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Witness Horizon 25 DES Simulation Modeling of Centrally Dispatched Automated Mobile Robots

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Abstract

When building simulation models, the objective is to, as closely as possible, mimic the real-world environment. This becomes especially important as digital twinning increasingly becomes a business imperative and the benefits of analysis become more immediate and tangible. The model discussed in this paper was developed as a concept of capability demonstration, addressing several open points raised by an existing factory simulation effort. During several discussions concerning the modeling of Automated Mobile Robots, a concept of prioritized central dispatching control for the AMR's was developed. And on that basis, the simulation of information transaction flows much as one would simulate the movement of objects in the model. As with Value Stream Mapping (VSM) information flows are as important as material flows in the model. Finally, as a point of interest, a method is demonstrated here for modeling of AMR battery state of charge and recharging based on distance traveled and drive motor effort.

Keywords
AMR, AGV, Cell Control, Discrete Event Simulation, Witness Horizon 25

1. Introduction
This paper is the consequence of a series of discussions between the authors about the differences between modeling Automated Mobile Robot behavior and actual AMR behavior in the factory with defined paths and central dispatching. As a result, the objective of this analysis has been the development of a standard DES simulation model demonstrating centralized factory control of the direction of AMR's. Development and proof of concept for this general model and its embedded code then lay a foundation for application to specific factory case studies.

Clearly, when building simulation models, the objective is to, as closely as possible, mimic the real-world environment. This becomes especially important as digital twinning increasingly becomes a business imperative and the benefits of simulation analysis become more immediate and tangible. The model discussed in this paper was developed as a concept of capability demonstration, addressing several open points raised by an existing factory simulation effort. During several discussions concerning the modeling of Automated Mobile Robots (AMR), a concept of prioritized central control architecture for dispatching AMR's was developed. And with that basis, the simulation of information transaction flows much as one would simulate the movement of objects in the model. As with Value Stream Mapping (VSM) information flows are as important as material flows. Finally, as a point of interest, a method for modeling of AMR battery state of charge, discharge and recharging based on distance traveled and effort was developed. The assessment criteria for this system are not, however, the efficient use of AMR's but the optimized through-put of the simple manufacturing system consisting of several AMR serviced machines.

There was also a discussion about Edge Computing and simulating an independent cell control that would act, in effect, as a traffic director. This was over-laid with teaching a lean manufacturing graduate-level class at Lawrence Technological University where there was particular emphasis on Value Stream Mapping. VSM is particularly notable for the requirement that in addition to material flow being analyzed, information flows are also equally or even more important in the analysis. Suddenly the question arose, why isn't the flow of information included in discrete event simulation modeling? Data is passed in packets. Why couldn't we treat these packets as objects like any other object in the model? This question led to the development of a model with central factory control. A model was created specifically to demonstrate several simulation modeling concepts, incorporating centrally directed automated mobile robots and a central traffic director. Additionally, since AMR's are battery powered, a central battery power tracking computer was modeled that determines battery state based on distance traveled and then directs low battery-state AMR's to charging stations.

1.1 Objectives
Develop a discrete event simulation model of a manufacturing process that features centrally controlled dispatching of AMR's to service the process machines and also to access charging stations as required, being directed by a central control center. Information flow is treated as an object whose location and delivery are directed by that factory cell control.

2. Literature Review
In parallel with the resurgence of Automated Guided Vehicles and more specifically Automated Mobile Robots, there have been many papers published in the last five years examining the modeling of track-based and GPS location control systems. The same is true for scheduling and dispatching of these AMR's. For simplicity, the more modern term AMR is used in this paper for both, despite the several differentiating characteristics between AMR's and AGV's. Finally, the reference papers focus on several topics common to the risks of equipment moving on the floor, co-mingled with humans in a manufacturing environment. In reviewing the literature, it became apparent that several common themes were present and these included scheduling, tracks, collision avoidance, mission control and digital twinning of the AMR ecosystem.

2.1 Scheduling, Prioritization and Dispatching
Paola, et al. (2009) discuss the prioritization, scheduling and dispatching of Surveillance Mobile Robots (SMR's). SMR's incorporate an array of sensing and actuating devices and perform tasks such as observation, tracking of people and manipulating objects. They propose a system control architecture based on missions, tasks and behaviors. The library of SMR tasks defines qualified characteristics for activities while the library of behaviors defines appropriate behaviors. These support what the authors characterize as a fully autonomous control scheme.

2.2 Tracks and Paths
We model with tracks and paths, and this reflects many current logistics transportation systems, but GPS positioning can be employed for loose positioning, embedded floor guides for high precision destination locations. Digital map of the environment is necessary. Skapinyecz and Landschutzer (2022) set their goal of minimizing mission transit distance. Accordingly, they discuss the application of Dijkstra's algorithm and employ a path distance and time data table for mapping missions. Their model includes use of paths but also incorporates real-time positional data for the AGV's.

2.3 Collision avoidance
There are three aspects to this consideration: collisions between AMR's, collisions between AMR's and other elements of the infrastructure (pillars, machines, doors) and collisions between machines and humans. For example, Roszkowska et al. (2023) treat collision avoidance as an implicit rather than explicit system objective.

2.4 Control systems and traffic management algorithms
Roszkowska et al. (2023) describe their study of multi-level structured control systems. Their focus is on control of multiple robots in the same environment, (MMRS). This thinking echo's earlier ground-breaking studies of Aibo pack behavior with wireless communication enabled Sony Aibo robotic dogs. The work of Roszkowska et al. bases their analysis on several assumptions including: group of autonomous robots, 2D space, each robot mission is planned independently and no interaction between autonomous agents. Their objective goal is to maximize efficient MMRS behavior while accomplishing their tasks. The authors do not consider whether efficient robot use necessarily correlates with manufacturing system performance optimization. Two levels, basic uncoordinated behavior and system control are modeled to assess effectiveness of the control assumptions. Košecká and Bajcsy (1994) begin their analysis with a discussion of the reactive nature of modeling which is common rather than proactive nature of prior art autonomous control systems.

2.5 Commercial off the shelf discrete simulation software and machine learning software
One of the issues with simulating AMR movement is that when we discuss simulation of AMR movement in the warehouse or factory environment, most of the DES software reflect a static view of AMR capabilities while, technological advances in sensors, sensor suites, sophistication of control systems including AI and GPS position management are constantly evolving. Experiments in herd behavior with Wi-Fi enabled autonomous robotics, and AI augmented traveling salesperson analysis conducted on a real time basis have demonstrated further increases in efficiency. Just as with the Smart Infrastructure initiative for automobile traffic management, collision avoidance is mitigated by each AMR knowing where it is in space as well as the location and vector of each of its comrades. This leaves only the problem of collision avoidance with humans who often enough do not know where they are or where they are going.

Greasley (2020) raises the challenges of integrating stand-alone Machine Learning software with commercial discrete event simulation modeling software tools. The approach that Greasley proposes is to embed the Machine Learning code directly into the DES software, since some DES software supports the capability to embed software written in C, Python or other languages.

3. Methods
Paths and movement routings have a specific purpose in simulation modeling (Figure 1). From prior work creating and defining walking paths for people elements in Witness Horizon, if an element like a person or vehicle is directed to move from one point in the model to another without defining a path, the element will take the most direct path possible and walk or drive straight through any other model element objects in the model. This means that people, desks, machines etc. are all fair game for a kinetic event. This is the sort of fun that appeals to the bumper-car loving child in each of us! But, by using tracks and paths we can ensure safe travel on predefined routes rather than through other model objects. In the image above, you can observe green colored lines marking out the path for Automated Guided Vehicle (AGV) traffic in the factory. Please keep in mind that just because something is called a "path" this doesn't mean that only operators can walk on it. Parts, resources (vehicles) and other objects can move along paths in Witness Horizon.

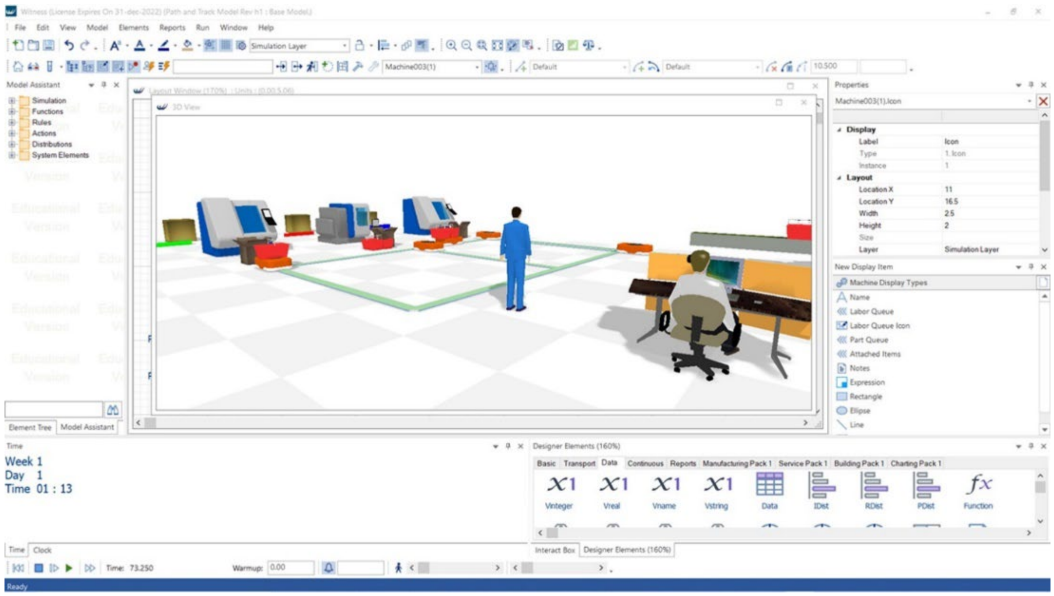


Figure 1. Paths and movement routings

When wire-guided AGV's were first used in the 1950's, laying out defined paths and embedding track wire in what were typically concrete floors often proved to be inflexible, inefficient as well as disruptive to on-going operations. And with limited sensors at that time, AGV movement represented a safety issue for production workers. But with the passage of time, new sensor suites, GPS based guidance and autonomous control systems which eliminate the need for an embedded guide wire, AGV's are making a return to the factory floor, and it is these systems that we will generally refer to as Automated Mobile Robots (AMR's) to reflect their expanded sensor suites and autonomous capability. Just as trucks, automobiles and agricultural machines are increasingly being equipped with automated guidance systems guided by autonomous vehicle controls, sensor suites and GPS, so too are AGV's.

Witness Horizon Conveyors, Paths & Tracks

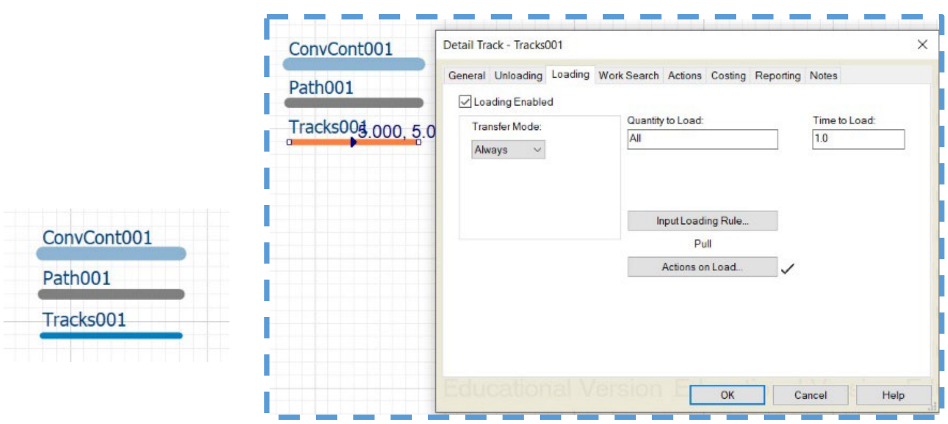


Figure 2. Conveyors, paths and tracks

As shown in the illustration to the left, Conveyors, Paths and Tracks are fundamentally the same from an appearance perspective and each can sit at floor level or be raised to a defined elevation above the floor (Figure 2). But each is endowed with some unique characteristics specific to its function. Sensors can be used on **ConvCont** conveyors.

Tracks in Witness Horizon have a unique characteristic compared with conveyors and paths, their special power – like any superhero - is that the modeler can specify loading and unloading characteristics for sections of track. The example above shows the window for the **Loading** function. As you can see, we can define both a loading rule, such as only load red parts, as well as being able to specify actions taken on loading. This is the same as the capability to define actions with other Witness Horizon Designer Elements. So, now when you think of tracks, you will immediately think of comic superheroes and special powers! And tracks don't need a cape, shield, lasso, or silly mask.

Generic Model Description

This model consists of three machines (Machine001, Machine002, Machine003) which pull one part, Part_A, Part_B, Part_C, from a buffer, perform some process and then load the parts, two at a time, in a part carrier (Pallet). A vehicle (AMR) picks up one pallet from a machine and then transports that pallet to Pallet_Unload machine where the parts are removed from the pallet and pushed to ship. We have a counter for total parts shipped as well as individual counts for each of the three parts. Our work cell operator, Bernd walks the path to storage Pallet_Unload_Buffer at the Pallet_Unload machine and then returns the pallets to the Pallet_Buffer where they are stored. The AGV follows the floor tracks as shown to service each of the machines.

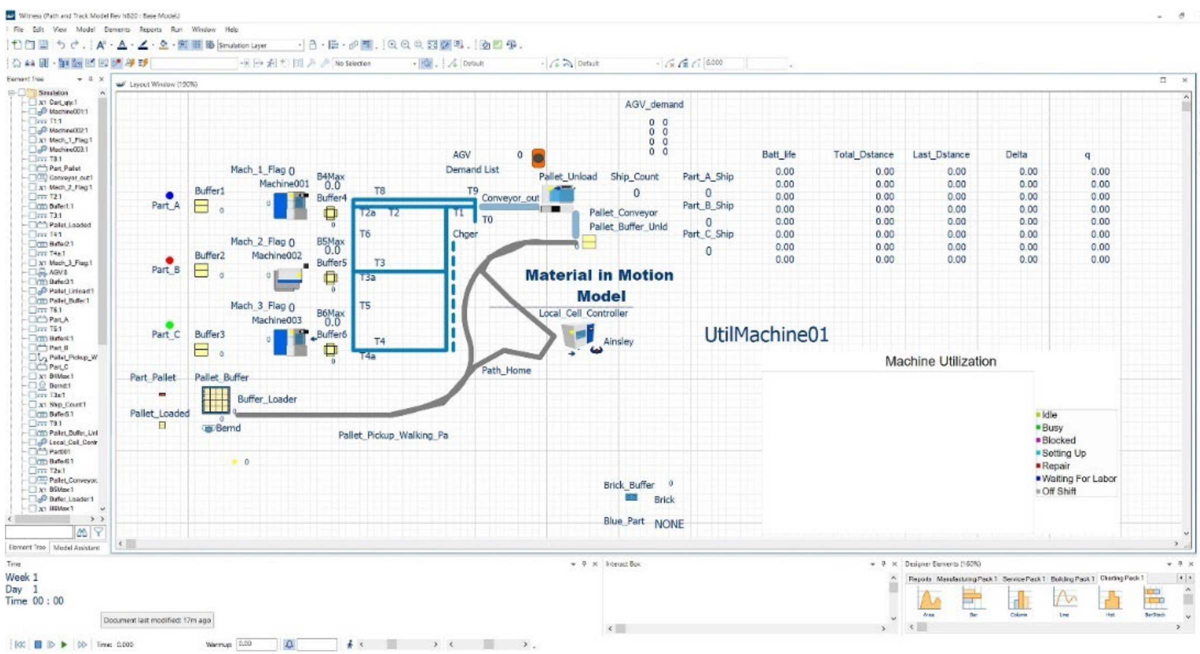


Figure 3. Model consists of three machines (Machine001, Machine002, Machine003)

Of course, we don't want AGV's driving idly about with nothing to do like teenagers on a Friday night with the keys to their parent's car (Figure 3). So, we will need to develop code that only sends out AGV's when there are parts to pick. Based on our track layout, AGV's leave the logistics center on track T0 when there are parts in any one of the machine buffers. There is a branching point at the end of T1 where we need to define whether the AGV travels on track T2 to Machine001, to track T3 to Machine002 or track T4 to Machine003. The actual tracks length is twice the length visible in the model. We will develop code that considers the loading of the machine buffers and decides where to send the AGV's based on part having the longest wait time.

We also introduce a new idea here that originates in Value Stream Mapping (VSM). In addition to process setup and cycle time, VSM gathers information. Cell Control was added, which initially directs a limited set of activities, but as will be demonstrated, this could be the hub for planning and scheduling various jobs.

This is our model layout which is titled, "Material in Motion Model, since that is its ultimate characteristic being demonstrated. Our AGV park is in the Material warehouse in the upper right-hand corner of the image. AGV's are introduced into our pathways at T0 track. The AGV's are called out and dispatched to the appropriate location when Local Cell Control has determined that one of the machine output buffers has at least 2 parts.

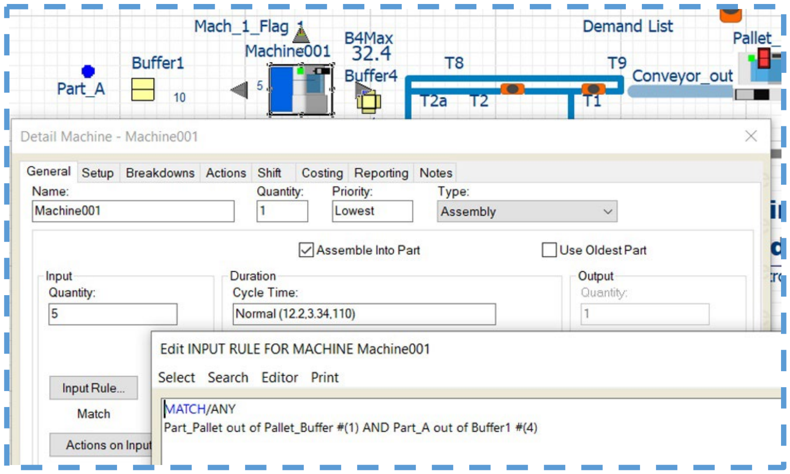


Figure 4. Three process machines

We have three process machines, Machine001 through Machine003 which pull parts from buffers, process them and load the parts onto pallets (Figure 4). The pallets loaded with parts are then loaded in the buffer for that machine. Later an AGV is directed to remove a pallet and transport it to the Pallet Unload Machine. Note that the Assemble into Part checkbox has been checked.

At the Pallet Unload machine, a general machine will be employed to unload the parts from each pallet.

We will also define our parts so that there is more Type information assigned as attributes. It might be useful to know if a part is Red, Blue or Green. Alternatively, you could assign a part number and serial number to each part for traceability. Merely create a Serial Number variable to store that attribute for each part. Attributes are an often-under-appreciated capability of Witness Horizon specifically and simulation modeling in general.

Prioritization Schemes and Local Cell Control

So then. We have at least two objectives: Maximize OEE for Machine001 through Machine003 and minimize number of AGV's that we require to maximize our asset utilization. This sounds like a Linear Programming (LP) problem, doesn't it. More specifically, since we can't use fractions of AGV's or move fractions of parts, it really is an Integer Programming problem. (There's probably a classical knapsack problem in here somewhere.) That would be one way to address this problem, and the other is to make use of Discrete Event Simulation to understand our system since that will allow us to build stochastic models.

Now, for the first time, we are going discuss using a machine that we will call a Local Cell Controller. As we know from our Lean Manufacturing education and practical experience, the communication of information is as important as movement of materials since timing is critical in pull systems. Now it is time to create a clock. A PLC controller continuously loops through its control program, checking sensor and data inputs, performing calculations, and then activating outputs. We are simulating a PLC so a machine has been configured to continuously loop through the following code which checks buffers fill and then sets an output status flag so that the AGV/AMR priority can be set. (Figure 5)

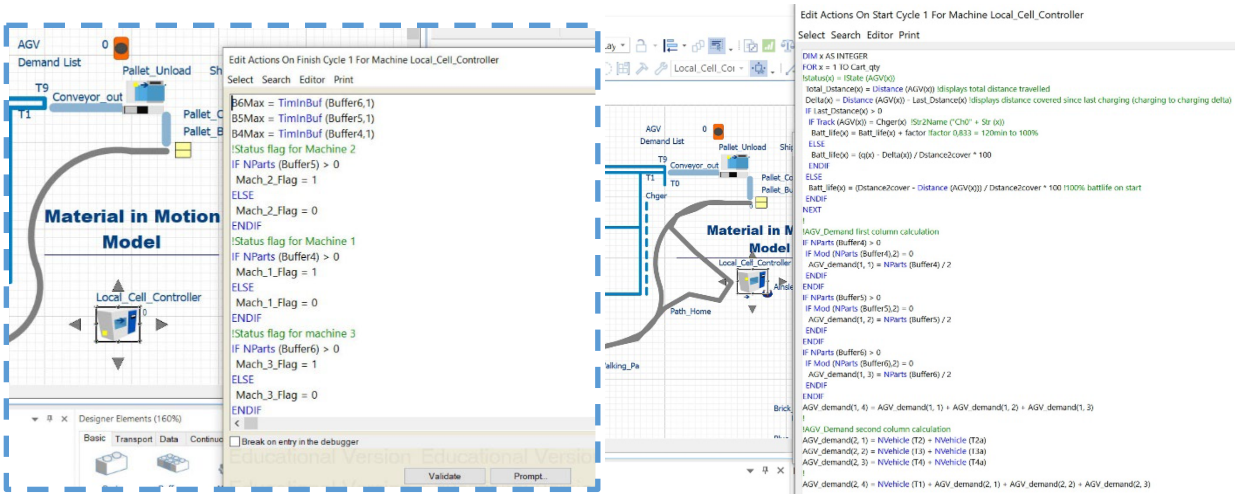


Figure 5. Prioritization Schemes and Local Cell Control

To cause our Cell Controller to cycle through this code continuously, we will pull an object, in this case what we are calling a “Brick” from a buffer, process it with a cycle time of 1 (this was chosen entirely arbitrarily) and then push the Brick back into the buffer. Think of it as our perpetual motion machine (Figure 6).

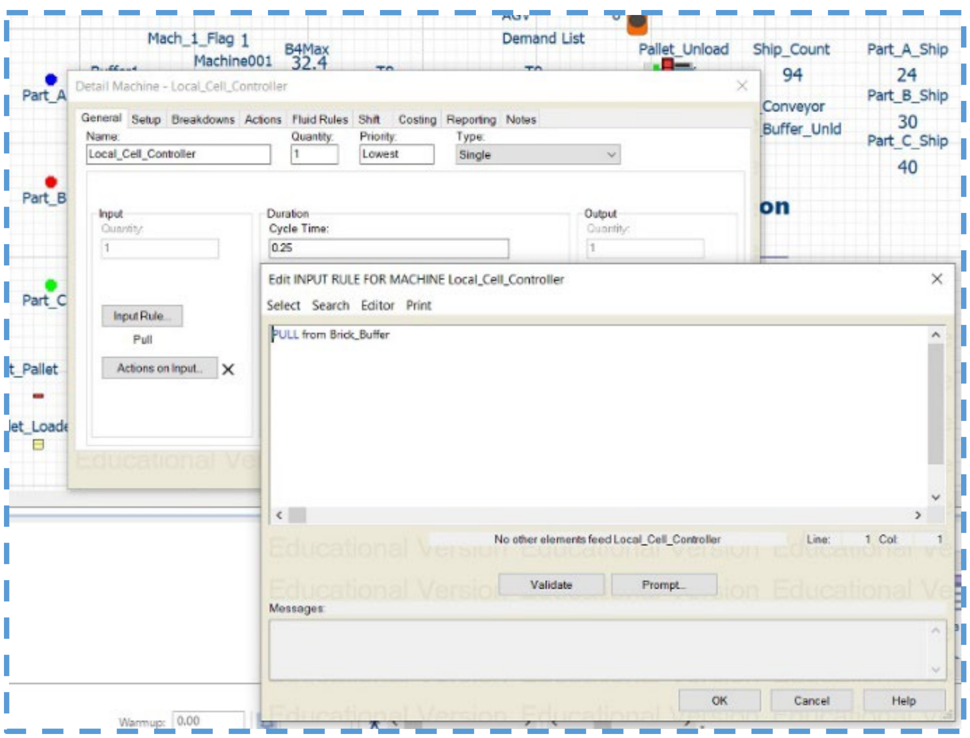


Figure 6. Perpetual motion machine

There are other methods to accomplish this, but for the moment we will use this approach. Interestingly enough, instead of moving or processing parts, this device will manage information! Think of it like the drummer in a rock band. The drummer sets the pace and transmits timing information. As we expand this model, adding other features, we can also add more functions that the Cell Controller will control.

Next, we will configure our AGV. This is shown in Figure 6. Simply enough we will define five AGV's, of course we can decrease or increase this at any time to assess the impact on the model.

From T0 at our logistics center, we want to send the AGV to the machine and buffer that has been waiting the longest. Correspondingly, T1 could branch to T2, T3 or T4.

Laying out the Tracks
Creating the tracks is quite simple and comparable with creating Path or Conveyor objects. From the example, you can see that we have numbered the tracks T0 through T9. Section T1 has a branching decision on where the AGV goes once it leaves T1. The AGV can travel from T1 to either T2, T3 or T4 correspondingly servicing Machine001, Machine002 or Machine 003. Additionaly, track "Chger" serves as charger for AGVs ((Figure 7).

The code shown here for Output To describes the branching decision with information provided by the Cell Controller (Figure 8).

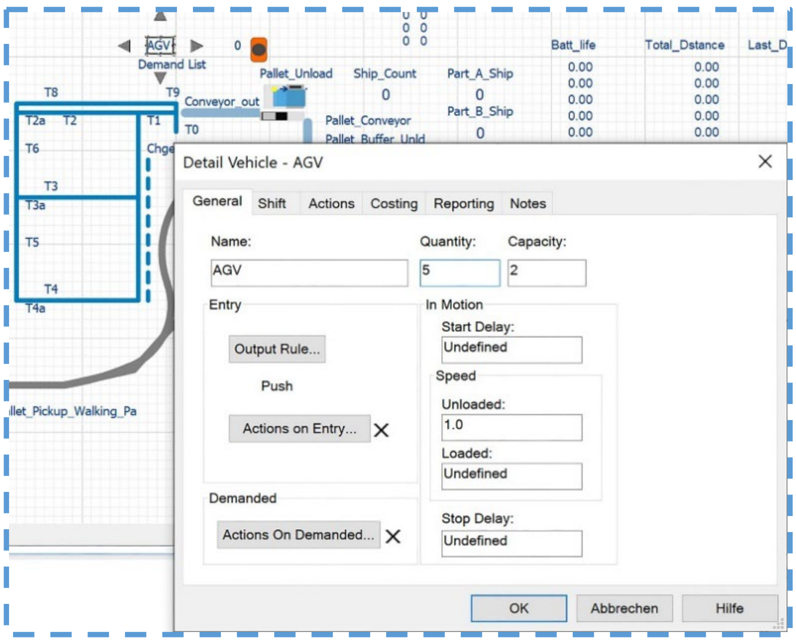


Figure 7 . Laying out the trucks

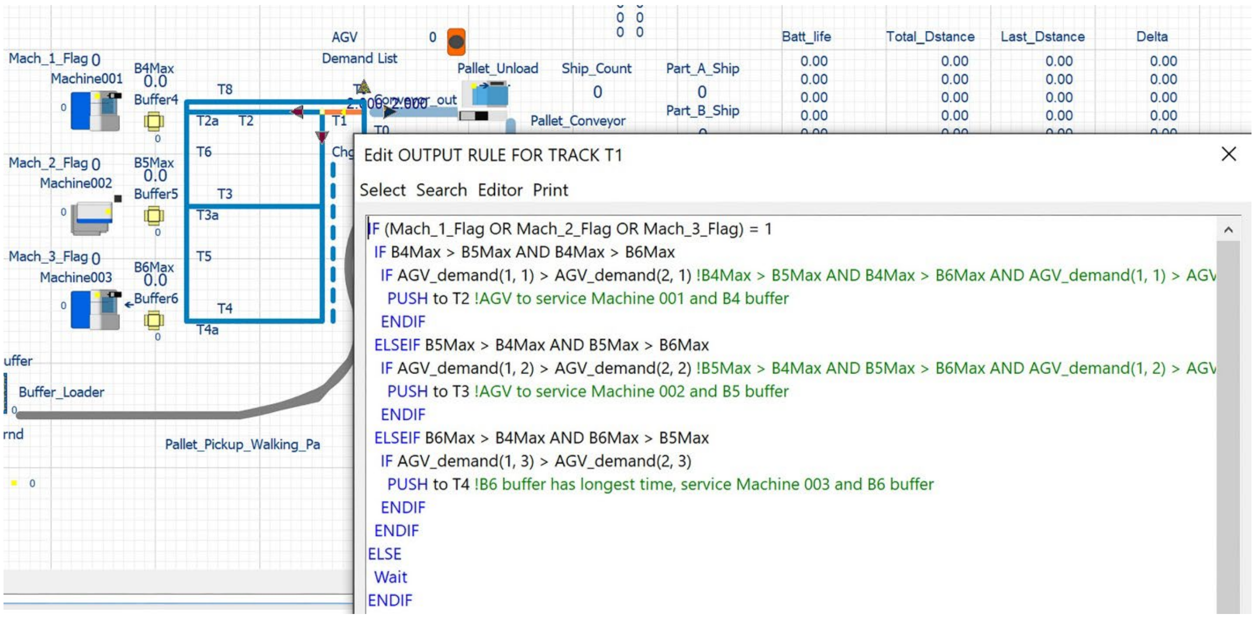


Figure 8. Code for output to describes the branching decision with information provided by the Cell Controller

Some of the tracks are segmented as you see in the next illustration. T4 feeds into T4a. T4 interacts with the Buffer B6 and then links to track T6. This facilitates loading, unloading and branching mechanics (Figure 9)

Figure 9. Segmented tracks

Load AGV from Buffer

Once the pattern of tracks has been created, it's necessary to define the points and actions associated with loading pallets onto the AGV's. The following image, Figure 10, shows the instruction needed to pull the pallet from the buffer.

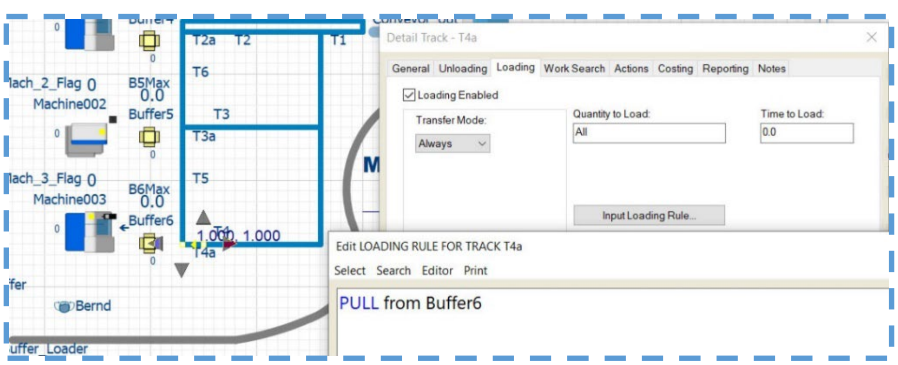


Figure 10. Load AGV from Buffer

Change Icon for Loaded AGV

It may be useful to change the Icon appearance and that is illustrated in the next graphic where the AGV Icon is set to 172. However, remember that it will need to be returned to its original at a later point when the AGV is unloaded (Figure 11)

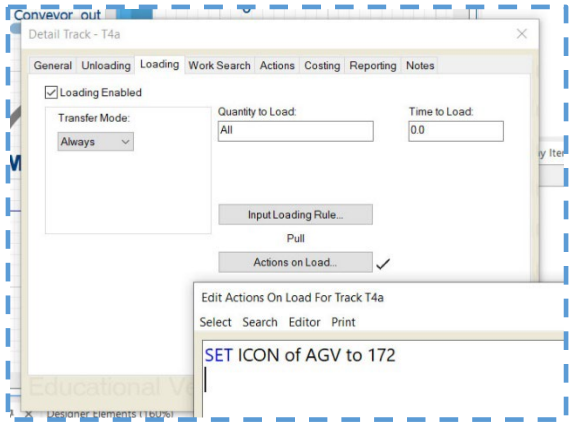


Figure 11. Icon for Loaded AGV

Move AGV to T5

Once the AGV has been loaded, we would prefer that it returns to the logistics center for unload, instead of wandering the factory, lost forever. Return tracks should be defined, T5, T6 and T8 in this model return the AGV's to the Unloader.

A few words on transporting parts on pallet

It's often the case in manufacturing that we want to move a group of parts as a batch or to handle some unique shape without transit derived damage, we need to load the part into a carrier for transportation during and between various manufacturing processes (Figure 12).

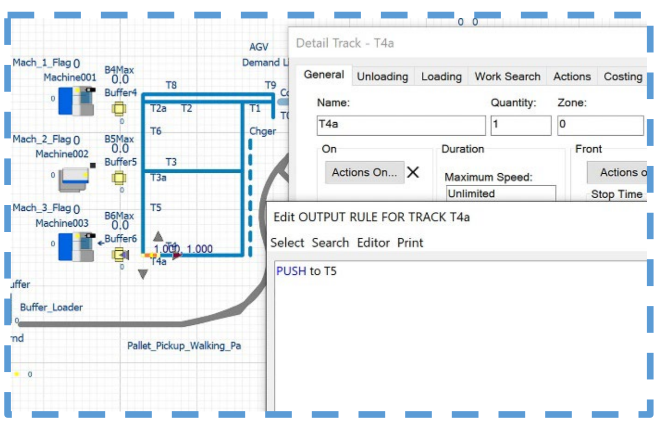


Figure 12. Transporting parts on pallets

Pallet size may be standardized within a factory so that mixed populations of parts can be processed in a common cell or line. Pallets, also known as workboard holders, may have onboard electronic technology to retain processing information, part serial number, date and times of processing, etc. Additionally for electronic or electro-mechanical modules being transported by pallets, there may be an electrical connection between the pallet and the module for electrical testing. If the module also has a wireless internet connection to a local cell control, all of this information is available to the cell and to process monitors real-time.

We have our Pallet_Unload machine which as you see is a Production Machine Type. You must check the checkbox, **Produce from First Part**. Notice that in Actions on Output, we are performing the various shipped parts counts. Since total parts shipped by part number is a useful metric that code is shown in the bottom graphic

Battery State of Charge
The common denominator for all AMR producers is safety systems and related legal requirements (ISO 3691). What distinguishes one AMR/AGV manufacturer from the other is e.g. battery size and type and related with that charging and draining time. One system prefers frequent, but short charging, whereas another a single charging cycle for a day or shift of work. One battery will have greater life span when operating between 80-100%, while for other has its best performance and life span range in the 20-80% range. Current consumption is almost never linear. The same principle applies to charging curve. That makes things more challenging for us (modelers). But as we don't work for AMR manufacturer, we need to take some assumptions and for this exercise, we will indeed assume a linear model for energy consumption and charging. It's tricky to simulate AMR, when you don't design the underlying system (logic) (Figure 13).

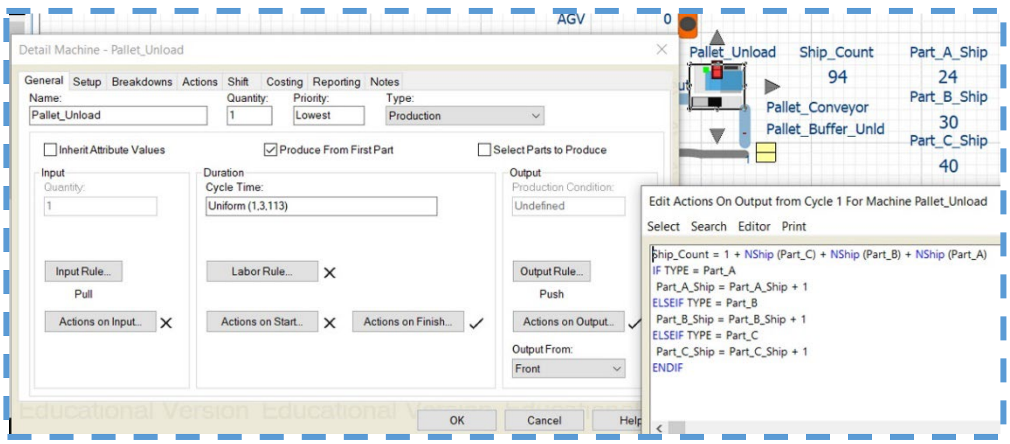


Figure 13. Battery state of charge

To make a complex topic even more complicated, there are two ways of simulating battery usage in AMR's. The first alternative is time dependent (distance independent), and the second is over distance (time independent). Standing on the customer side of this technology, we don't have much choice, and we're forced to simplify things to the bone. As the energy consumption varies a lot when accelerating, decelerating, standing idle, running at a full speed, running loaded or running empty, we personally prefer to calculate possible maximal distance covered by AMR on one fully charged battery, reduce it by around 30% (we never have perfect conditions) and use mileage to calculate battery life. These assumptions provide us with a useful model rather than a model with high precision since usefulness is more important to daily operations.

To start, key variables were identified:
- Batt_life (to display current battery level),
- Total_Dstance (total distance covererd by each of AMR's),
- Last_Dstance (AMR odometer reading during last charging),
- Delta (difference between Total_Dstance and Last_Dstance),
- Q (expected range after last charge)

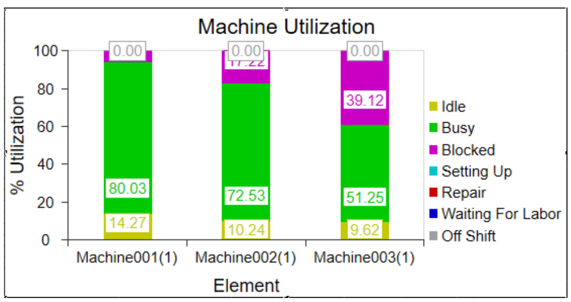
4. Data Collection
As previously discussed, most of the reference papers reviewed focused on optimization of the autonomous AMR behavior as opposed to optimization of the manufacturing factory capability. What is the ideal goal? Efficient

AMR's or and efficient factory. As with Value Stream Mapping, this analysis has a stated objective to optimize manufacturing system through-put and not the optimization of the transportation system (Table 1).

Table 1. To see the system performance, three sets of data have been prepared and run in simulation model.

Scenario	Number of pallets	Buffer4 capacity	Buffer5 capacity	Buffer6 capacity	Number of AMRs
1	20	4	4	4	5
2	25	8	8	8	8
3	30	8	8	12	8

The Machine Utilization chart will help us in stating whether we are getting closer or further from our goal. After one day (24h) of simulation time, system performance for the first scenario is as shown in the Machine Utilization graph (Figure 14).



UtilMachine01.Utilisation

Name	Element	Idle	Busy	Blocked	Setting Up	Repair	Waiting For Labor	Off Shift
UtilMachine01.Utilisation	Machine001(1)	14.272983...	80.027916...	5.6990993...	0	0	0	0
2	Machine002(1)	10.244117...	72.531425...	17.224457...	0	0	0	0
3	Machine003(1)	9.6212021...	51.254482...	39.124315...	0	0	0	0

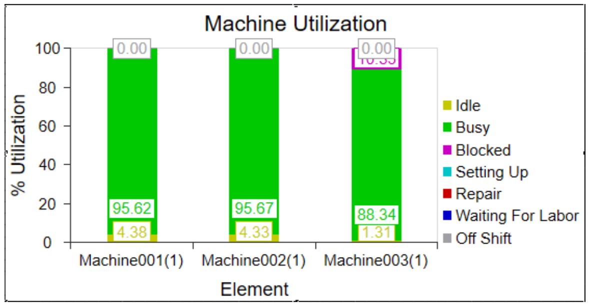
Figure 14. Machine Utilization Graph

From the utilization status graphs, it is clear that both idle time and time that a machine is blocked are contributing to machine utilization. Further, it is demonstrated that Machine_003 is blocked more often than Machine_001 and _002 which indicates an imbalance in AMR servicing. Being "Blocked" is defined as time that the machine is unable to perform its function because the existing completed work as not been pulled to the next station.

From the blocking imbalance between the three machines being serviced it is apparent that a randomizing component should be employed in conjunction with the pick from longest buffer time strategy.

System performance for the second scenario

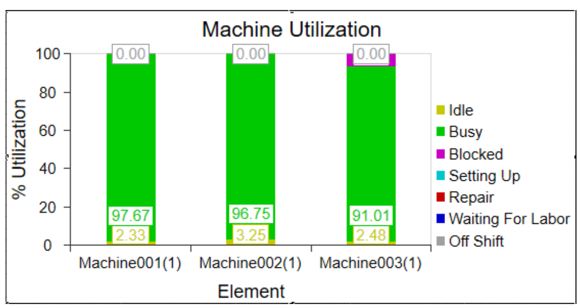
With the second scenario, there is still idle time, but the amount of time lost to the machines being blocked is significantly reduced. As machine utilization is increased, the idle time is reduced to some point where increasing AMR availability has no real effect (Figure 15).



Name	Element	Idle	Busy	Blocked	Setting Up	Repair	Waiting For Labor	Off Shift
UtilMachine01.Utilisation	Machine001(1)	4.3828584...	95.617141...	0	0	0	0	0
2	Machine002(1)	4.3332322...	95.666767...	0	0	0	0	0
3	Machine003(1)	1.3099903...	88.341473...	10.348536...	0	0	0	0

Figure 15. System performance for the second scenario

System performance for the third scenario:
The third scenerio demonstrates that while blocking time percentage has been effectively managed, there remains 2.33% to 3.25% idle time which may be the percent of time lost to the mechanics of the machine load and unload cycles. This question deserves further investigation (Figure 16)



Name	Element	Idle	Busy	Blocked	Setting Up	Repair	Waiting For Labor	Off Shift
UtilMachine01.Utilisation	Machine001(1)	2.3347308...	97.665269...	0	0	0	0	0
2	Machine002(1)	3.2536668...	96.746333...	0	0	0	0	0
3	Machine003(1)	2.4776692...	91.006643...	6.5156868...	0	0	0	0

Figure 16. System performance for the third scenario

5. Results and Discussion

5.1 Results

Finally, a side-by-side graphical comparison is provided for the initial state and the final state of the model through the two scenarios (Figure 17).

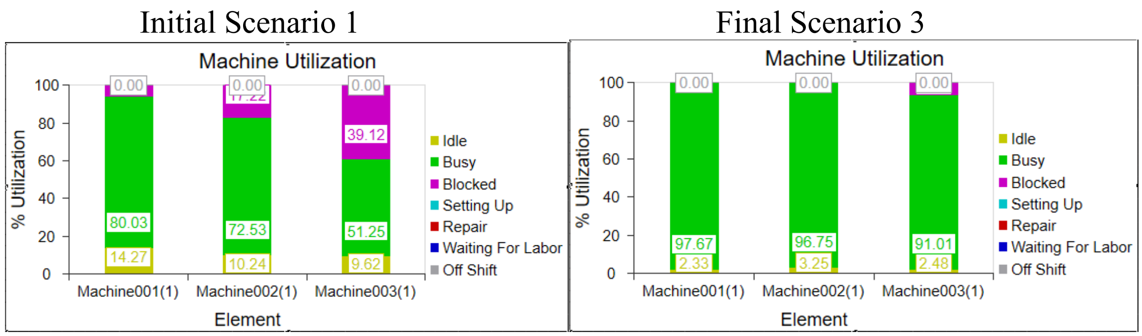


Figure 17. Initial state and the final state of the model through the two scenarios.

Comparing "before" state (scenario 1- on left) and "after" state (scenario 3 - on right) we can say that the difference in "Busy" time share, between them for Machine001 is 22,0% higher (increase from 80,03 to 97,67), for Machine002 is 33,4% higher (increase from 72,53 to 96,75) and for Machine003 is 77,6% higher (increase from 51,25 to 91,01). The "Blocked" time share dropped to zero for Machine001 and Machine002. For Machine003 it reduced to 6,5%. The "Idle" time share also decreased by 83,7% for Machine001 (to 2,33%), by 68,3 for Machine002 (to 3,25%) and by 74,2 for Machine003 (to 2,48%).

Ultimately the intent has been to maximize production machine utilization and product output at the expense of AMR utilization since the first adds value and the second contributes to overhead costs. Reducing the time that each machine is blocked has the most direct effect on utilization improvement.

5.2 Future Directions and Limitations

The violet part of the bar chart representing machine "blocked" time indicates the need for an increase in the output buffer size for produced parts and increase in the number of AMRs in the model. All three objects need to be addressed. The yellow section of the bar chart, showing "idle" time, tells us that the machines aren't fully loaded, as a result, there is a further opportunity for improvement.

Another area for future analysis is the exploration of fully autonomous AMR's operating as independent swarming agents, perhaps employing a "bidding" system to compete for the next available task. Bidding "points" might be based on distance to pick-up location, remaining battery state of charge and other criteria. Swarming AMR's with simulated R2R communication, (the AMR equivalent of V2V for automobiles) have the possibility of demonstrating a hive-like behavior. Additionally, use of stochastic battery capacity and charge-time models could enhance mirroring of the actual factory within the model.

As demonstrated here, DES software such as Witness Horizon and others support embedded code to enhance functionality, but this code brings with it the cost of increasing computational intensity. Finally, increasingly sophisticated DES models also become more difficult to validate in all potential cases.

6. Conclusion

All three factors (number of pallets, buffer size, number of AMRs) play key role in increasing machine utilization. Even when it appears that the process is stable and runs smoothly, then comes the reality and fact that AMRs don't run on air! They need to be charged from time to time. Reduced number of available AMRs causes longer pick up times. In order to maintain interruption-free continuous production with the highest priority, an increase of output buffers was necessary. That caused an increased need for available pallets. And the addition of pallets is more economical than the addition of additional production machines. Theoretically it's possible to increase the number of resources endlessly, but practically, which one of these is the most cost-efficient? That's a question along with continuous induction floor recharging for another research.

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