, if the desired performance is not yet reached, by increasing subsequently the number of charging stations, being careful to avoid reaching the point in which their number has a negative marginal impact on the average idle time.

This behavior well explains the quantitative results of the analysis:

- the size of the buffers grants the system larger flexibility when a sub-optimal number of tuggers is actively operating while the rest is charging.
- the number of charging stations (assumed far from the point which is detrimental to the performances) reduces the time window during which there are not enough tugger trains active.
- additional tugger trains allow the system to balance out eventual synchronous conditions.
- the load capacity of tuggers trains is not so relevant for this system since is not a limiting factor.

As a final suggestion, we think it could be extremely beneficial to adopt a dedicated charging policy to get the optimal set up at the start of every day of production.

A

Data Collector

Despite not being at the centre of the system's analysis we thought it might have been interesting to dedicate a few lines in this section to explaining how we managed to collect the data to perform our studies.

```
#######################################
## Decide what to do with the script ##
#######################################
isSearching = True/False  # Perform grid search
runWithSelectedN = True/False  # Run with selected N
findN = True/False    # Find Runs N

# Parameters to find N
N = 2  # Starting N
alpha = 0.05
precision = 0.1

# Save output
path = "./output/output_N/"
export_df_to_csv = True/False
export_df_to_feather = True/False

#########################
# Model hyperparameters #
#########################
hyper_tugger_train_number = [6]
hyper_ul_buffer = [[3, 3, 3, 3, 3], [4, 4, 4, 4, 4]]
hyper_tugger_train_capacity = [4]
hyper_n_charging_station = [2, 3]

##########################################
# List to keep track of system evolution #
##########################################
lines_production = {0: [], 1: [], 2: [], 3: [], 4: []}
lines_buffer = {0: [], 1: [], 2: [], 3: [], 4: []}
lines_idle = {0: [], 1: [], 2: [], 3: [], 4: []}
charging_status = []
average_idle_times = []
```

Indeed, the script could be intended as different grouped-together sub-simulation models which can be run separately or not, depending on the goal.
Overall, the different models are four and can be grasped from the piece of code reported below on the left. Notice that for each configuration the possibility to save files has been given, either in *Comma Separated Values* or *Feather* or both.

Run Just Once. Setting the first 3 lines all to False allows the user to run the model once and print the system performances, without saving any results, though. If more than one combination's set of hyperparameters is given, only the last one will be performed.

Find Runs Number. By switching the *findN* to True and keeping the rest to False (for the sake of your PC) it is possible to run the model an increasing number of times until the N allowing to meet the precision and alpha constraints is found. No output will be saved under this precise configuration.

Cont…

A

Data Collector cont.

```
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## Decide what to do with the script ##
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lines_idle = {0: [], 1: [], 2: [], 3: [], 4: []}
charging_status = []
average_idle_times = []
```

```
hyper_tugger_train_number = [6 for i in range(N)]
```

Check Multiple Parameters. By setting just *isSearching* to True a grid search is performed: the model will be run trying all the possible combinations of parameters that have been given. For example, let's assume that in our case we want to run the simulation with 6 tuggers, a combination of buffer sizes of [3, 3, 3, 3, 3] and [4, 4, 4, 4, 4] and with 2 or 3 charging stations. The hyperparameters will have to be set as it is shown on the left. By doing so, the model will run 4 different simulations with different combinations of parameters.

N Times Multiple Configurations. This configuration is the one that has been exploited to obtain the graphs depicted in the previous slides of this project’s part. In fact, it allows to run the model N times for each set of combinations that have been set. The only difference from what is shown on the left consists of the number of times specification, which is done as showcased in the small quadrant.

ASSIGNMENT PART 2
TEAM 1

For a more comprehensive view of the work done, the script of the code is available. In addition, to facilitate understanding of the script, the file "*HOW-TO*" better explains which simulations can be performed through the script and how.