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Planning of flexible manufacturing lines with AGV material handling for the entire life cycle

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Abstract: The article is related to recent research focusing on the design of flexible manufacturing systems. It is not possible to design a flexible production system without planning the related logistics, material flow and its management. A key component of flexible manufacturing systems is material handling systems, which are often means using AGVs to transfer parts from station to station. With the increasing prevalence of the advanced control logics and artificial intelligence, AGV is poised to become a fundamental element of many production lines and logistics operations. Many studies focus on how many AGVs are needed for a given production line or logistics area. However, those papers do not deal with the effect of battery degradation during the life cycle of the production line or logistics area. During this period the battery of these devices degrades and thus their capacity is significantly reduced. The article explains how discrete event-based simulation can support the planning of AGV-based systems, particularly analysing the impact of AGV battery degradation during the life cycle of a flexible manufacturing system. The result of this article is a general methodology that is suitable for determining the required number of AGV units for the entire life cycle of a given production site or logistics activity.

1 Introduction

A very exciting period of transformation of production processes is taking place these days. Customer needs are changing significantly, customers want to buy more and more unique and customized products [1]. Accordingly, manufacturing companies must also transform from the former mass production to flexible production [2]. This change happens so dynamically that in many cases there are no developed methods and practices for creating production lines and production processes that meet the needs. Important factor is that flexible production usually requires more flexible and therefore significantly more expensive equipment, therefore it is realistic for manufacturing companies to expect that this equipment can be used for a longer period [2]. It means that the life cycle of flexible production lines getting longer. In this article, we examine the life cycle of flexible production systems and production lines and its elements. In the second part of the article, the AGV (Automated Guided Vehicle), one of the most common material handling devices in flexible production systems, is examined from a design point of view. Finally, we analyse an example how the development of the capacity of AGVs during the life cycle of the production line can be considered with digital tools.

2 Literature review

Production systems produce products, so understandably their life cycle cannot be separated from the life cycle of the product manufactured on them. In fact, the production line is also a product, so its life cycle is characterized by everything that is characteristic of a product's life cycle [1], although the names of the phases are closer to the terms used in production (Figure 1).

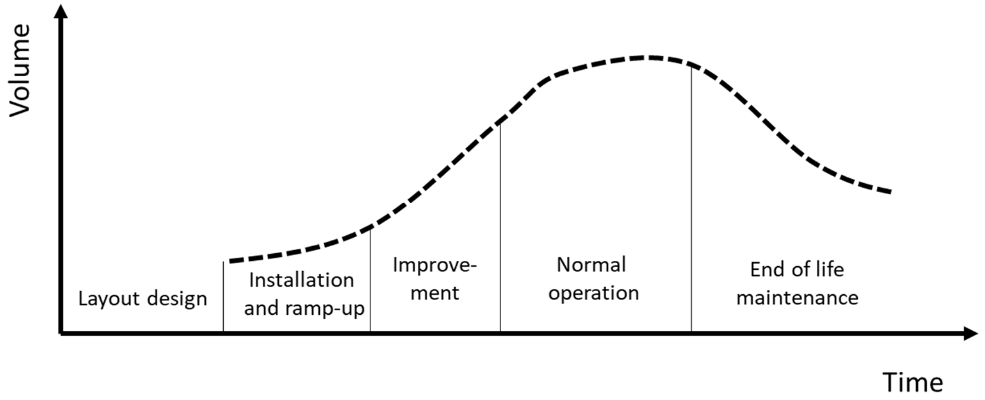


Figure 1 Lifecycle of a production line [3]

In the case of production lines, the design phase has changed a lot over the years. In addition to the existence of many manual methods for planning production lines [4-6], the increase in the complexity of production processes required the introduction of new methods. One of the most widespread methods is the construction of a digital twin of the production line and conducting experiments to find the appropriate operating parameters.

Table 1 summarizes what the digital twin can be used for in the different life cycle steps of the production line.

Table 1 Lifecycle steps and use cases of the Digital Twin during the lifecycle steps

Lifecycle step	**Use cases for a Digital Twin**
Layout design	Process planning (manufacturing and logistics) Capacity planning Resource planning (number of machines, palettes, AGVs, etc.) Line balancing Cost/investment optimization
Installation and ramp-up	Ramp-up analysis Virtual commissioning
Improvement	Bottleneck analysis System parameter optimization Update of process parameters from real world Energy efficiency optimization
Normal operation	Further optimisation of the system Operational support for the shop floor New product introductions (NPI)
End of life maintenance	Maintenance planning

3 Conceptual framework

The basic purpose of flexible manufacturing systems is to ensure the production of different products within the same system. Flexible production systems can produce products that are even significantly different from each other if their technological steps and needs are similar. Another typical purpose of flexible production systems is to support the customization of products during production [3].

Most flexible manufacturing systems consist of the following 3 main elements [7]:

- Work machines, which can be machining or any other processing machines.
- The material handling system, which, depending on the design, can be conveyor or AGV-based material handling system.
- The control system, whose task is to operate the system in changing conditions, controlling both the working machines and the material handling system.

In terms of layout, 4 main types can be distinguished [7,8], these are as follows:

- In-line layout,
- Loop layout,
- Ladder layout,
- Open-Field layout.

Their schematic diagram is shown in Figure 2.

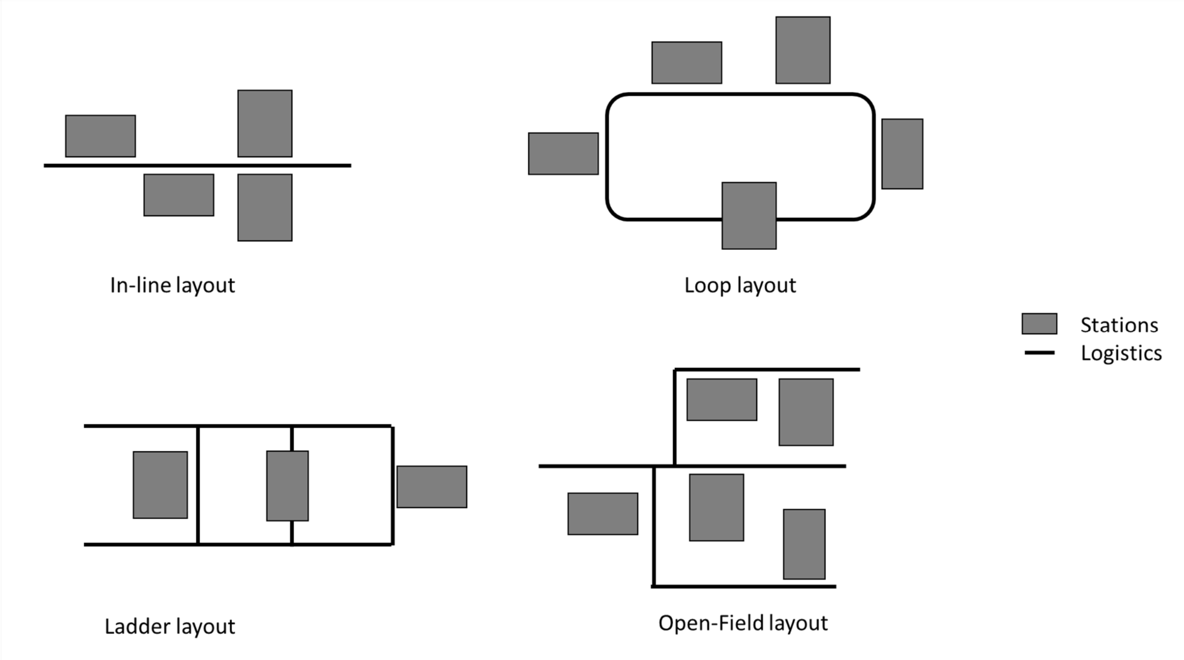


Figure 2 Types of the Flexible Manufacturing Systems [7]

In the case of Loop, Ladder and Open Field layouts, material handling is solved either with conveyor systems or often with AGVs. There are several advantages and disadvantages of AGVs compared to conveyor-based material handling (Table 2)

Table 2 Advantages and disadvantages of using AGVs

Advantages	**Disadvantages**
Flexible material handling	Although the price of the technology is falling, the price of the battery limits further significant price reductions
It helps to make the surrounding production system more flexible	A more advanced IT environment is required for its control
It enables good material flow control	Due to the battery, the environmental impact is higher
The layout they serve is easily to modify	Due to the charging cycle, a complex control system is required for their best utilization
Easily replaceable in case of failure or breakdown	
Easy maintenance	
Flexible and adaptive control can be built around it	

From the table above, most of the disadvantages of AGVs (price, more complex control, etc.) are due to the nature of the battery, so it is worth examining this topic in more depth. Older AGVs mainly use Lithium-ion batteries, which have a lifetime of about 2000 charging cycles [9]. In the modern AGVs Lithium-titanium (LTO) batteries are typically used [10]. These batteries have a very serious life cycle, they can withstand approximately 20,000 charge cycles [11,12].

Currently, there is relatively little long-term experience with AGV battery degradation, so we had to rely on the (sometimes admittedly optimistic) specifications provided by manufacturers. However, it is clear [6] that after approximately 4,000 charging cycles these batteries can already suffer a significant capacity reduction of more than 15% (Figure 3).

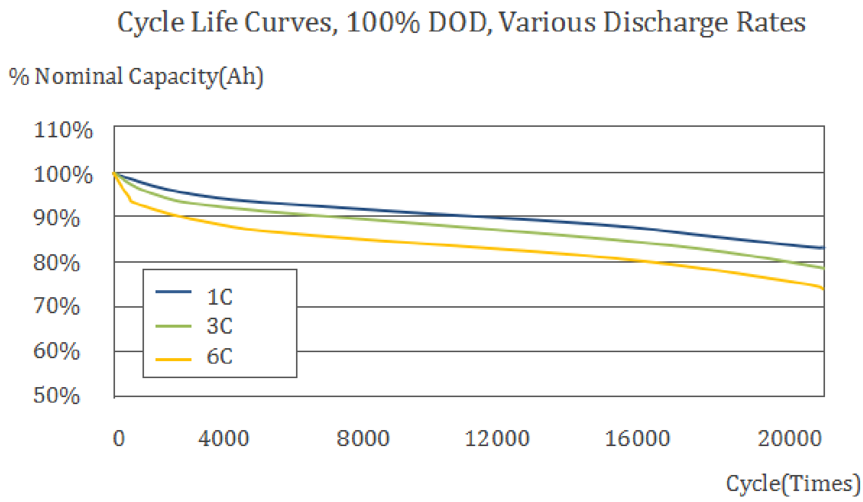


Figure 3 Degradation of the LTO batteries over the time [10,13]

Apart from degradation there are several additional factors that affect the lifetime and behaviour of battery powered AGVs [13]:

- Operating temperature – this can reduce capacity by 5-10% in extreme cases [13],
- Number of charging cycles,
- Depth of Discharge (DoD),
- Storage time,
- Number of starts and stops during the operation,
- Weight of the transferred load.

The influencing effect of these can be determined mainly by experimentation and measurement.

In the case of AGVs, two main methods are used for recharging, battery swap and battery charge. In a production environment, the latter can be implemented and handled more simply, so we will deal with this in the following.

An average AGV can operate for 4 hours with one charge, followed by 1-2 hours of charging, so in the case of a three-shift production, it goes through 4 charging cycles per day, counting the minimum typical 200 working days, this is 800 cycles per year. This also means that approx. After 5 years, only approximately 90% of its original capacity can be used, and after another 5 years, this value may drop to 80-85%. In extreme cases (for example, AGVs which are carrying car bodies) the operational time between two charges is less than 2 hours, the charging time is 1 hour. In this case, for an AGV which works in 3 shifts every day, it has 8 charging cycles. It means that the battery degradation will have significant effect on the performance after just 2 years of usage.

4 Research methodology

During the research, we used a discrete event simulation system for the concept building and the analysis of the results [14,15]. Discrete event simulation is a reliable tool to analyse systems, where the eclapsed time is a critial factor [16,17]. We selected the Siemens Plant Simulation system to prepare the analyses. This discrete event simulation software is widely used by manufacturing companies [18,19]. The system also has the advantage of supporting the modelling of AGVs, and even has built-in functions to manage AGVs' battery-related characteristics and battery charging. Plant Simulation handles the following battery characteristics for AGVs [20] (Table 3) and collects the following statistical values from the simulation (Table 4).

Table 3 Battery related simulation attributes for AGVs

Attribute	Description
Charge (Ah)	The active charge of the battery (0 < Charge < Capacity)
Basic consumption (A)	Basic consumption no matter if the AGV is moving or not
Driving consumption (A)	Addition to the Basic consumption if the AGV drives
Capacity (Ah)	The capacity of the battery
Reserve (Ah)	Below this value the battery needs to be recharged, system calls the charge control
Charge current (A)	The value of the charging current

Table 4 Battery related statistical values collected by the simulation model

Attribute	Description
Number of Charges	Number of times the battery was charged
Portion	Portion of its life-span during which the battery of the AGV was charging

During the modelling, AGVs can be either fixed-track or free-moving. Among the FMS layout types, the Loop and Ladder layouts usually have fixed tracks, while the Open field design uses freely moving AGVs.

The AGV energy consumption is can be calculated as follows (1):

$$Energy\ consumprion = Basic\ Consumption + Driving\ Consumption \quad (1)$$

where the driving consumption could depend on several factors, like the speed, the weight of the transferred part or the environmental temperature as we discussed before. These values can be determined by measurement or can be extracted from the logs of the control software of many AGVs.

5 Experimental analysis and presentation of the results

To analyse the previously discussed problem area, we used an example from the automotive industry. Figure 4 shows the model and its layout. It is a flexible production system with a loop layout, with robotic welding and automatic assembly stations. The products are car body parts. The line is designed for a life cycle of at least 10 years. The factory works in 3 shifts in 7 days.

During the test, we are now testing the system for one product type, assuming that:

- The production times of the products at the stations are very similar.
- There is no setup between products at the stations (except the test station).

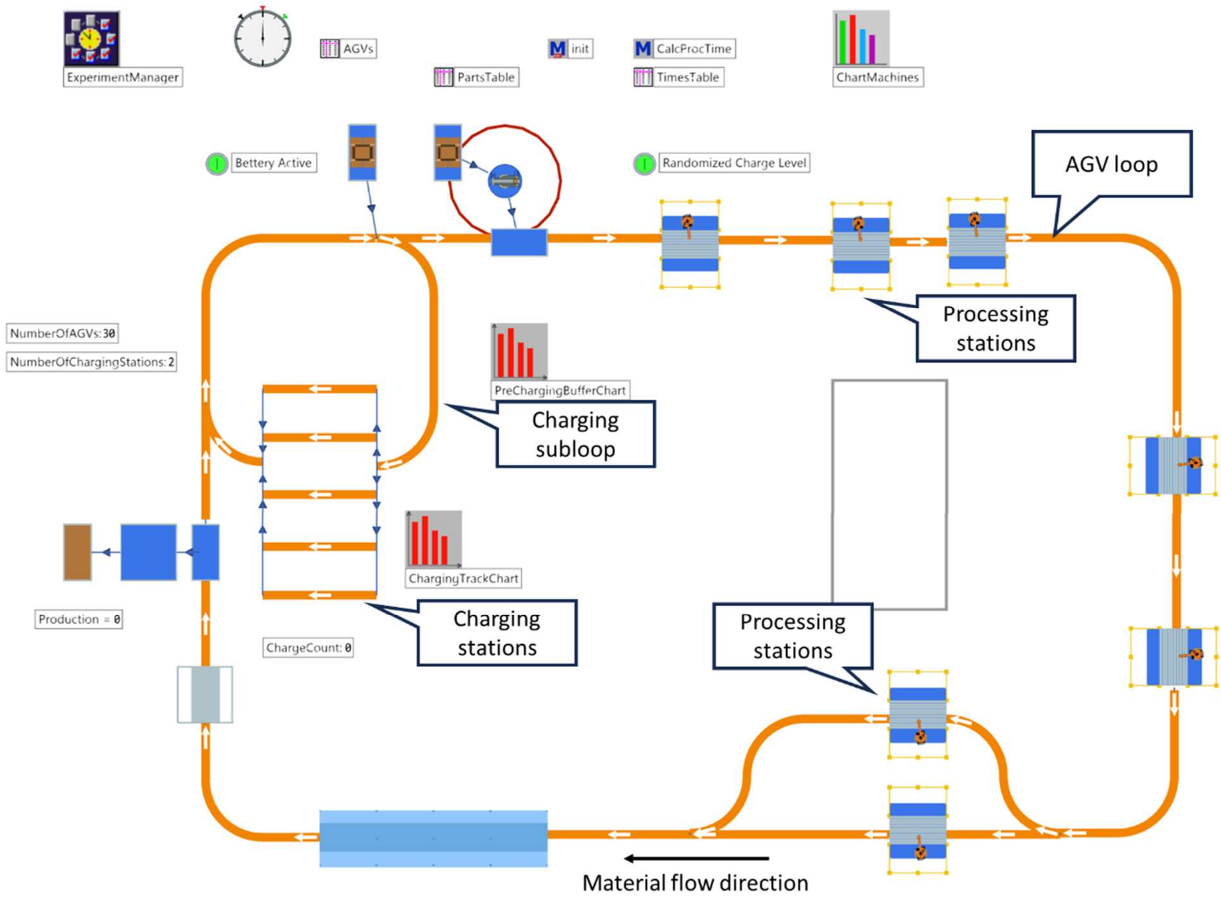


Figure 4 The layout of the experimental model

In the example we use SHARP TYPE B AGVs in the simulation model [21] with load capacity of 200 kg, 60 m/min (1 m/s) maximum speed, and 2 series of 42 Ah batteries. The assumed hours of operation for this AGVs are 8 hours, so they can theoretically serve a whole shift without the need of recharge.

During the modelling, we wanted to visualize the battery level, hence we extended the AGV object with the colouring of the loading plate depending on the battery level (Figure 5).

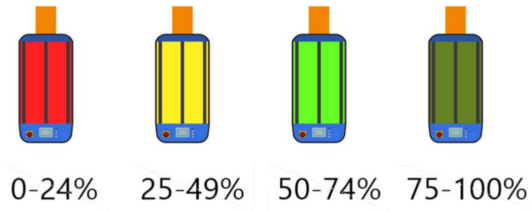


Figure 5 Colour coding of the AGVs based on the available battery capacity

As a result, the charge status of each AGV is clearly visible in the model (Figure 6), making the analysis and understanding of the digital twin easier.

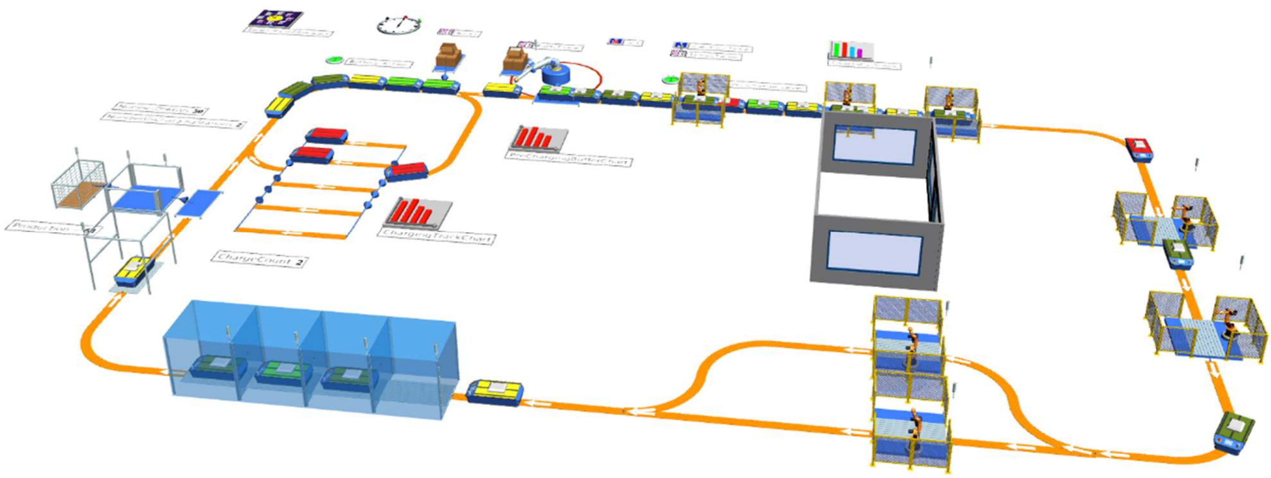


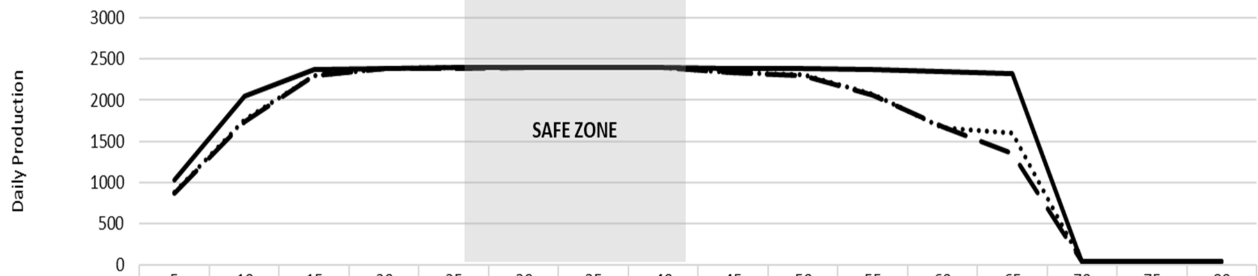
Figure 6 Model run with the coloured AGV battery states

We developed a 3-step planning process for system modelling and analysis (Table 5).

Table 5 Steps for the system planning and analysis

Process Step	**Comment**
1. Calculation of the necessary AGV capacity	Run simulation experiments with full capacity AGVs with unlimited battery
2. Calculations and experiments with the actual AGV fleet	Finding design issues, calculation of the number of the necessary charging stations. This step also gives information for the programming of the AGV fleet control software (normally supplied by the AGV manufacturer)
3. Experiments with the future planned changes of the line, products and AGVs	Could include experiments about the AGV degradation and other parameters which will likely change during the lifecycle of the production area

The purpose of the first experiment is to determine the number of AGV units required continuously in normal operation. In the model this is done in an "ideal" environment, where the AGV battery usage is not simulated. However, all stochastic parameters of the line are included in the study (machine failures, etc.) (Scenario 1). In the second step, the effect of battery degradation and recharging of the AGVs is analysed. This tells how many AGVs are realistically needed on the production line. Here we can also determine how many charging points are required (Scenario 2). And the final, third step is to examine how many AGVs are needed later in the lifecycle of the production line. At that time the degradation of the AGV batteries is significant. In this step the number of required charging stations may also change, as AGVs in worse condition require more frequent charging (Scenario 3).



Number of AGVs	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
Scenario1	1032	2042	2368	2385	2395	2401	2398	2393	2388	2380	2369	2351	2319	34	34	34
Scenario2	880	1760	2299	2377	2391	2396	2399	2394	2334	2314	2075	1661	1596	34	34	34
Scenario3	873	1740	2295	2378	2388	2398	2399	2393	2330	2301	2059	1670	1352	34	34	34

Number of AGVs

Scenario1 Scenario2 Scenario3

Figure 7 The daily throughput depending on the number of AGVs

Based on the graphical representation of the results (Figure 7), the following conclusions can be drawn. Clearly, too few AGVs result in very low productivity, and too many AGVs obstruct each other, so the number of produced units is drastically reduced. This is typical behaviour of all logistics systems where the material handling is managed with pallets or AGVs. In the first case, the number of produced parts decreases due to waiting for, and in the second case, due to blocking of material handling devices.

It can be clearly seen that, by plotting the results of all three cases, the AGV number between 30-40 ensures the maximum number of manufactured pieces in all three cases.

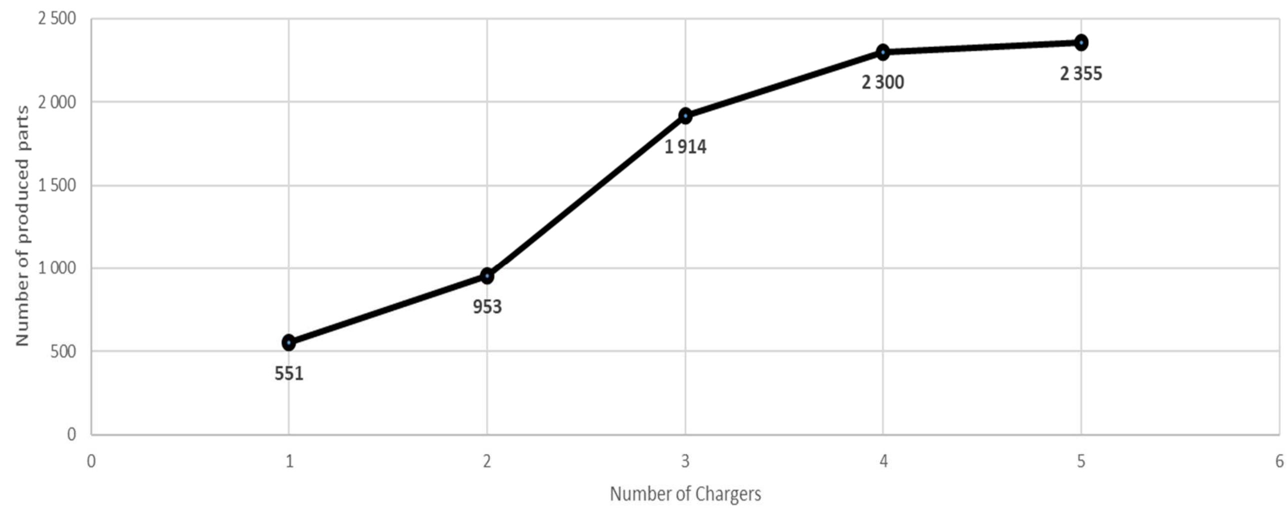


Figure 8 Results of the simulation of the necessary charging station number (AGV number is fixed, 35)

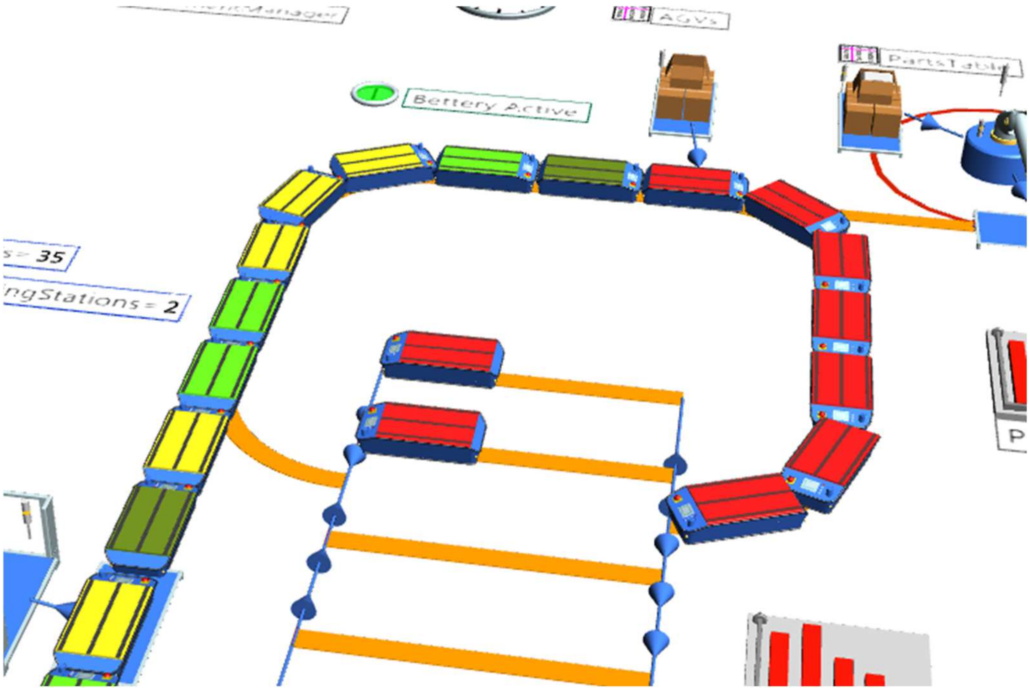


Figure 9 Blocking issues within the charging subloop

Using the above results, a further study was carried out to determine the required number of recharge stations. The result of it is shown in Figure 8. In the case if we have 1, 2 or 3 charging stations, the reason of the low number of produced parts was a layout problem. That is clearly visible in the simulation (Figure 9):

- The AGV charging subloop is congested and this loop is practically blocked, along with the main production circuit. This can be handled by expanding the length of charging subloop in the layout.
- By increasing the size of the charging subloop, another problem arises, that if too many AGVs are waiting in line for charging, it may happen that by the time the AGV gets to the charger, it will run out the power while waiting. This shows how important it is for the AGV to properly set the reserve level at which the AGV already starts towards the charging loop in the branch.

6 Conclusions

Apparently, within the design of flexible production systems, the implementation of material handling tasks with AGVs is a complex problem. The above article showed why it is not enough to simply determine the number of AGV units required to ramp-up the line. The degradation of batteries during the life cycle of the production line and having AGVs with batteries of different capacities in the production process represent a serious control and capacity planning task and challenge. During the research, we developed a simulation framework that is suitable for examining various AGV-based logistics processes and analysing the life cycle of AGVs. The simulation-based digital twin, constantly updated with current data (battery status, etc.), is suitable for providing support in determining the appropriate operating parameters during the operation of the actual production line. Since more and more research is being done on battery life, my future research direction may be a more accurate description of the degradation process in the digital twin. The advantage of simulation in this case will be that any mathematical model can be incorporated into the system. This mathematical model can consider the main AGV degradation parameters, such as the nature of the charging cycles, the operating temperature and the weight of the transported pieces.

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