UNIVERSITY OF TWENTE. | FRAUNHOFER INNOVATION PLATFORM FOR ADVANCED MANUFACTURING

Department of Engineering Technology

Master's thesis (202000249)

Designing and Optimizing a flexible Battery Pack Manufacturing Process Incorporating Cylindrical and Prismatic Cells: Key Factors and Strategies

Yadhukrishnan s2700891 , Mechanical engineering, Design and Manufacturing
committee chair UT :prof.dr.-ing. S. Thiede
Supervisor UT : dr. P. Ghafoorpoor Yazdi
Supervisor FIP : Beumkes, Gijs
External committee : dr.ir. P.K. Chemweno
Date of colloquium : 26th September 2023
Document number : DPM2039

Enschede, September 18, 2023

Abstract

The demand for battery packs, for all categories, like large EVs, and light EVs, is on the rise, and with this, the scale of manufacturing of battery packs has to keep up too. Companies all around the world have invested a significant amount of time and money in developing new technologies regarding safety, efficiency, and high production rates of battery packs. Even though most battery packs are made of cylindrical cells, the demand for packs made out of prismatic cells is also on the rise. Seeing this as an opportunity companies may want to produce both cylindrical and prismatic cell battery packs to capture the market share as much as possible. This paper presents an opportunity to look into the various factors that go into when designing a flexible battery pack production process, where this flexible assembly line can manufacture battery packs that can be made out of any type of cell, cylindrical, prismatic, pouch, etc, including any capacity of these packs

A literature review has been carried out to look into battery packs that are produced in the real world, to understand the process requirements that should be setup in the assembly line. Since the intricate details that go behind the production of battery packs are unknown, certain key process has been identified. Visual components software is used to simulate the effects of varying certain factors to see implications on the production. The key parameter to focus on when designing a process layout for a flexible assembly line has been identified. In this report the application for the battery pack produced is considered to be of an e-bike, the processes and the timing are assumed keeping in mind this use case. Fraunhofer Innovation Platform has provided certain machine and product designs that are used in the simulation. This model will serve as a stepping stone for the creation of a digital twin in the future when the integration of sensor data happens with this model.

Nomenclature

EV	Electric vehicle
BMS	Battery management system
CTP	Cell to pack
CTC	Cell to chassis
CTMTP	cell to module to pack
NiMH	Nickel metal hydride
LiPo	Lithium polymer
Ni-Cd	Nickel cadmium
VCTP	Volumetric Cell to pack ratio
GCTP	gravimetric cell to pack ratio
CATL	Contemporary Amperex Technology Limited
BYD	Build your dreams
IOT	Internet of things
AGV	Automated guided vehicles
TRIZ	Teoriya Resheniya Izobretatelskikh Zadach (theory of inventive problem solving)
CAN	Controller area network
P&P	Pick and place
PLC	Programmable logic controller

Contents

1 Introduction

Ever since the creation of the first electric car in the 1830s, the technology of these machines has tremendously advanced since then. Electric vehicles even though emerged in the early 19th century, became popular only in the 21st century, with advancements in battery technology and Tesla's pivotal role in popularizing electric vehicles[1]. Until recently, ICE-powered vehicles offered long-range, quicker refueling, and were economically a better option as compared to an electric vehicle, but with recent advancements in battery technology, like the introduction of new battery types, the most popular one is the lithium-ion battery, because of its high energy density, low self-discharge rates, fast charging, long cycle life, almost all commercial electric vehicles have lithium-ion batteries now[2][3]. Electric vehicle demand has been increasing over the years, thanks to the improvement in technology and heavy support from the government. Various incentives, grants, and tax breaks were initiated by various governments to boost the development and production of electric vehicles[4]. With the government's aid, charging station infrastructure has also been developed concerning the increase in electric vehicles on the road. As seen from fig 1 in 2022, 13-14% of the total car sales are electric, as compared to 9% in 2021 and less than 5% in 2020. 3.3 million EVs were sold in China in 2021 which was more than all other countries combined.

The supply chain of lithium-ion batteries is primarily centered in China, which owns

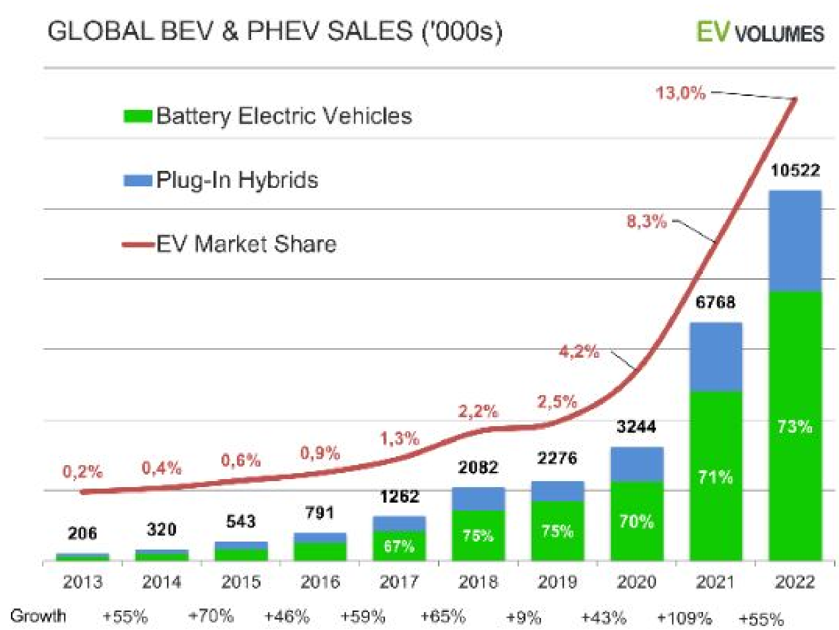

Figure 1: Global EV sales [5]

75 % of the market share in the production of these batteries and also owns 70 % of the production capacity of cathodes and 85 % of anodes. US and Europe are stepping up their production of EV batteries significantly but it's nowhere near the scale at which

the Chinese produce it[6]. Even the EV category of e-bike battery pack has seen a tremendous amount of growth, with a current market size of 11.24 billion dollars and it is expected to grow to a 21 billion dollar market by 2028[7].

During the pandemic, there was a huge spike in demand for EVs across the world which put a lot of pressure on the supply chain of several critical components of an electric vehicle, primarily raw materials like cobalt, lithium, and nickel. This situation was further exacerbated by the Russia-Ukraine war[8]. In May 2022, lithium prices increased to more than 7 times the prices in 2021 and Russia was a key supplier of high-purity nickel. With its increased cost, companies were struggling to meet the market demands[9]. Even after all these troubles, the electric vehicle markets are seeing exponential growth with total sales exceeding 10 million in 2022. These exceptional sales are expected to continue through 2023 as well[6].

As seen from 2 the demand for Lithium-ion cells globally is expected to rise significantly in this decade, from a requirement of 700GWh in 2022 to 4.7TWh by 2030. EV

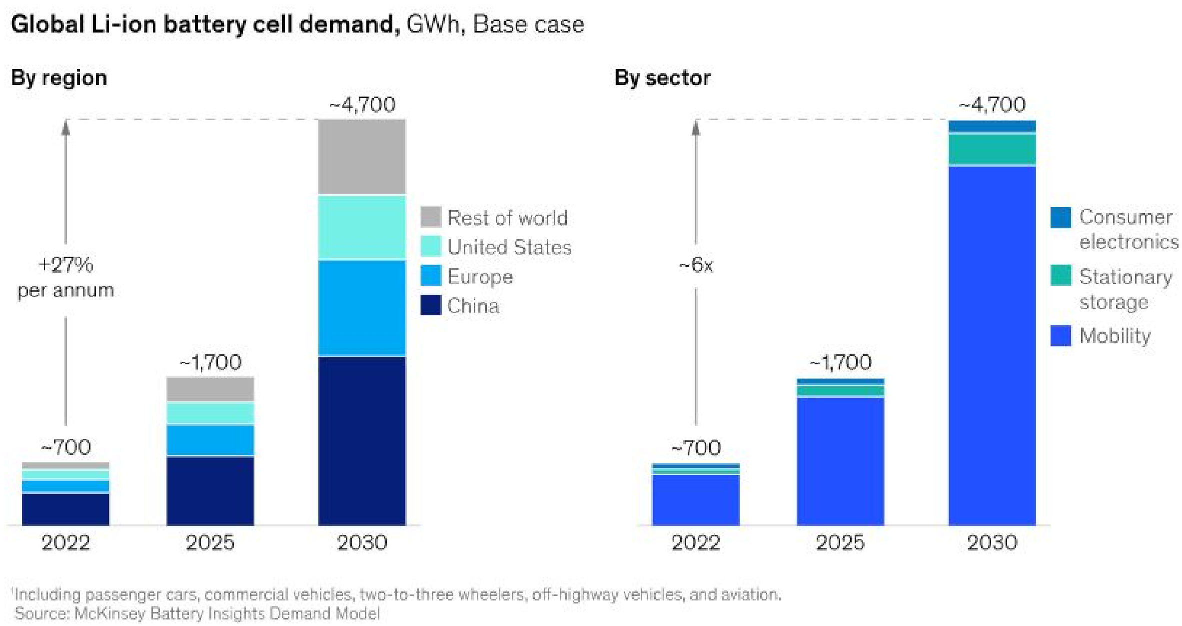

Figure 2: Present and forecast of lithium demand[6]

companies have to develop new technologies, and better production methods to meet the market demands. However recent reports from companies like TESLA suggest that they are not able to ramp up their production rate to meet the rising demand for electric vehicles. When looking into the challenges of a company manufacturing electric vehicles, it reveals that one of the biggest bottlenecks in the manufacturing process is the assembly of battery packs[10]. This process involves a variety of automated methods and manual processes that are unable to handle the increasing demands. Therefore careful planning and new technologies have to be made so that battery packs can be manufactured to ensure the market demand is met.

2 Research goals

Battery packs for light electric vehicles like e-bikes, mobile workshops, and small commercial vehicles are smaller in size as compared to a standard battery pack of a commercial car the Tesla Model S. Production of these packs requires less time than big battery packs. Let's consider that a company has to set up a factory floor to produce a variety of battery packs, Some may include packs for e-bikes, some for a mobile workshop, etc., which can also be made by using cylindrical cells, prismatic cells, or pouch cells. With this many selections of outputs, there is a need to design a flexible production facility. In this paper, an investigation of the current battery pack manufacturing process was carried out to design a flexible pack assembly process, where the pack can be made out of cylindrical or prismatic cells, and also to investigate factors influencing process design decisions. Several inputs were taken from the Fraunhofer innovation platform for advanced manufacturing at the University of Twente.

3 Classification of cells

The source of energy for an electric car is the battery packs, which consist of hundreds, sometimes thousands of individual cells packed together. Several types of batteries are used today, each with its own set of advantages and disadvantages like lead acid, nickel metal hydride, nickel cadmium, and lithium polymer which are used in various applications[11].[12].
Lithium-ion batteries because of their high energy density and high power-to-weight ratio, serve as an ideal candidate for EVs. A lithium-ion battery does not have a memory effect, which means it does not lose its maximum energy capacity because of repeated charging and discharging, which is not the case for batteries like Ni-Cd, NiMH, and lead acid batteries[12]. Lithium-ion batteries can develop high temperatures during operations which can reduce their performance and decrease safety[11].

3.1 Different structures of lithium-ion cells

Battery cells come in different shapes as shown in fig 3, primarily cylindrical and prismatic shape, The prismatic cell can further be classified into another shape depending on the housing stability, pouch cell.[13]

3.1.1 Cylindrical cells

As the name suggests, have tubular shapes. Certain cell types like 18650 (18mm diameter, 65mm length), 21700 (21 mm diameter, 70 mm length) and 4680 (46mm diameter and 80mm length) are some of the industry standard cell types used. For example, Tesla uses 21700 cells in their model 3 and model Y cars[14]. Cylindrical cells are the most widely used cell type in the EV market which includes e-bikes to cars. As mentioned in the previous section, because of its robust construction which reduces the chances of physical damage and compression, high heat dissipation rate, which is critical for efficient thermal management and increasing safety, these cells are widely used for manufacturing battery packs for EVs. There are certain limitations of this type of cell as well, like it has low energy density and because of its shape, it may be less space efficient as compared to other shapes.[15]

3.1.2 Prismatic cells

Prismatic cells on the other hand are rectangular or square shapes depending on the application. These are generally used in laptops, tablets, and some electric vehicles. Prismatic cells offer certain advantages as compared to cylindrical cells, like it is space efficient, it has a higher energy density and there is plenty of opportunity for customization of its shape. Prismatic cells, unfortunately, do present its own disadvantages[16]. Its heat dissipation can be slightly less effective as compared to the cylindrical shapes because of its shapes, making thermal management of the system less efficient which can impact the safety of the pack, and the construction of prismatic cells is a complicated process compared to the cylindrical cells because of its need for different sealing techniques and specialized casing.[17]

3.1.3 Pouch cells

Pouch cells are similar to prismatic cells in shape, but the structure is made out of a flexible and lightweight packaging material. It provides the same benefits as a prismatic cell, of being highly flexible, higher energy density, but it also has poor thermal management because of low heat dissipation, and because of its packaging being flexible and light, it is prone to damage from physical pressure which can decrease the safety of the system.[18]

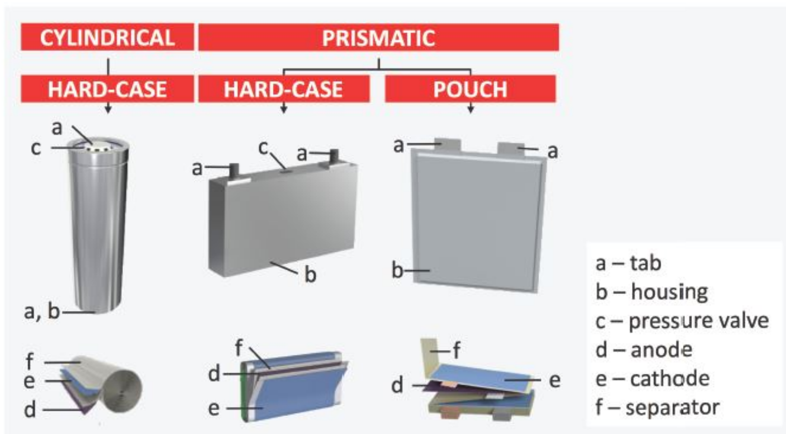

Figure 3: Different structure of cells [17]

4 Battery pack assembly

4.1 Essential components in battery pack

A battery pack is a collection of modules/cells that are interconnected in series, parallel, or a combination of both to achieve the desired voltage and capacity specifications to provide electrical energy to electric systems, which may be an electric vehicle or an energy storage system. To manufacture a battery pack, there is a variety of components that should be assembled. Depending on the application, like a battery pack for a car, e-bike, energy storage solution, etc. some components may vary but there are a few components that are the key elements of the battery packs. It is as follows

- Battery cells: Cells are the main source of energy for EVs, which come in 3 shapes, cylindrical, prismatic, or pouch. The cell chemistry can vary based on company choices like lithium ion, nickel metal hydride, etc. These cells can be further put together to form modules.
- Battery management system (BMS): It a one of the most critical components of a battery pack whose main function includes voltage monitoring, current monitoring, temperature monitoring, Cell balancing, state of charge(SoC) determination, etc. These are key performance factors that are monitored by BMS to ensure the utmost safety and to improve the performance of the packs[11]
- Cell interconnects: It is a conductive material used to connect cells in the pack
- Thermal management system: It is a system whose purpose is to regulate temperature within the pack. It is done by using heat sinks, cooling fans, or liquid cooling systems. As a battery pack's temperature fluctuates because of charging, discharging, or usage of the vehicle, the heat generated has to be cooled to ensure the high performance of the packs, maximizing the lifespan of cells and ensuring it is safe to use.
- Connectors, switches, harness, and other electronic components
- protective structures: This can include protection circuitry which consists of devices like fuses, switches, and emergency controls to shut down the battery packs if any fault happens, Support structures, insulation, and sealing.

4.2 Battery Module

A module is a collection of cells interconnected in series, parallel, or a combination of both to achieve desired voltage and capacity. When multiple modules are interconnected, the produced structure is a battery pack. This is a standardized method before manufacturing the pack[19][20]. Producing modules for a pack gives many advantages, increased overall strength, increased heat dissipation, and easy maintenance. The Fraunhofer innovation platform has defined the intended design of the module made out of cylindrical cells as shown in fig4. It has 3 main elements, One being the cell, the cell holders, and conductor templates. The cell holders are designed in such a way that they can be further attached to other modules to form a complete pack as shown in fig 5. Creating a module like this will eliminate the adhesive dispensing process, unlike a Tesla Model Y battery pack where the cells have an adhesive bonding between them. Recycling, repairing, and re-manufacturing these kinds (Tesla model Y type) of packs becomes very difficult. The module type that's given by the Fraunhofer innovation platform provides the flexibility to produce any variety of battery packs that can serve various functions. For the production of the prismatic cell module, since the exact specifications of the prismatic cells are not provided by the Fraunhofer innovation platform, the structure and specs of prismatic cells are assumed.

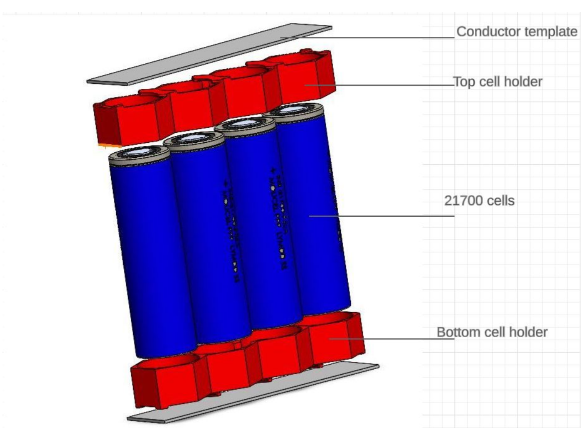

Figure 4: Cell module exploded view

Figure 5: Combination of multiple modules form a pack

5 Current methods for battery pack production

As battery pack production of every company is different in terms of the machines used, process times, etc., the process in which the pack is produced in principle is the same. Tesla is the largest EV producer in the world. Although the intricate details of the production process are a company secret, the overview of the production process is well known, which is as follows

- Cells are passed through a sorting process wherein these cells are tested for voltage and quality requirements. They must have uniform voltage and size with no defects. This uniformity provides higher performance and longer life for the battery packs. The machine for this sorting process can be specialized based on the company's requirements The cells which do not meet the required criteria are rejected. The ones with less voltage are sent to be charged and the others with defects are completely removed from the process.[15]

- The approved cells are passed to the module production process. The cells are placed into bottom inserts individually. The inserts are designed in such a way that the cells are evenly distributed. This will help in increasing the cooling effect and prevent the cells from accidentally touching each other. This uniform spacing of the cells helps increase the performance of the modules. The cells are oriented in such a way that the desired polarities are facing up. If this is not done, then there will be uneven voltage in the module. The schematic of this module is shown in fig 6

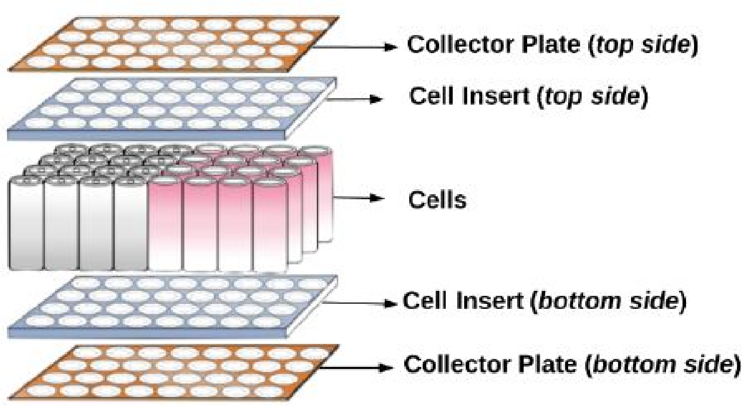

Figure 6: Battery module components [15]

- The top cell insert is placed on this. After the inserts are all fixed, an adhesive like Loctite is injected into the space between the cells and the inserts. This provides a secure bond to the structure.

- After the adhesive dispensing process, a collector plate is placed on top of the inserts aligning with the cells. Pressure is applied to the plate to ensure proper bonding between the collector plates and the top inserts. The process of placing inserts, collector plate, and injecting adhesive is repeated after flipping the module (to work on the bottom surface)[15]

- This finished product is then taken to a wire bonding machine where aluminum fuse wire is used to bond the conductor template and the cells. Now the module production is complete.

- The next steps is placing a number of these modules based on the EV requirements on a housing structure and manually assembling the other components like the BMS, cooling systems, and other electrical and electronic components

5.1 Developments in pack production

The standard production process for battery pack involves cell-to-module-to-pack flow(CTMTP), where cells are manufactured separately, assembled the cells to form modules, and assemble the modules to form the final battery pack, as shown in fig **??**

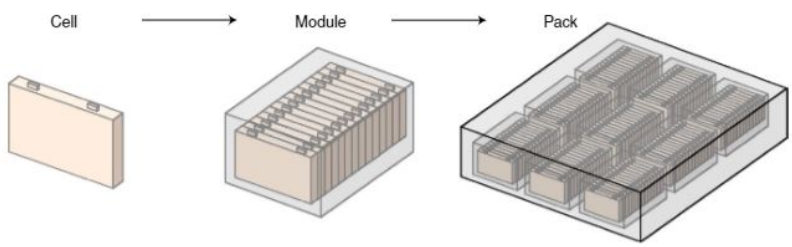

Figure 7: Conventional flow of production of battery pack

The disadvantage of manufacturing a battery pack using CTMTP is the use of additional components to form the modules and the extra processes it takes. Because of this, there is an increased processing time for the production of battery packs and extra weight because of those extra added materials, which can include additional support structures, additional electronic components, etc. New concepts such as cell-to-pack (CTP), cell-to-stack (CTS), or cell-to-chassis (CTC) are developed to decrease production times, simplify the production process and reduce the cost of assembly[21]. looking into the gravimetric CTP ratio(GCTP) (ratio of specific energy at the pack level to cell level)of most Ev's they are around 0.55-0.65, which means 35-45 % of the pack's weight is used by inactive components elements like cables, BMS, cooling systems, support structures etc, and if volumetric efficiency(VCTP) of packs are looked into, then for most commercial EV's they are less than 0.4[21]. To improve these values and make the pack more efficient in terms of space and mass, companies like CATL and BYD [22]have developed cell-to-pack technology where the module process is entirely removed.

Cells are directly integrated into the pack structure in CTP. For example in a blade battery pack from BYD, all the module-related parts have been stripped off. The cells themselves act as a support structure, so all the components that were used for support structures in CTMTP are not present by which the blade batter pack was able to achieve a GCTP of 0.85 and VCTP of 0.62. Fig 8 shows the difference between a conventional battery pack with multiple modules and the blade battery pack of BYD with CTP technology, where the cells are placed in such a way that they act as a support structure. Cell-to-chassis technology (CTC) is where the cells are directly integrated

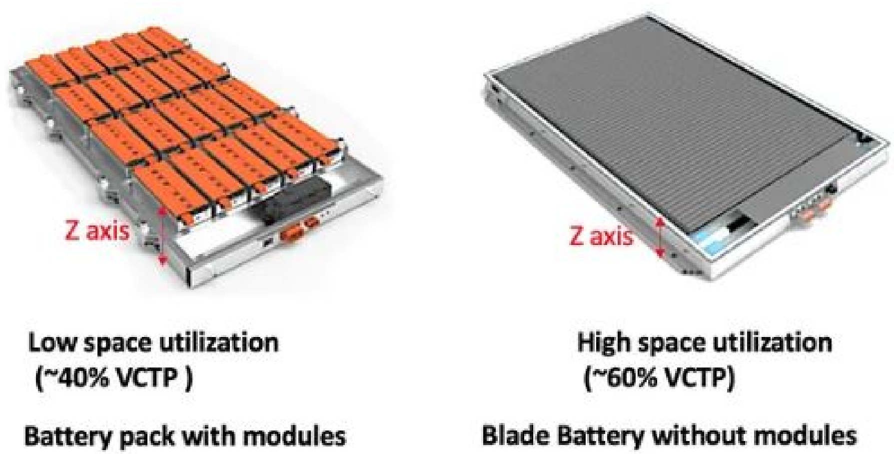

Figure 8: image on the left is a pack with multiple modules and image on the right is the blade battery pack by BYD[23].

into the chassis and underbody of the car as shown in fig9. This will eliminate the requirement for separate battery pack for the car, In such a CTC setup, the cells will provide structural support and the chassis will provide protection to the cells.

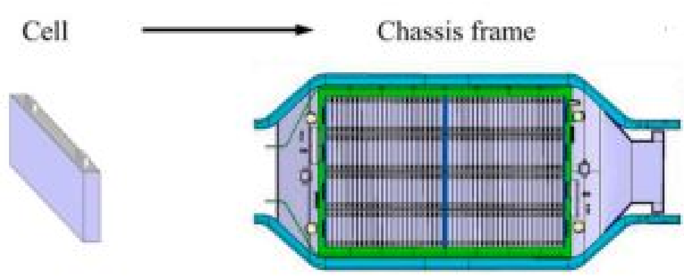

Figure 9: illustration of cell to chassis technology[24]

5.2 Processes and tools involved in battery pack production

5.2.1 Cells sorting

Cell sorting is the process where cells are separated/sorted from a batch of cells based on some quantitative criteria like capacity, voltages, etc. For a battery to work optimally, one of the most important factors is that each cell should have the same capacity and voltage. Variations in these values between cells will make the pack less consistent in its operations, which will adversely affect the discharge performance of the battery packs. Throughout its life cycle, it will deteriorate even further. A cell sorter works in the following way.

- The cells are fed into the machines using a conveyor belt or any other conveying equipment.
- The machine will measure factors like voltage, current, capacity etc. for each cell. The type of measurements that need to be checked can be varied using an onboard panel that controls this.
- The measured data is then compared to preset values that will determine the grade and category of the battery
- After this the sorting process happens where, based on the preset classifications, the ones who do not meet this criterion will be separated from the pile of cells whose measurement data coincides with the preset values.
- These sorted cells can be transported to their next process via any transport solutions like AGVs, conveyors, etc.

For example, looking at a cell sorter machine like WinACK WA-AS-9S cells sorter shown in fig 10, it has a maximum sorting capacity of 5000 cells/hour. There are multiple products like this with various production capacities like 3000/hr, 4000/hr shown in table 1, etc. Depending on the requirements and budget, selection can be done on what kind of cell sorting machine to use. This kind of variation can be seen with prismatic cell sorting machines, albeit not as efficient as a cylindrical cell sorting machine. Two cell sorting machines were considered to understand the differences in sorting speeds.

specification	Xiamen LITh-FN-5	TOB-FX-10-T
Power supply	AC220V $\pm 10\% 50Hz$	AC220V $\pm 10\% 50Hz$
Voltage	800W	$\leq 1000W$
Sorting speed	$\geq 80PPM$	$\geq 76PPM$
Productivity	5000pcs/hr	4800pcs/hr
sorting channels	5	10

Table 1: 21700 battery cell sorter machine specs[25]

Unfortunately, there are no Off-shelf machines that sort both cylindrical and prismatic cells. This type of machine should be custom-built. Since the operating principle

Figure 10: WinACK cell sorting machine [25]

is the same as mentioned above, for a custom-built machine the main focus should be on the feed system that can handle both these cell types. These custom-built cell sorter machines have high precision, high consistency, good reliability, high productivity, other sorting options, etc.

5.2.2 Transport systems

Transport solutions are those tools that are required to transport products from one location to another. This can be between workstations, storage facilities, etc. Transport solutions may include AGV, conveyors, tracks, humans, etc.
Automated guided vehicles(AGVs) are autonomous mobile robots that follow a pre-programmed route or a specific pathway which can be defined by marking on the floor. For example, OTTO 100 is an AGV with specifications listed in table 2

Max capacity	150 (including payload attachments and carts, if any)
max speed	2m/s
Max docking speed	0.3m/s
Integrated lift	62mm
Max turning radius	1.25rad/s

Table 2: OTTO 100 specifications[26]

Transport between stations can be done using a conveyor or a track system. In industries, the standard practice is to use traditional conveyor belt systems to transport

Figure 11: OTTO 100 AGV[26]

products from one station to another. There are other track-based transport systems like Montractec track system which is ideal for maximum flexibility in the production processes. Depending on how flexible the assembly line has to be, transport solutions like that of contractor's rail system can be looked into. The Montratec rail system is a smart transport system that utilizes a shuttle to transport products, and the shuttle itself will be on a rail as shown in fig12.

Figure 12: Montratec shuttle [27]

The are various elements of the rail system, like track switches, track curves, and incline tracks examples of which can be seen in fig13, which helps in routing the products to its desired location. The whole flow of components will be controlled by Montratec controllers. The whole system is autonomously controlled using the master controller.

Figure 13: Various rail system tools for routing of components[27]

5.2.3 Welding systems

Welding is required to establish strong and reliable connections between each cell. Each cell has to be connected in series, parallel or a mixture of both to achieve the desired voltage and capacity. The welding material is very thin on the surface of the cells which ensures low-resistance electrical connections. These weld materials can also help in improving heat dissipation as these welds will be an efficient path for heat transfer to occur between the cell and the external environment. There a various joining techniques as shown in table 3 used for welding of cells with their own set of advantages and disadvantages.

Figure 14: Laser welding machine HY-4000w with max welding speed of 500m/s

Id	Joining technology	Advantages	Disadvantages	Issues and concerns
1	Resistane spot welding	Fast process, Low cost, good quality control, easy automation	Difficult for highly conductive or dissimilar materials	Difficult to produce large joints, joining of more than 2 layers
2	Ultrasonic welding	Fast process, high strength and low resistance, low energy consumption, able to join dissimilar materials	only suitable for pouch cells, slow joining	Access of anvil and sonotrode need to be well designed
3	Micro-TIG welding	Low cost, high joint strength, low resistance, able to join dissimilar materials, easy automation	High thermal input and HAZ, porosity	Difficult to join aluminum to steel
4	Ultrasonic wedge bonding	Fast process, able to join dissimilar materials, low energy consumption and easy automation	Only only suitable for small wires, low wire and joint strength	clamping of the batteries in critical
5	Soldering	Can join dissimilar materials, widespread use in electronics industry	High heat, slow process	Joining strenght
6	Laser welding	High speed, less thermal input, non-contact process, easy automation	high initial cost, additional shielding systems may be required	Need good joint fit-up, high reflective materials
7	Magnetic pulse welding	Solid state process, able to join dissimilar materials, high joint strength, dissimilar materials	Potential large distortion, rigid support required	Possibility of eddy currents passing through the cells
8	Micro-clinching	Cold process, no additional part, clean process, able to join dissimilar materials	Only suitable for pouch cells, 2-sided access required, slow joining	Loosening under vibrations, moisture ingress
9	Mechanical assembly	Easy dismounting and recycling, easy repair	additional weight, high resistance	Potential mechanical damage and go loose

Table 3: Various Joining processes[28]

In laser welding, the heat required for joining is produced by focusing a laser beam to create localized heating which will join the parts. As the laser spot can be extremely localized with high energy concentration, higher weld speed can be achieved, and because these beams are narrow, the heat-affected zone is extremely small, which increases the safety of the process as the materials inside these cells are heat sensitive. An example of a laser welding machine can be seen in fig14

A laser welding system is often preferred for welding lithium-ion cells because of its advantages mentioned in table3. Since there are 2 types of components with different dimensions and shapes, the platform for the welding machine should be customized in such a way that it can accommodate both modules of cylindrical cells and prismatic cells [29].

5.2.4 Manual work stations

Some of the processes involved in battery pack assembly have heavy use of manual work. Processes like wiring, electronics assembly, and final testing have a high involvement of manual work. This is because the intricacies involved in doing such processes require innovative robotic systems which are often expensive. One of the processes in manual stations is testing the battery packs. The testing happens at 2 levels

- Module level: This test generally involves charging and discharging the module to check whether there is any failure on the electrical connections. An additional test to check whether the cells are balanced, voltage requirements are met and certain electronic components can also be tested[30].
- Pack level: This test is typically done in the last stage of the full pack assembly process. After the packs are hermetically sealed to prevent foreign materials from contaminating the cells inside, several tests are done to ensure the battery pack is in its optimum condition. This may involve performance evaluation of safety systems, BMS systems, other hardware, etc. After these tests the pack can also undergo additional testing to simulate packs working in real-life scenarios, for example, the pack can be run on a specific driving profile cycle to check the impact of these cycles on the performance of the battery pack[30]

Some common tests that are run on battery packs that are industry standard are as follows:

- Performance cycling and stress Tests: In these tests, the battery packs undergo charging and discharging cycles which simulate real-world conditions. This may include driving profiles, flight profiles, or grid cycles. A life cycle test is conducted over a short period to project the failure rate of the battery pack. Stress tests are mechanical tests conducted to validate whether the battery pack can withstand harsh conditions like high vibrations to extreme temperatures.
- Reference Performance tests: This test is a combination of multiple tests that is used to determine the impact of combinations of variables on the pack. For example, a pack will have to undergo a reference performance test to evaluate the storage capacity, of a car after it has traveled for 200, 300, 500 km, etc.

- Hardware testing and BMS data validation: BMS testing is the most important test the battery pack has to undergo. BMS communicated with other components in the pack using various protocols like CAN, Modbus, etc. The performance of these protocols has to be tested to make sure the BMS and all other components are working safely, are in sync, and working accurately.
- External components and testing: Mechanical testing of external subcomponents like harnesses, connectors, and support structures has to be tested in simulated real-world scenarios for validation. These tests are critical to ensure the battery pack performs safely in the real world.

5.2.5 Pick and place system

A pick-and-place system can be extremely useful for the automation of processes where components are picked and placed onto something. For example, picking and placing enclosures, electronic components, etc. FIP has provided the structure of the vention system that will be used to pick and place some components to the battery pack. These may involve switches, enclosures, and some electronic components

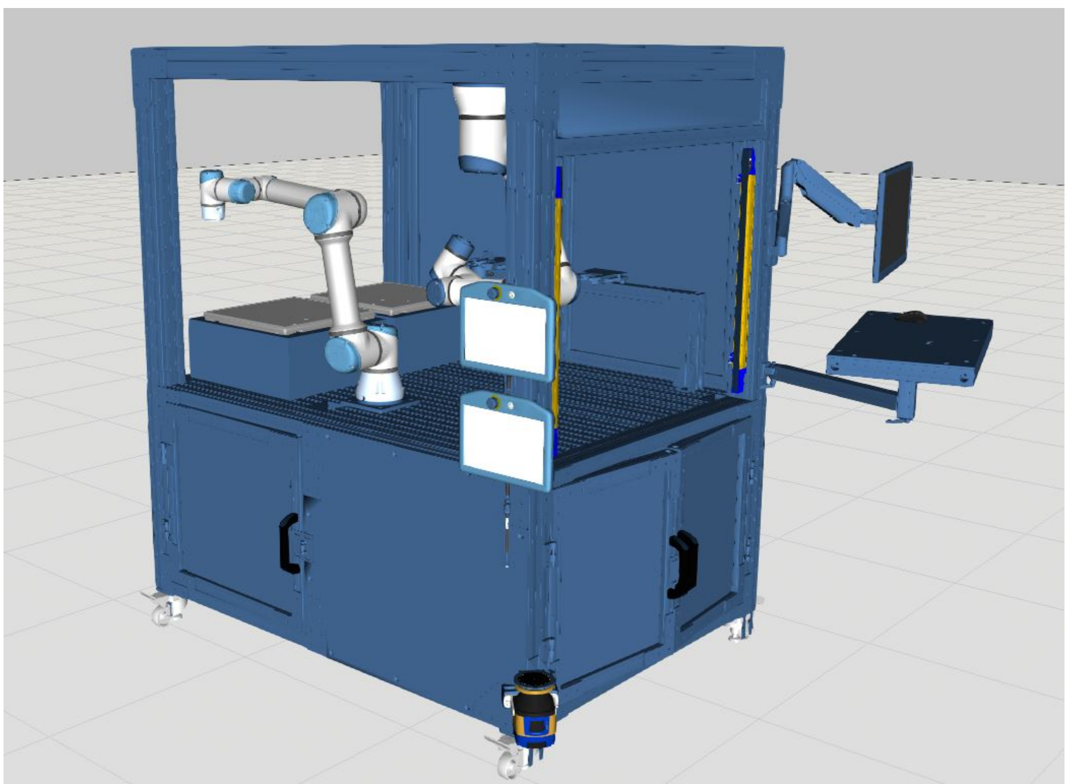

Figure 15: Vention pick and place system

5.3 Factors affecting production

Several factors may affect the production of battery packs. Improvement in these factors can positively impact the production rate of the battery packs.

5.3.1 Automation in the process flow

In the modern age, to meet the market demand, there is a need to produce huge quantities of products, concerning this report, battery packs. Unfortunately, humans are a limitation to this revolution. Some limitations of manual process are as follows:

- Humans cannot work for long hours continuously without taking a break. These breaks and inefficiency in working will lead to lower production rates
- There is a high chance of a human error occurring in the process, which may lead to the breakdown of equipment, halt in production, etc.
- More time and money have to be invested in training humans to work on the assembly line. This training has be to given in regular periods to ensure all workers are well versed with the process.
- Human cooperation is a very important factor that can be overlooked. In a worst-case scenario, if the worker starts a strike or is not so cooperative, the production rates will fall drastically. This issue will never happen with robots/automated systems.

Every manufacturing industry is investing heavily in automating its production process. Although a huge investment initially, the return on investment makes this a worthwhile endeavor [31]. There have been significant developments in industry 4.0 systems. Some notable developments are;

- Integration of various machines to IOT systems, to extract process-related information.
- Big data analytics have been improved to work with large data that you may get from various machines in a production process.
- Cyber security and cyber-physical systems: As industries move more into storing information in the cloud, Adequate security has to be provided to ensure all sensitive information is kept safe
- digital twin setup: It is a digital counterpart of the actual production process layout. It can also have a real-time locating system, which can be further used to analyze the movement of components, humans, and AGV in the factory. This twin setup can also help in reducing time and money for optimization. Optimization of the process can be done on a digital twin to understand the implications of certain parameters on the processes[32].

5.3.2 Worker training and skill enhancement

Even though manufacturing companies are moving towards automation and robotics, there are still some processes that require a human element for now. In assembling a battery pack, certain processes are manual, like wiring of systems, attachment of electronics, and certain mechanical and electrical tests like leak tests. Although these processes can be automated, right now industries are still behind in developing robotics to do these processes. For such a complex process, the workers have to be trained to do such tasks efficiently. This type of training takes time and money, which is a recurring expense, as such training sessions have to be conducted periodically.

5.3.3 Production planning and scheduling

Production of products should be planned. Concerning this report, if the goal is to produce 20 packs made of cylindrical cells and 20 packs made of prismatic cells tomorrow, then the planning has to be done at least a day ahead. This is done so that proper routes can be selected for certain components if the flow is via an AGV or conveyors, the number of workers assigned on certain stations could change based on the planned production rates, etc.[33]

5.3.4 Production line layout

For a given layout the flow of components might not be the most efficient one. In one layout the total traveled distance for a component might be 10meter and for another, it may be 20 meters. The optimization of the layout should be done in such a way that will reduce bottlenecks on the line, increase output, higher machine utilization, etc.

5.3.5 Quality and Testing

In a battery pack assembly process, a significant portion of the total process time is consumed by inspection and testing of the battery pack. New methods and technologies have to be developed to decrease the time required in such stations.

5.3.6 Logistics

Efficient routes have to be set between each workstation, workstations to storage, and vice versa. The routes should be based on the least amount of distance required to reach a location, whether it is a storage section or a workstation.

5.3.7 Maintenance

All the workstations, testing equipment, and transport systems should undergo periodic maintenance. This is to ensure all the equipment is working in good condition because any failure in this equipment might lead to the process being shut down. Adequate redundancies have to be provided for these equipment to ensure a smooth process flow.

5.4 Proposed battery pack system and layout for assembly

Fraunhofer innovation platform for advanced manufacturing at University of Twente is going to set up a production line to assemble battery packs for various applications. One of the applications is e-bike battery packs as shown in fig 16

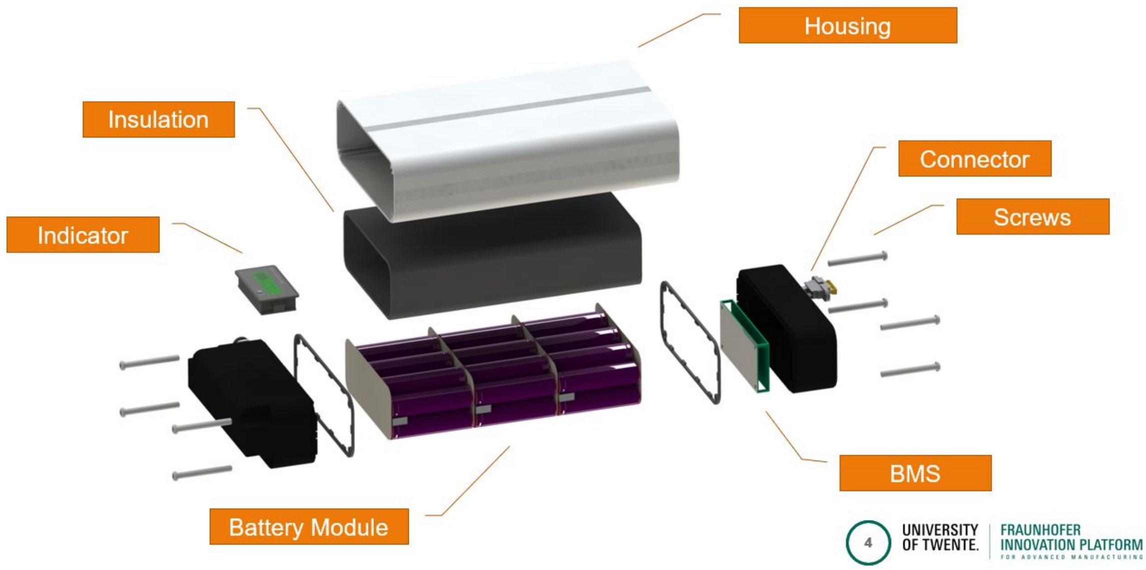

Figure 16: FIP battery pack

5.4.1 layout specifications

FIP has laid out certain aspects of the production process that will be used for further modeling and simulation. The production floor is split up into 3 sections which will be named cell 1, cell 2, and cell 3. Each cell on the factory floor is designated to do certain tasks.

Cell 1 is designated to do cell sorting, cell 2 is designated to perform module production, and cell 3 is designated to assemble the final battery pack. The general overview of the factory floor can be seen in Fig 17 These individual cells can be further explained:

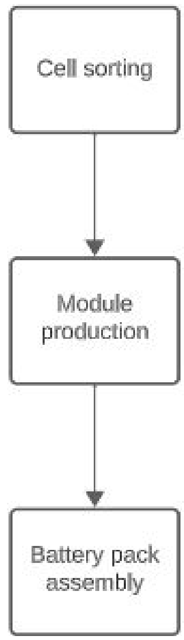

Figure 17: General work flow

- Cell-1: As shown in fig 18 this is the station where cell sorting takes place. A tray of cylindrical or prismatic cells is passed through the machine and placed at cell-1 through conveyor belts which are then checked for voltage and charge. A process node is placed inside the machine setup to simulate the sorting process. There are 3 output points for cell 1. The sorted cells are passed to one output, and the defected/uncharged cells are directed to output 1 and 2 as shown in fig 18. Output 1 and output 2 receive uncharged cells and defected cells which will be transported to a storage section via an AGV. The cell tray which is optimum for module production is then transported to cell 2 where the module is produced

- Cell-2: As shown in fig 19 this station contains all the required processes to produce the modules. There are 5 inputs to cell 2, one input is from cell 1, and the other 4 inputs are for the infeed of top and bottom inserts, conductor templates, and fasteners. All these processes are carried out in cell-2 and later transported to cell-3 via an AGV

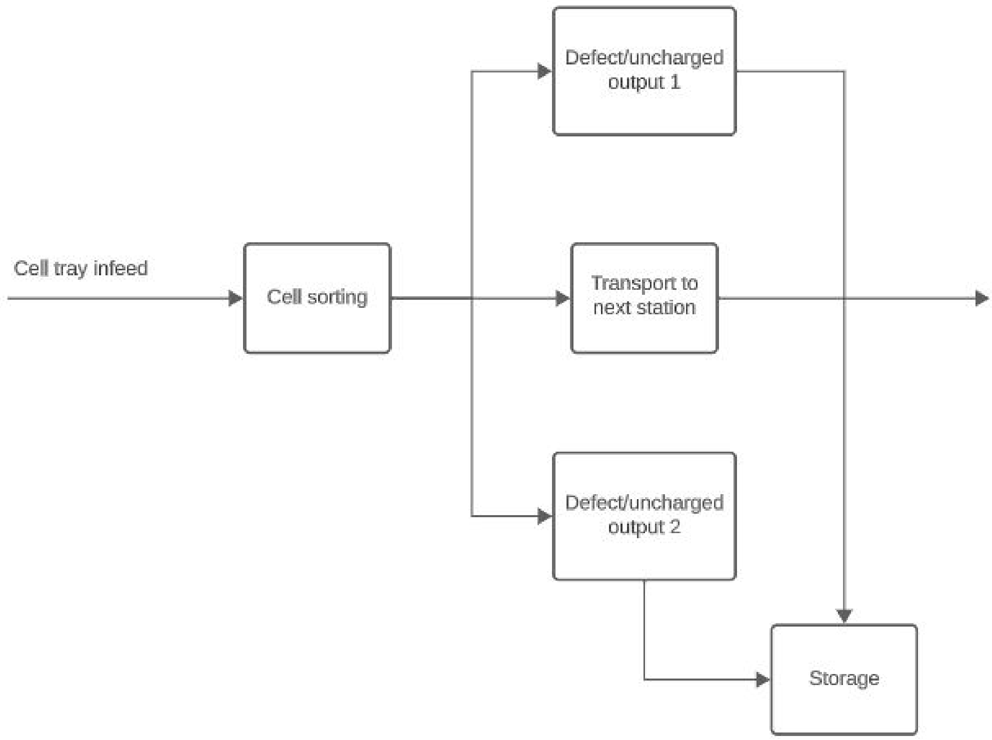

Figure 18: flow of components cell-1

- cell-3: As directed by FIP, there are a total of 5 stations in cell 3. These stations are a welding station, 2 manual work stations, and 2 pick and place stations. Each module whether it is made of cylindrical cells or prismatic will go through 3 main stations in cell 3 as shown in fig 20

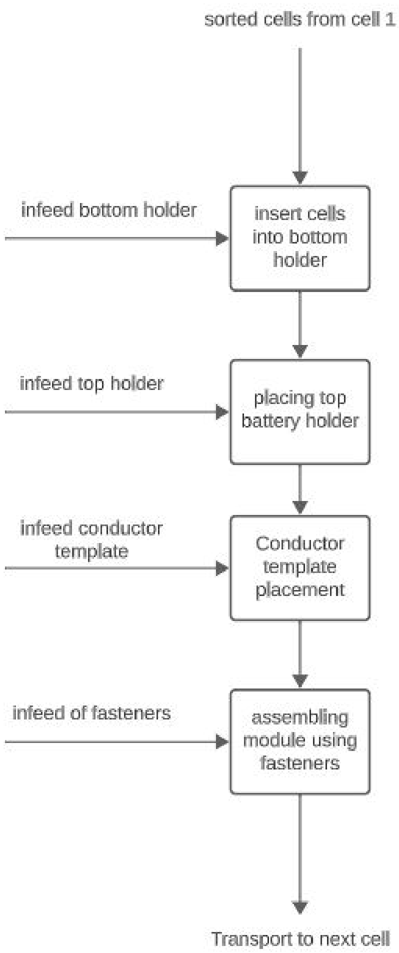

Figure 19: flow of components cell-2

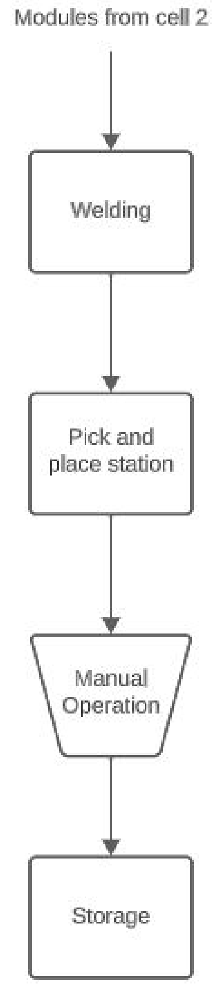

Figure 20: flow of components cell-3

5.4.2 Full process list

The total processes that happen in cell 1, cell 2, and cell 3 can be seen in table 4

process no.	Process action	Description
Cell 1-1	Battery cell grading	Sorting of cells based on voltage, charge, defects
cell 1-2	Voltage check	Each cell's voltage is checked to see if it is uniform or if any cells have less than the required voltage
Cell 1-3	defect check	Cells are checked to see any physical defects are present
Cell 1-4	Transport to storage	uncharged cells and defected cells are transported to storage via an AGV.
Cell 1-5	Transport to Cell 2	Cells that undergo the sorting process is transported to Cell 2 via an AGV
Cell 2-1	Infeed bottom battery holder	Bottom battery holder for the modules are fed through one of the inputs
Cell 2-2	Infeed battery cells	The battery cells which were transferred from cell 1 are placed inside the bottom battery holder
Cell 2-3	Infeed top battery holder	The top battery holder is placed onto the cells
Cell 2-4	infeed conductor template and fasteners	The conductor template is placed on the assembled cell module and fasteners are attached to secure the module.
Cell 2-5	Transport to cell 3	The assembled module is then transported to cell 3 via an AGv
Cell 3-1	Welding station	The assembled modules are welded to form contact between the conductor template and battery terminals
Cell 3-2	Cell stack mounting	The cells module stacks are placed into a battery pack housing
Cell 3-3	Infeed BMS	BMS is fed and placed onto the cell stack
Cell 3-4	Infeed electronics	Pick and place additional electrical components like indicator lights, switches, etc
Cell 3-5	Connect electronics	all electronics placed are then wired to the BMS
Cell 3-6	Equipment testing	Measure the voltage of the cell stack and functionalities of the electronics

Table 4: battery pack Process table

Table 4: battery pack Process table

Cell 3-7	Check functionalities	Check if all assembled components are working optimally
Cell 3-8	infeed module top	The top part of housing structure is placed onto the assembly
Cell 3-9	Pack function and leak test	The final battery pack is then tested to check for any abnormalities
Cell 3-10	attach QR code and transport	QR codes are placed onto the packs and it is then transported to storage via an AGV

Since Prismatic cells can easily be assembled into a module because of their simple shape, it does not require any specific cell inserts to hold them together. So comparing the process list in table 4 there is a slight change in the process for producing a prismatic cells-based pack. Instead of 4 processes of cylindrical cells, where there are inputs for the bottom holder, top holder, conductor templates, and fasteners, for prismatic cells, it would only require clamping of the cells, and attaching the conductor template on it. Table 5 shows the process flow of prismatic cells in cell 2

Process no.	Process station	description
Cell 2-1	AGV transport from cell 1	sorted cells are placed in cell 2, which were transported by an AGV from cell 1 to cell 2
Cell 2-2	Clamping station	The prismatic cells are clamped together to form a module
Cell 2-3	infeed conductor template	conductor template are attached to the assembled prismatic cells
cell 2-4	AGV transport	The assembled module is then transported to Cell 3 via an AGV

Table 5: Process flow for prismatic cells in cell 2

As mentioned above, each machine in each cell does a specific list of task. Table6 shows what each station/machine will contribute to the overall process

Machine	Process action
Cell sorter	Battery cell grading, voltage check, defect check
AGV	transport between cells and storage
Cell 2 machine	infeed of bottom and top holders, conductor templates, fasteners, cells and their integrations to assemble a module
Welding station	Welding of modules
Vention system	pick and place station for housing and electronics
Vention system	pick and place station for housing and electronics
Manual station 1	Wiring, final assembly, testing
Manual station 2	Wiring, final assembly, testing

Table 6: machine processes description

6 Simulation setup

Visual Components is the selected software to simulate the flexible battery pack assembly line. Among other simulation software like tecnomatrix plant simulation, emulate 3D software, etc., visual components have a very user-friendly interface. Visual components use a Python scripting environment which can be used to program custom robot processes. A model made in visual components can easily be modified and tailor-fitted to reassemble the physical layout with minimal effort. Since assembly lines need continuous improvement to meet demands, the digital copy of it should be easy to handle. Visual components also come with various industrial communication interfaces like Siemens S7, Beckhoff ADS, and OPC UA by which it can be directly connected to a PLC system like those of Beckoff and Siemens.

6.1 Simulation methodology

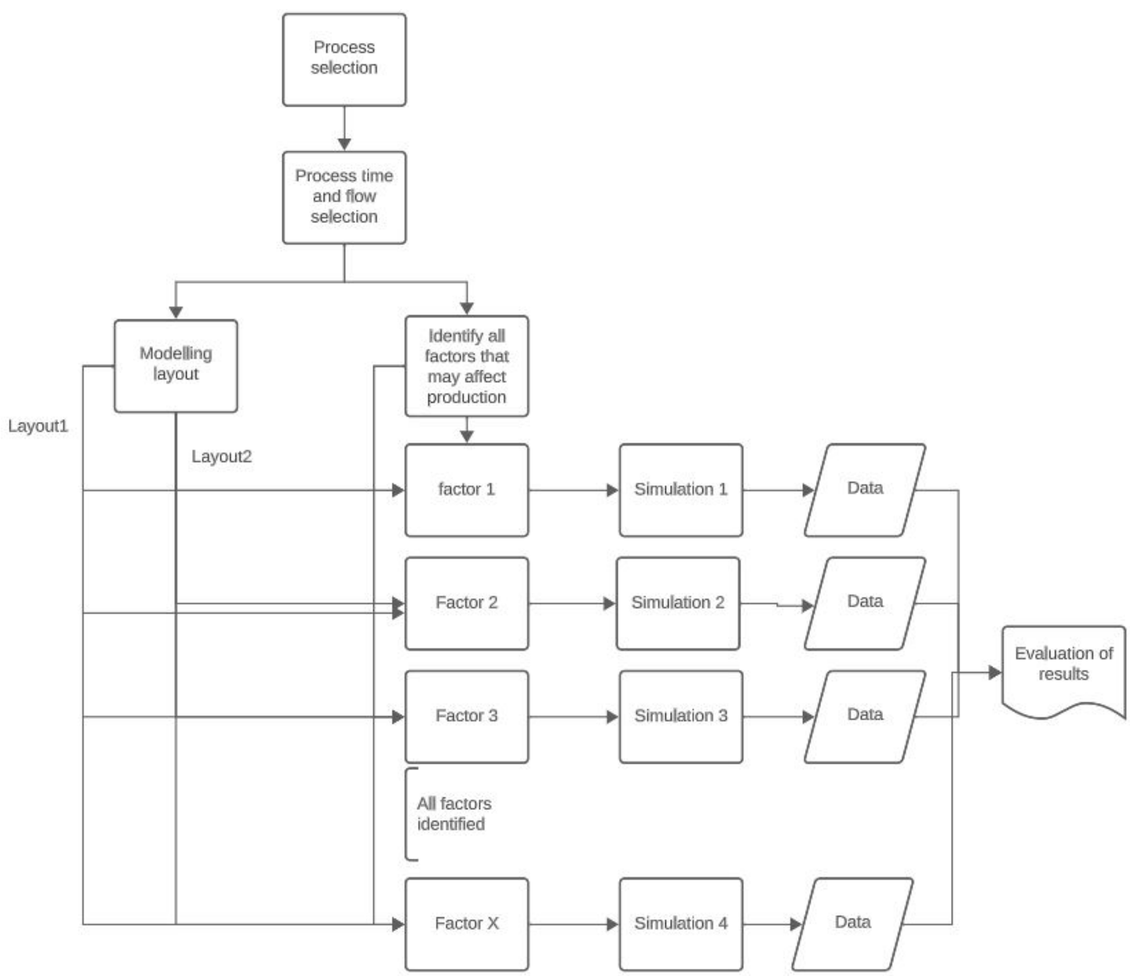

Figure 21: Flow chart for simulation methodology

The simulations were carried out following the methodology as shown in fig21. In the modeling process, multiple layouts can be modeled based on space requirements. Since process selection has already been done in section 5.4.2, process time has to be fixed for the simulation.

6.2 Process Time setup

Before the simulation is carried out to collect data, the processing time for each process in the battery pack assembly layout has to be entered. Time study analysis of the production of battery packs is a closely guarded secret by companies, so the process times at each station have to be assumed. This process time will be the same for all simulations moving forward. Since a machine capable of sorting both prismatic and cylindrical cells was not found, information available on the cylindrical cells sorter machine was used as a reference for calculating the processing time for the cell sorting station. For calculating the processing time at the cell sorting machine, assume a tray of 160 cells is fed to the sorter machine. Based on a speed of at least 80ppm as mentioned in table 1 it will take 120 seconds to sort the cells. It is assumed that it will take the same amount of time for prismatic cells.

Since visual components' UI makes it easy to edit the processing time, when the physical model is established and actual process times are calculated, it can be entered into the process node in visual components easily. For all the simulations that are done ahead, the process times are considered based on table7 There are a few boundary conditions that are fixed for the simulation.

- The Total length of the cell 3 section is fixed
- The max allowable length of the factory floor is 30 meters
- The arrangement of conveyors(aside from the location of the workstation) in cell 3 is fixed

machine	process	time (s)
Cell sorter	cell grading, voltage check, defect check	120
Cell 2 machine	Bottom cell holder infeed	30
Cell 2 machine	Top cell holder infeed	30
Cell 2 machine	Conductor template infeed	30
Cell 2 machine	Conductor template 2 infeed and fasteners attachement	30
Cell 2 machine	prismatic cells clamping	30
Cell 2 machine	primsatic cells conductor template	30
Welding station	Welding of modules	30
Vention system 1	pick and place station for housing and electronics (prismatic cells)	30
Vention system 2	pick and place station for housing and electronics (cylindrical cells)	30
Manual station 1	Wiring, final assembly, testing	600
Manual station 2	Wiring, final assembly, testing	600

Table 7: Battery pack production Process time

6.3 Layout modelling

Since two different types of modules are to be used, one with cylindrical cells and one with prismatic cells, Two types of battery packs will be produced.
Reference to the process and framework of layout is defined in section 5.4.1 and table 4 . Now each machine has to be assigned a process time in the simulation. Process nodes that simulate a process are readily available in the visual components library. This node can be placed inside a machine to simulate the process. As seen from the fig 22 there are 2 vention pick and place systems, 2 manual process stations, one welding station in the cell 3, 1 module production section in cell 2, and 1 cell sorting machine cell 1.

Now the flow of components has to be assigned. Certain assumptions are considered while deciding the flow groups of cells. They are as follows:

- The flow of both cylindrical cells and prismatic cells will be the same from cell sorting to module production station. Since there is no fixed design of the prismatic cells, it is assumed that the process is similar to that of cylindrical cells
- Vention PP 1 and manual process 1 will be dedicated to assembling battery packs made of prismatic cells
- Vention PP 2 and manual process 2 will be dedicated to assembling battery packs made of prismatic cells
- The parts required for assembly when the components reach a station are already present there.

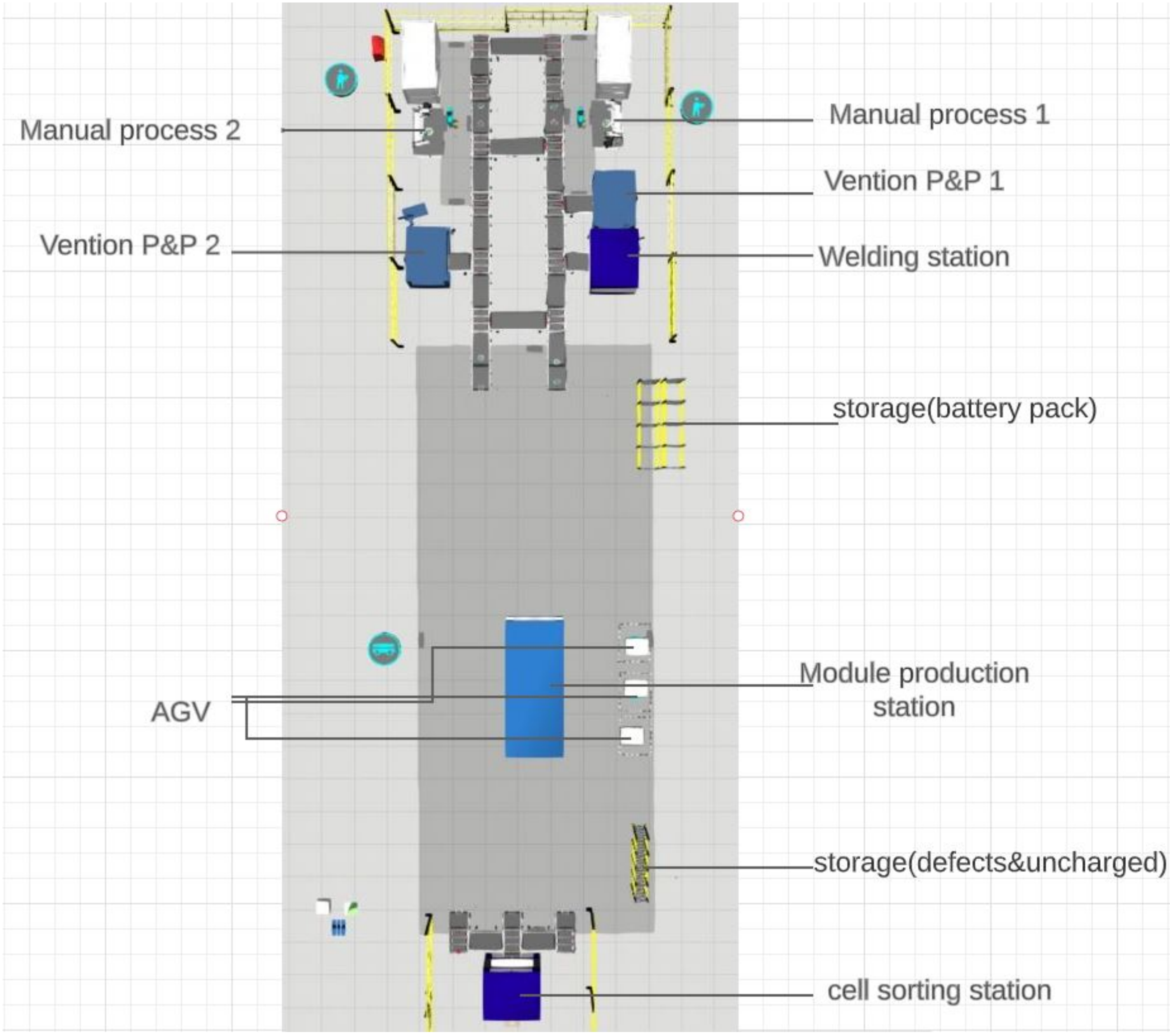

Figure 22: Base layout general information

- The number of stations in the simulation is fixed (excluding the storage compartments)
- Possible rejection of battery packs at the end of its assembly process is not considered.
- The speed of AGV is considered to be 2m/s unless specified in any section
- The flow of components from the beginning of the process will be a batch of 2 trays of cylindrical cells, 2 trays of prismatic cells and 2 defective cell trays(this is to ensure uniformity in simulations)

Fig23 and fig 24 shows a magnified view of cell 3 and the flow of materials on it. Several routing conveyors are strategically placed to redirect components to their intended process location

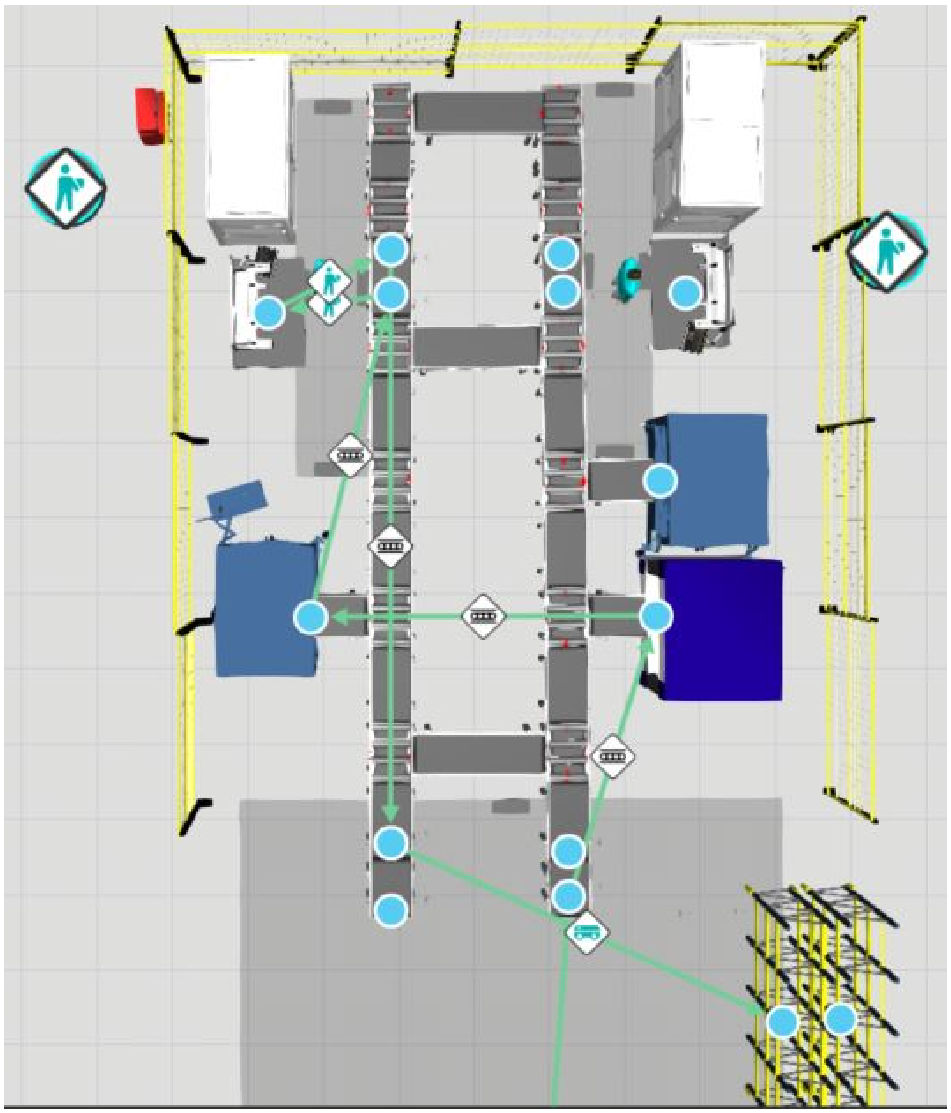

Figure 23: flow group of cylindrical cells in cell-3

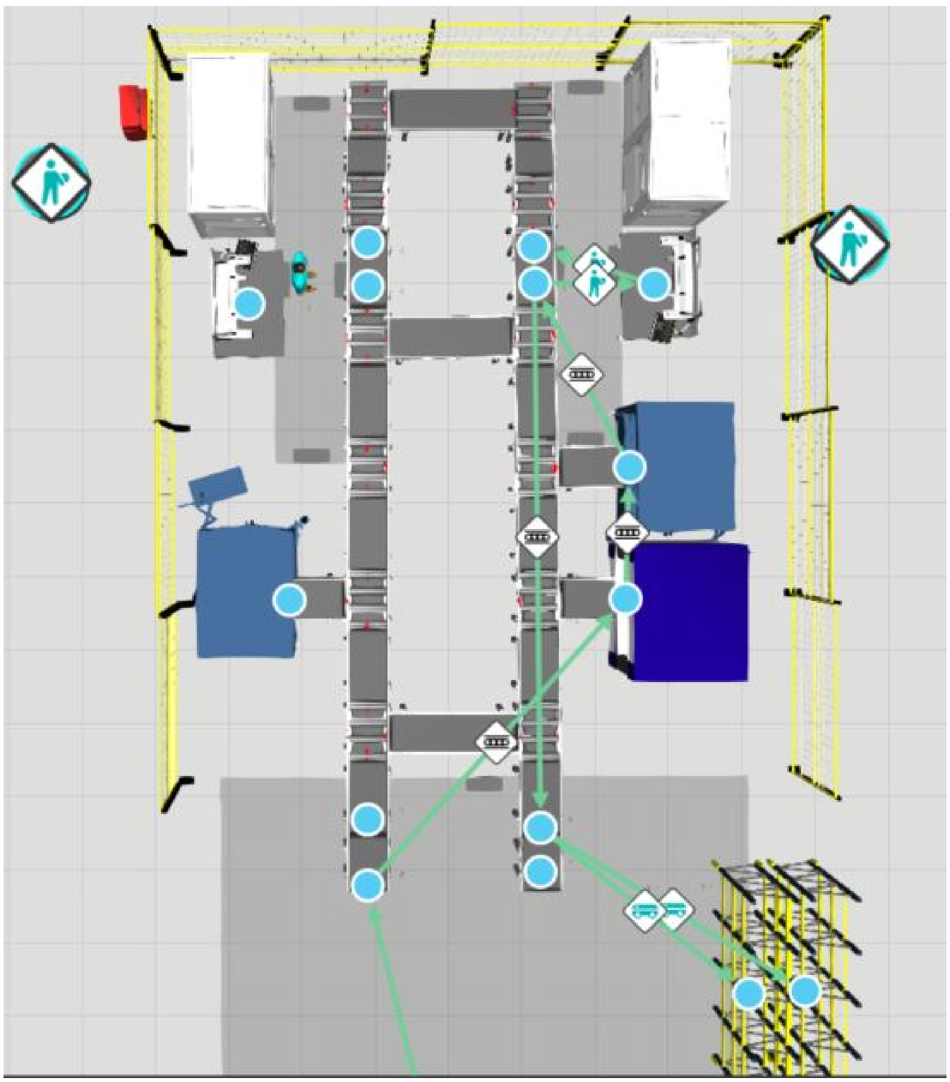

Figure 24: flow group of prismatic cells in cell-3

6.4 Factors identification

To understand and identify factors that may impact the production of packs in the assembly line designed, certain lean optimization was referred to. There are various ways to optimize a layout using lean principles, like optimization by reconfiguring workstations, implementing just in time principles to make sure all components required for the process are present at the station when needed, use of automation wherever necessary, advance planning and scheduling, etc. Using these optimization methods, certain factors that may have an impact on production were identified. Several other factors are used in the simulation to understand its implications on production.

A total of 8 factors were investigated through simulation which is as follows:

- Impact of feed rate and number of transport solutions
- Impact of variation in Cell 3 process route and location of workstations
- Impact of the location of the storage
- Impact of AGVs speed on production
- AGV route selection
- Pick and place method between conveyor and AGVs
- Impact of number of humans
- Impact of variation in the flow of components

These factors are then simulated under various scenarios which can be seen in table 8

Factors	Variations	total simulations (30m layout)	total simulations (18m layout)
Impact of feed rate and number of transport solutions	4 feed rates with 1,2 and 3 AGVs	12	12
Impact of variation in Cell 3 process route and location of workstations	4 feed rates with 1,2 and 3 AGVs	12	12
Impact of location of storage	5 distances with 1,2, and 3 AGVs at threshold feed rate	15	15
Impact of AGVs speed on production	4 speeds with 1,2 and 3 AGV at threshold feed rate	12	12
AGV route selection	4 speeds with 1,2 and 3 AGV at threshold feed rate, route changed	12	12
Pick and place method between conveyor and AGVs	6 time values with 1,2 3 AGVs at threshold feed rate	18	18
Impact of number of humans	2 cases	2	2
Impact of variation in flow of components	3 different batch order with 1,2,3 AGVs	9	9

Table 8: All simulation parameters considered

7 Simulation of layouts with variation in certain process factors

7.1 Impact of feed rate, length of layout and number of transport solutions

Layouts with 2 different total lengths are considered for this and all simulations moving forward as shown in fig 26 and fig 25. The impact on the final throughput of the battery packs by variation of feed rate and number of AGVs present will be carried out. The simulation is run for 4 hours(since the values per hour were very small, for representation purposes 4 hours is taken) to get the data on the total parts produced. For the feed rate, 2-time intervals are important

- Batch interval
- component interval

The feeder at cell 1, will be a tray of cells that will be sorted out in the cell sorting machine. Cylindrical cells and prismatic cells are in 2:2 order, which means the first 2 trays of cylindrical cells will be fed, and then 2 prismatic cell trays are fed into the cell sorter machine. The gap between the batch of cylindrical cells and prismatic cells is called the batch interval. Component interval is the time taken between 2 simultaneous cylindrical cells or prismatic cells.

- 30m length layout with no route change
- 30m length layout with route planning

By altering the batch and component interval values, the feed rate of the unsorted cell tray can be controlled.
3 main feed rates with batch intervals being 1000, 1500, and 2000 (all the values are in seconds) are considered. An additional feed rate, which will be the lowest possible value for the specific layout before stopping the simulation is also considered. These values will be termed as the threshold value of feed rate
If the feed rate goes below a certain threshold, i.e. if the flow of components after a threshold is increased, then there will be a development of a choke point in the assembly line. A choke point here, means the several components of different flow groups collide with each other to stop the total flow of the process. This can be seen in the layout with a length of 18m. Once the feed rate becomes too low. A choke point as pointed out by the black box in fig 27 will happen
All the variations in feed rates are also applied to variations in the length of the layout as well. For layout configuration of both lengths 18m and 30m, Variation in the number of AGVs used is also tested out

As seen from this graph 28, the number of total battery packs produced is highest in the layout with a length of 18m, 200s batch interval, with a total of 23 battery packs in 4 hours. It can be seen that the lowest possible value of feed rate for a configuration

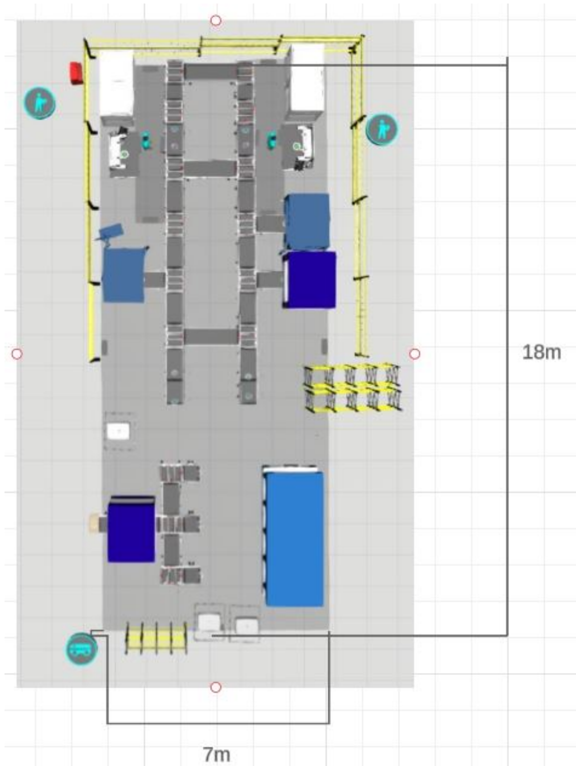

Figure 25: Dimensions of 18m layout

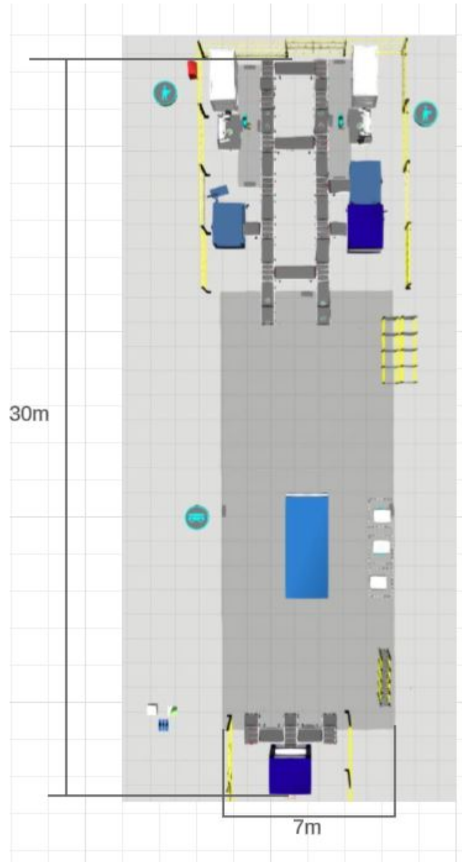

Figure 26: Dimensions of 30m layout

with a 30m length is 205s and the lowest possible value of feed rate for a configuration with an 18m length is 200s. The feed rates of 1000s, 1500s, and 2000s have the same output of battery packs comparing both the layouts. The layout with a length of 18m has 2 more additional battery packs produced in 4 hours than the layout with a 30m length.
This same analysis can be done for 2 and 3 AGVs For configurations with 2 AGV, it can be observed that there are no changes in the throughput of the battery pack as shown in fig29. This is in its least possible value of feed rate, with 180 seconds being of layout with 30m length and 210 seconds of layout with 18m length. The same trend for decreasing throughput with increasing the feed rate can be seen Fig30 shows the throughput of battery packs when 3 AGV are in process. In this configuration as well, it can be seen that the maximum battery packs produced is 23 packs per 4 hours.
From referring to fig 28,fig29, and fig30, certain observations are made which are listed as follows.

- Aside from the threshold feed rate, all the other feed rates produce the same number of battery packs, corresponding to their initial value, i.e. 10 packs produced with a feed rate of 1000s with a layout of length 30m and length 18m. Even the number of AGVs in this scenario did not affect the result

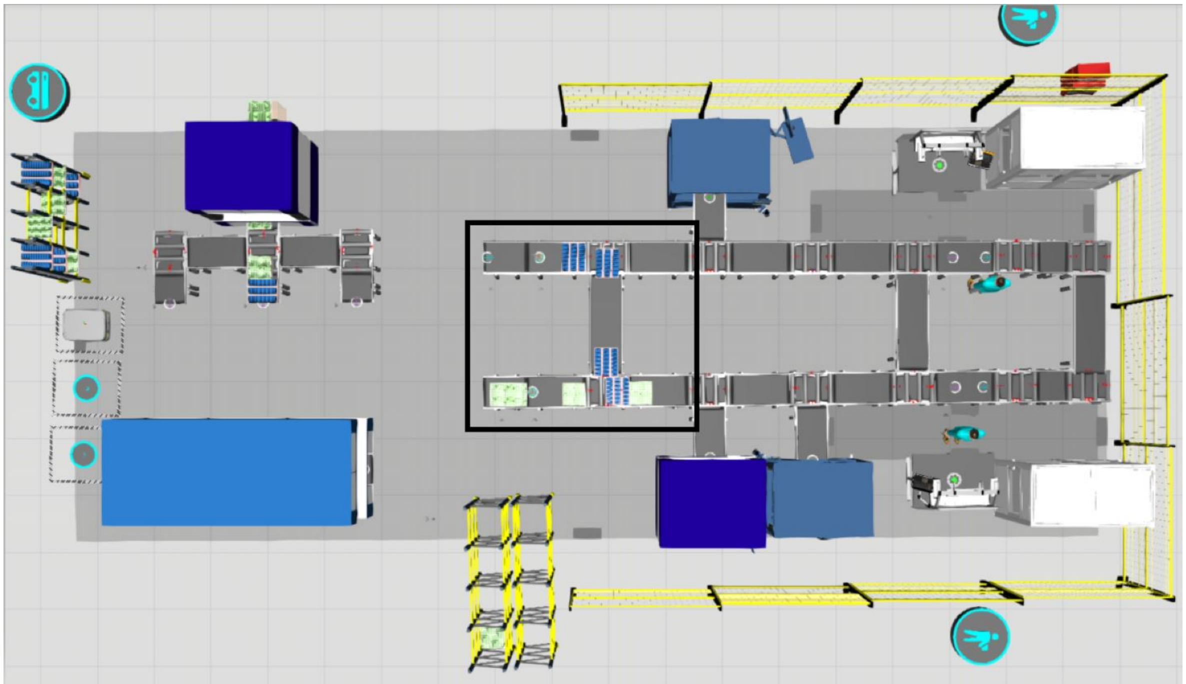

Figure 27: Choke point

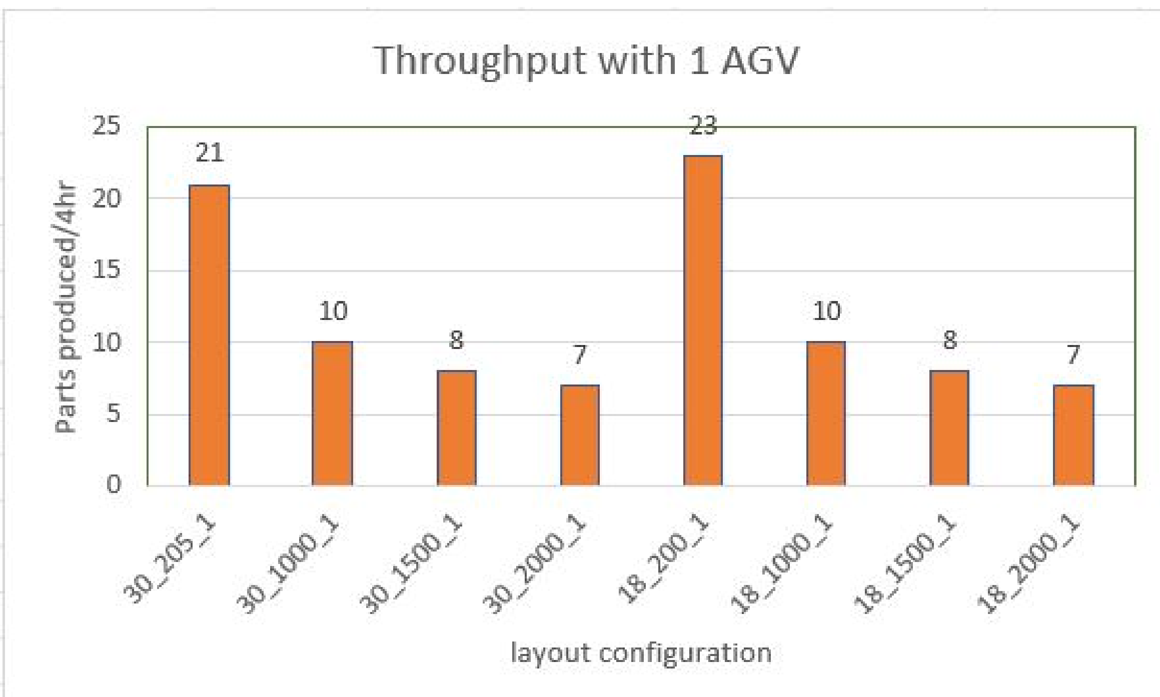

Figure 28: Throughput with 1 AGV, X-axis is in the format of [layout length_feed rate(s)_number of AGV used]

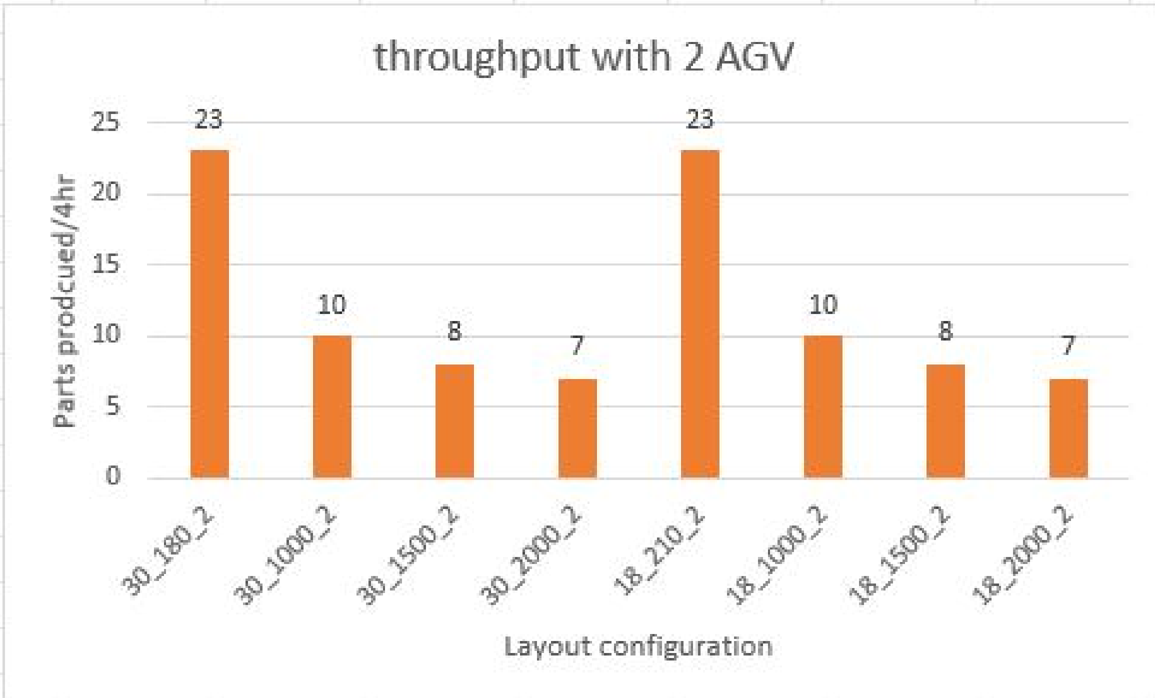

Figure 29: Throughput with 2 AGV, X-axis is in the format of [layout length_feed rate(s)_number of AGV used]

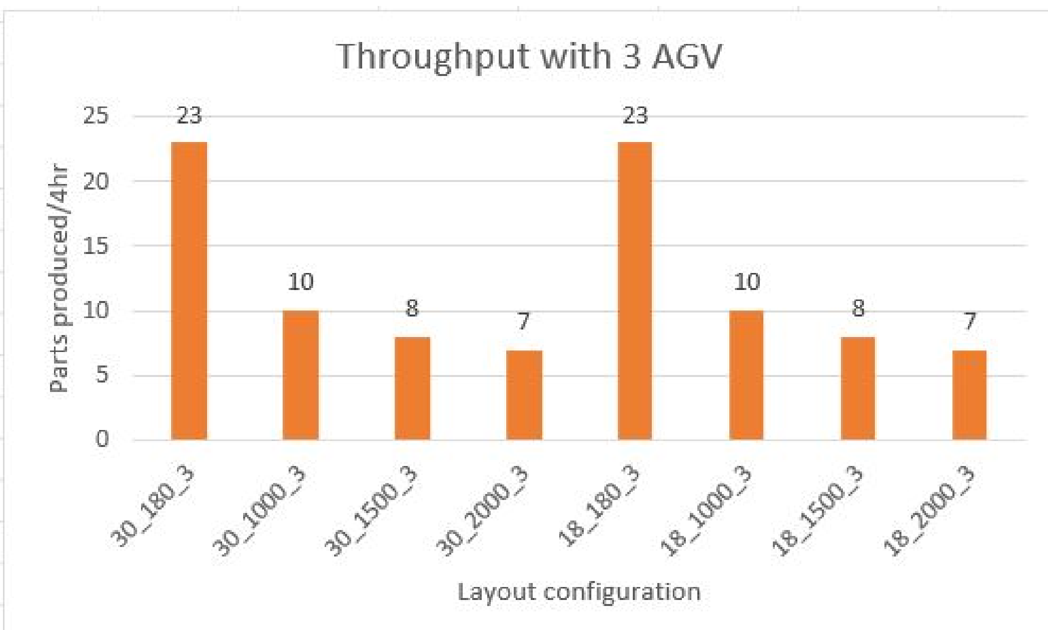

Figure 30: Throughput with 3 AGV, X-axis is in the format of [layout length_feed rate(s)_number of AGV used]

- For the layout with a length 30m, there is an increase in the throughput of battery packs between 1 AGV and 2 AGV by a factor of 2. Any more additions of AGV did not improve the result

- For the layout with 18m length, any increase in the number of AGVs did not increase the throughput of the battery pack.

7.2 Impact of variation in Cell 3 process route and location of workstations

Looking at the flow of components and process times used in the simulation of section7.1, it can be noticed that the biggest constraint for the assembly line is the manual workstation. To reduce the effect of this constraint on the throughput of the assembly line, in the second set of simulations changing the location of the manual workstation is considered. The manual stations are relocated to one side of Cell-3 and all other stations to the other side of Cell-3. Change in process location causes the flow of components to also change which can be seen fig 33 and fig24. The process for the manufacturing of the battery packs remains the same, with the same process times as used for the previous simulation. Since there is a change between the station locations, the overall flow of components changes. In the previous simulation, there were 2 terminals that can be used as both input and output. For this simulation, only one input and one output will be considered.[20]
Now for this configuration, data is collected the same way as the previous simulation. In this simulation also, 4 feed rates will be considered, 3 of which are 1000s, 1500s, and 2000s, and one will be the least possible feed rate, which may vary based on individual configuration.

From fig 34 it can be observed that the number of battery packs produced at the lowest threshold feed rate of 180s is 25 packs for layout with 30m length and 27 for layout with 18m length. The trend of decreasing the number of produced battery packs with respect to decreasing feed rate(increasing batch interval), remains the same. From fig35, the total packs produced with 2 AGV in layout with a length of 30m is 29, with a feed rate as 140s, whereas the layout with 18m length was also able to produce 28 packs in 4 hours with 150s feed rate. configuration.

Comparing fig35and fig36, it can be observed that the total packs produced in both cases with 2 and 3 AGV did not change. Comparing it with fig34 it can be observed that there is a significant increase in the production of battery packs in the layout of 30m length with 1 and 2 AGV, but the increase in the layout of 18m length is small. (only a factor of 1) If the comparison is done between the total number of packs produced between layouts with no change in process location and changes in process location, it can observed that there is a significant increase in the throughput of the pack The blue shaded box indicates the throughput of layouts without process location change and boxes with orange indicate the throughput of layout which has undergone process location change

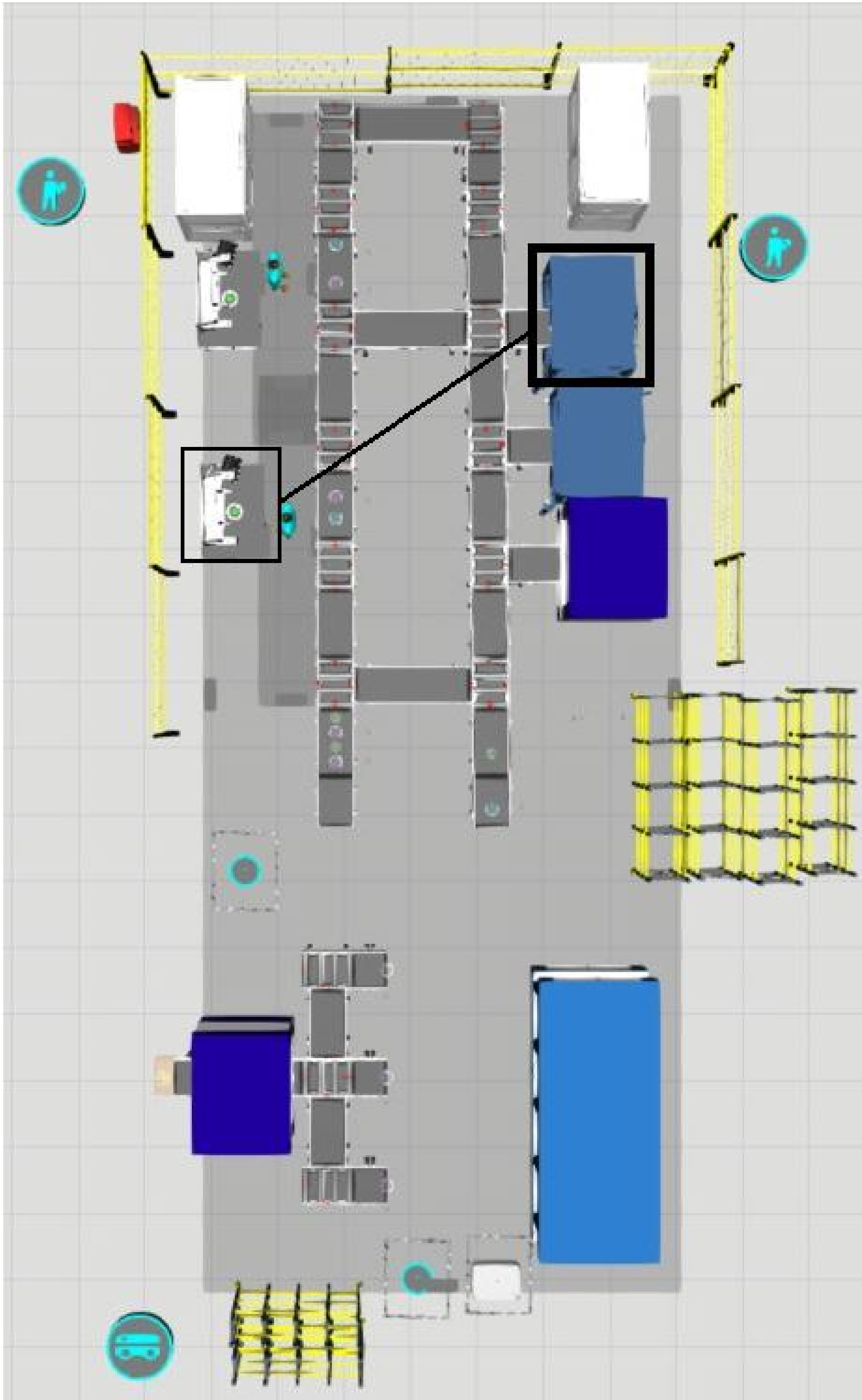

Figure 31: Process location change for 18m length

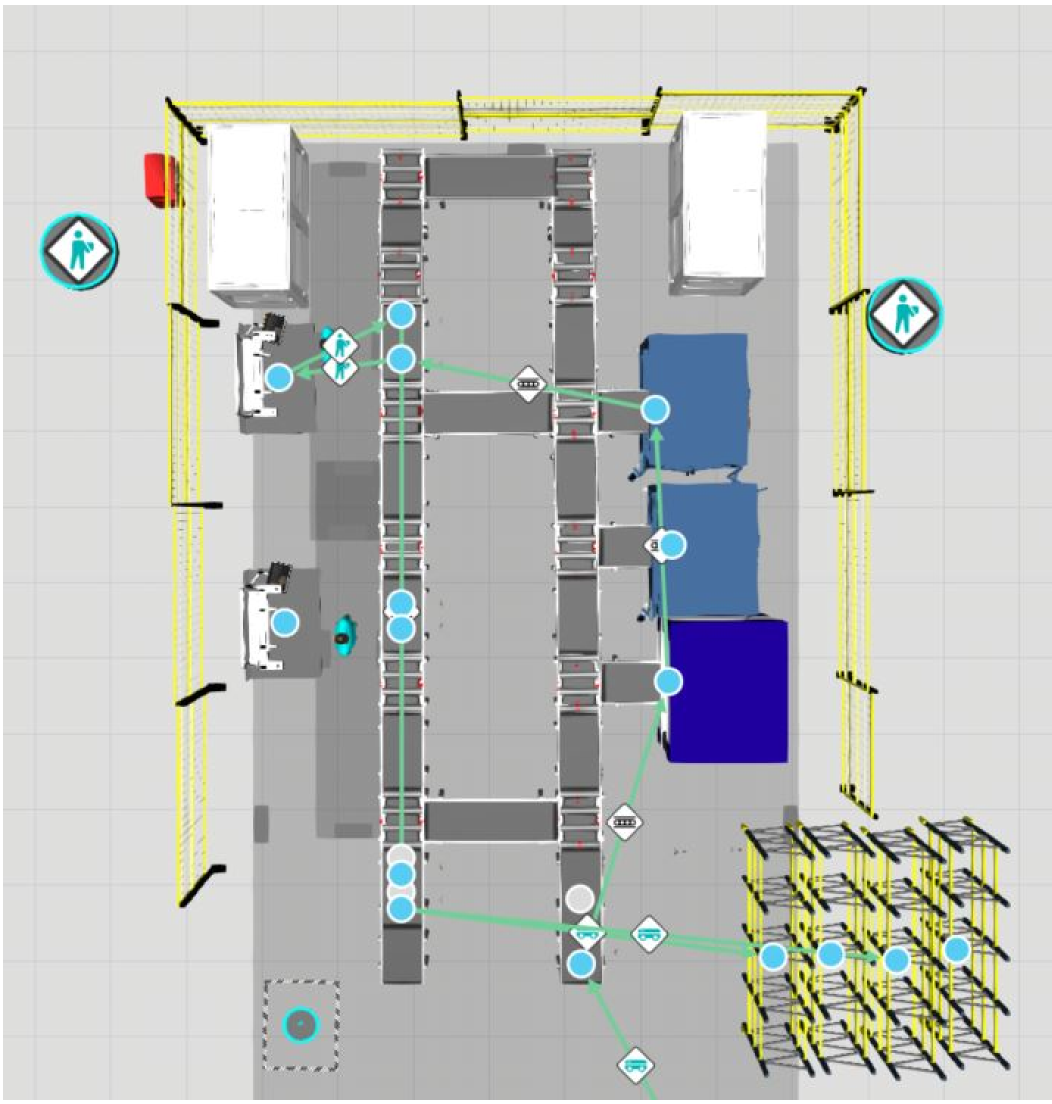

Figure 32: Cylindrical cells flow for location changed layout(cell-3

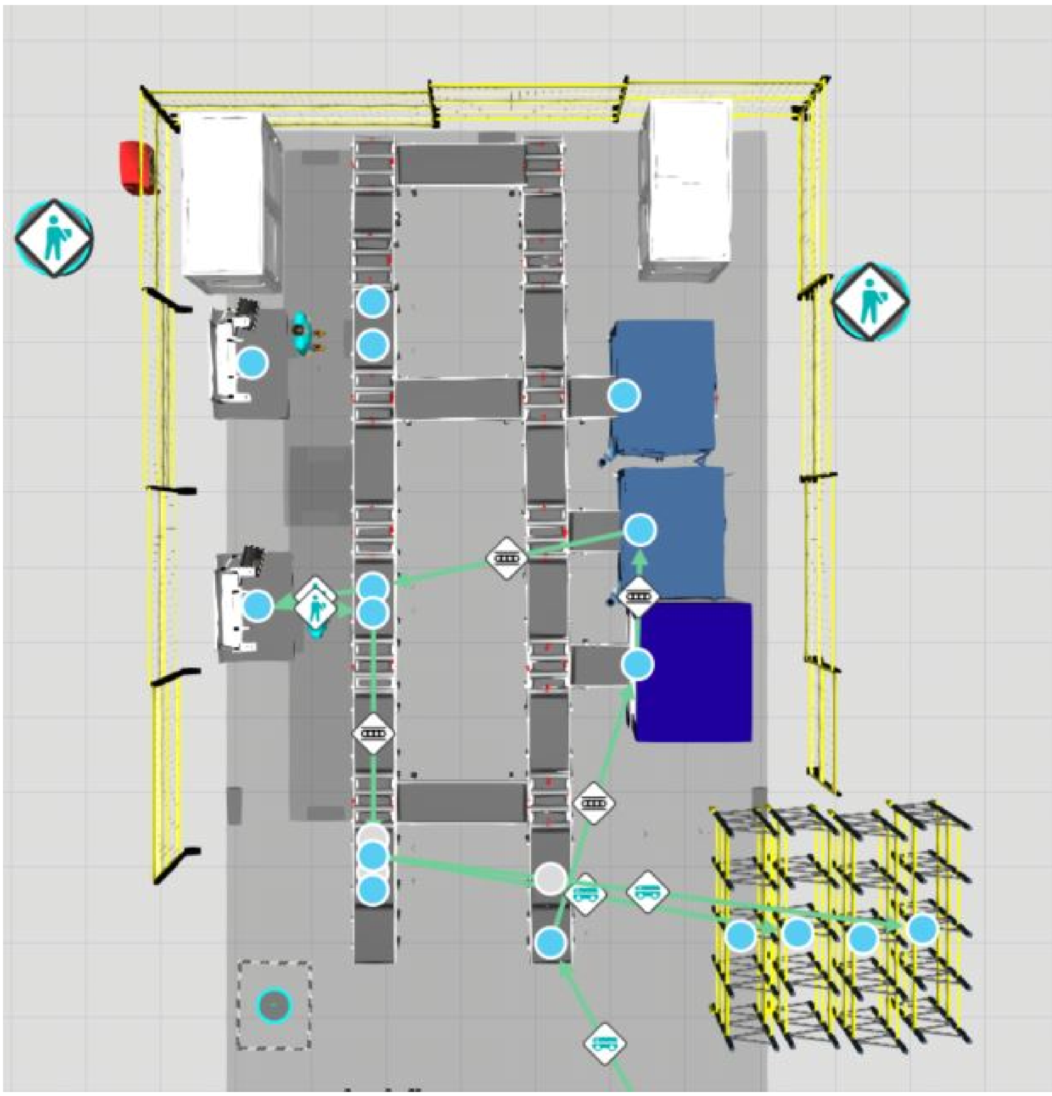

Figure 33: Prismatic cells flow for location changed layout(cell-3)

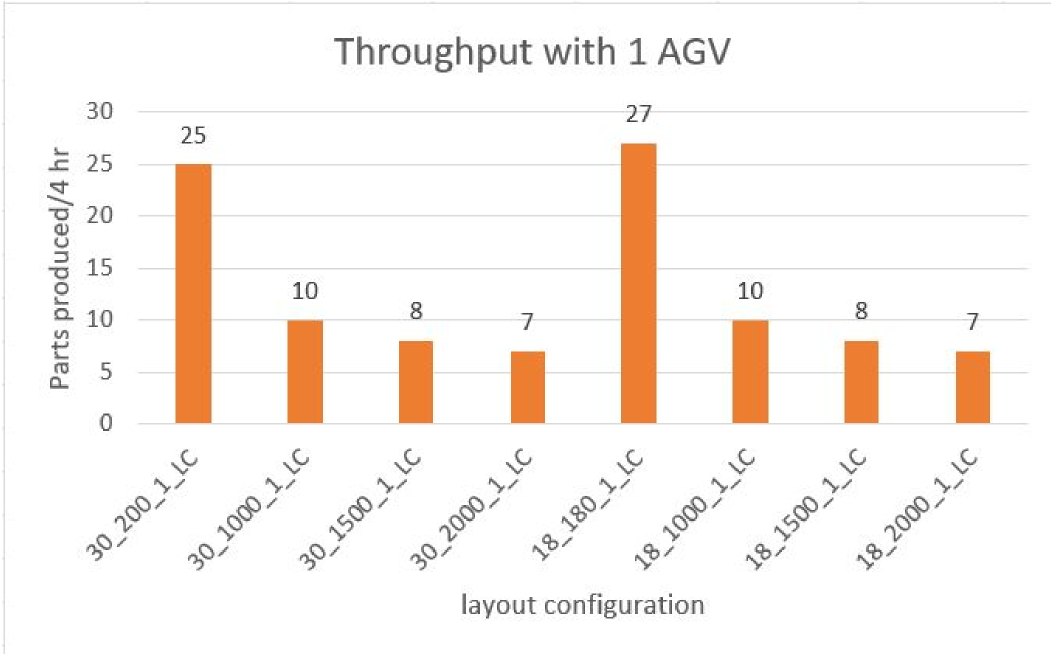

Figure 34: Throughput with 1 AGV for changed process location, X-axis is in the format of [layout length_feed rate(s)_number of AGV used_location change]

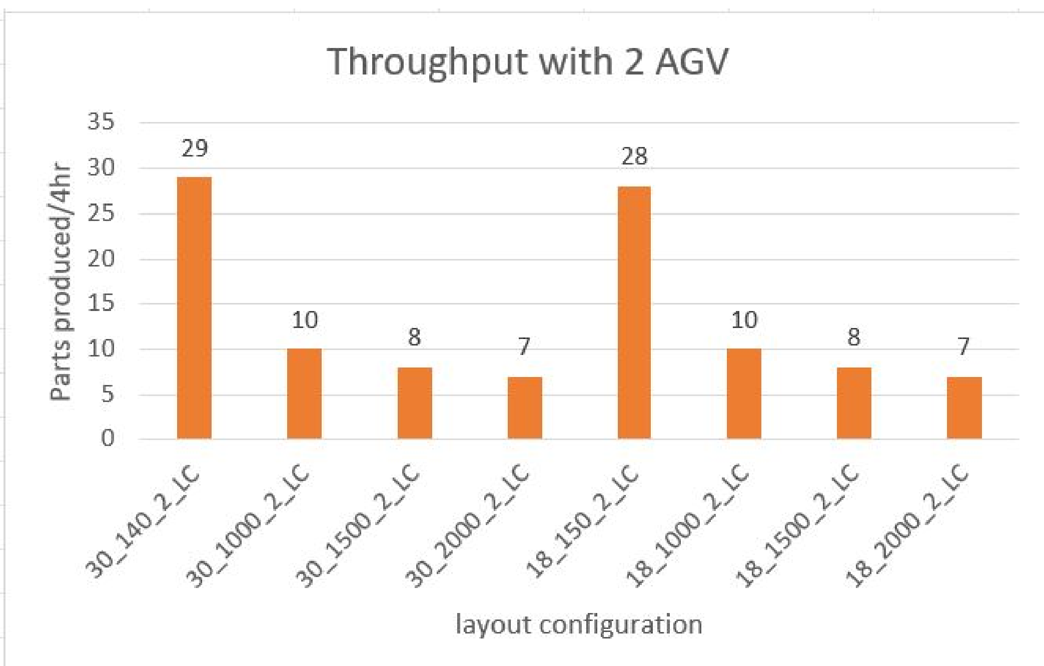

Figure 35: Throughput with 2 AGV for changed process location, X-axis is in the format of [layout length_feed rate(s)_number of AGV used_location change]

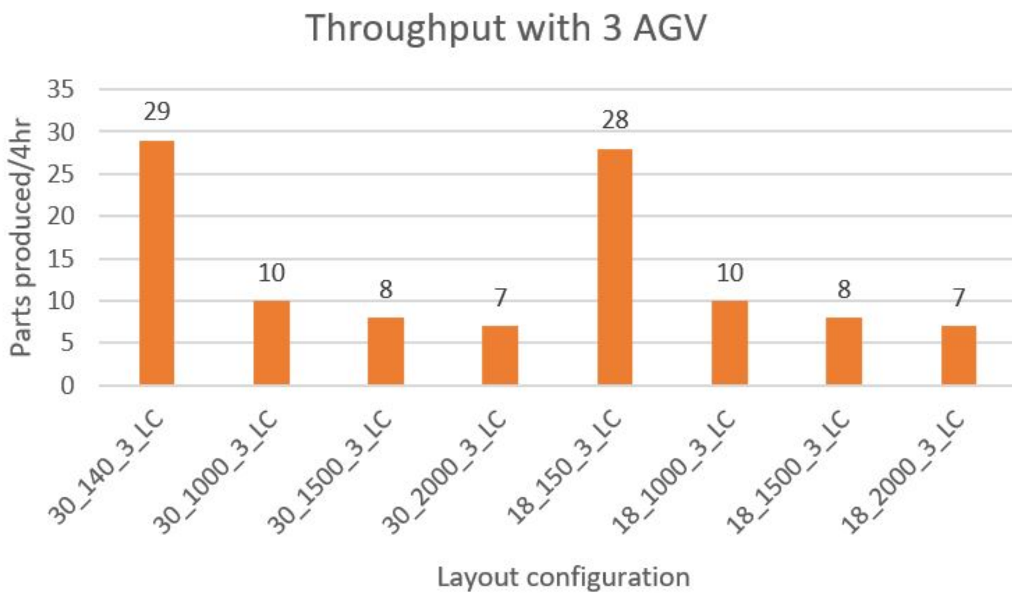

Figure 36: Throughput with 3 AGV for changed process location, X-axis is in the format of [layout length_feed rate(s)_number of AGV used_location change]

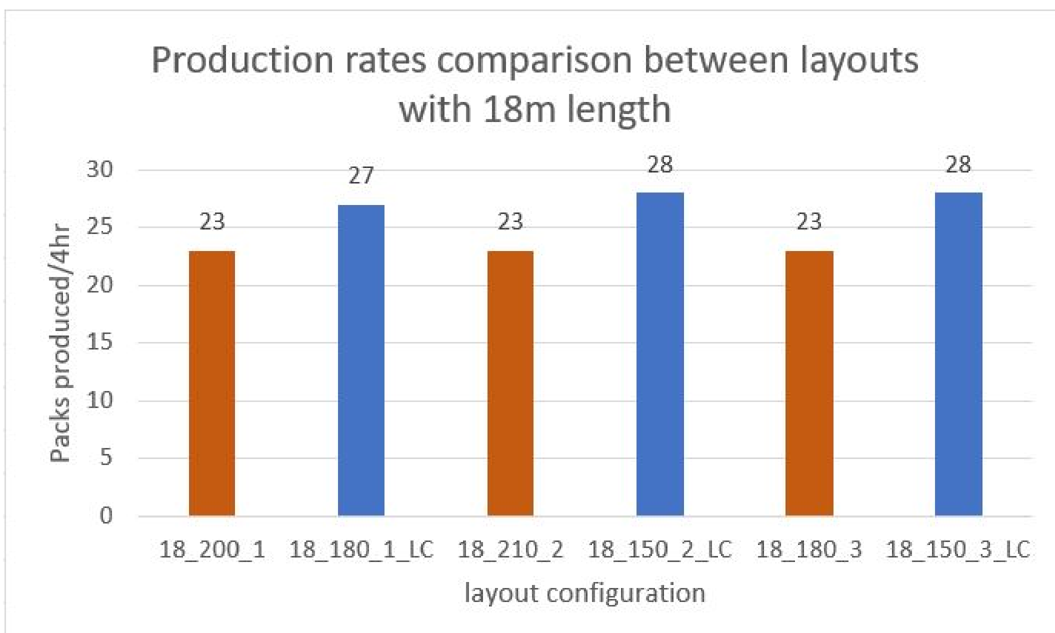

Figure 37: Throughput comparison between layouts with 18m length, red bars indicate layouts prior to the change in location of manual workstation, blue bars indicate layout with change in location of the manual station. The format of X-axis is [length of layout_feed rate(s)_number of AGV]

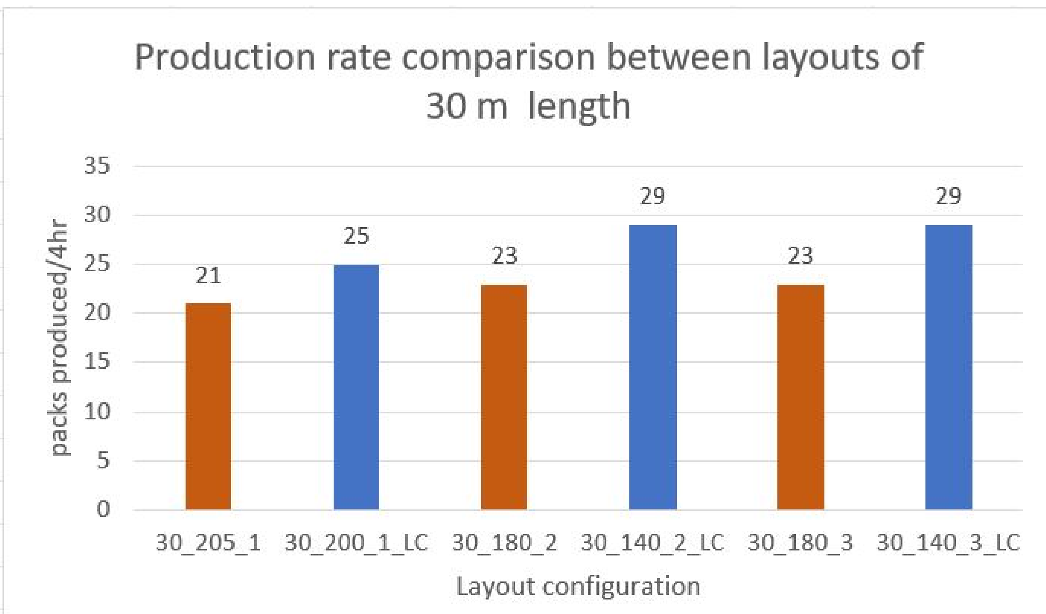

Figure 38: Throughput comparison between layouts with 30m length, red bars indicate layouts prior to the change in location of manual workstation, blue bars indicate layout with change in location of the manual station. The format of X-axis is [length of layout_feed rate(s)_number of AGV]

7.3 Impact of location of storage

Let's investigate how the throughput changes based on the location of the storage module. The Layouts will be simulated using their respective threshold feed rate (lowest feed rate) value that was found in section 7.2 and check the impact of the location of the storage module. Those are:

- Layout of 30m total length with 205 s batch interval(feed rate for 1 AGV)
- Layout of 18m total length with 200 s batch interval (feed rate dor 1 AGV)

The distance of the storage locations from the reference line as shown in fig 39 is varied with the values 10m, 30m, 50m,80m,120m. The simulation is run for 4 hours and the number of packs produced is compared. It can be seen from fig 40 in layouts with

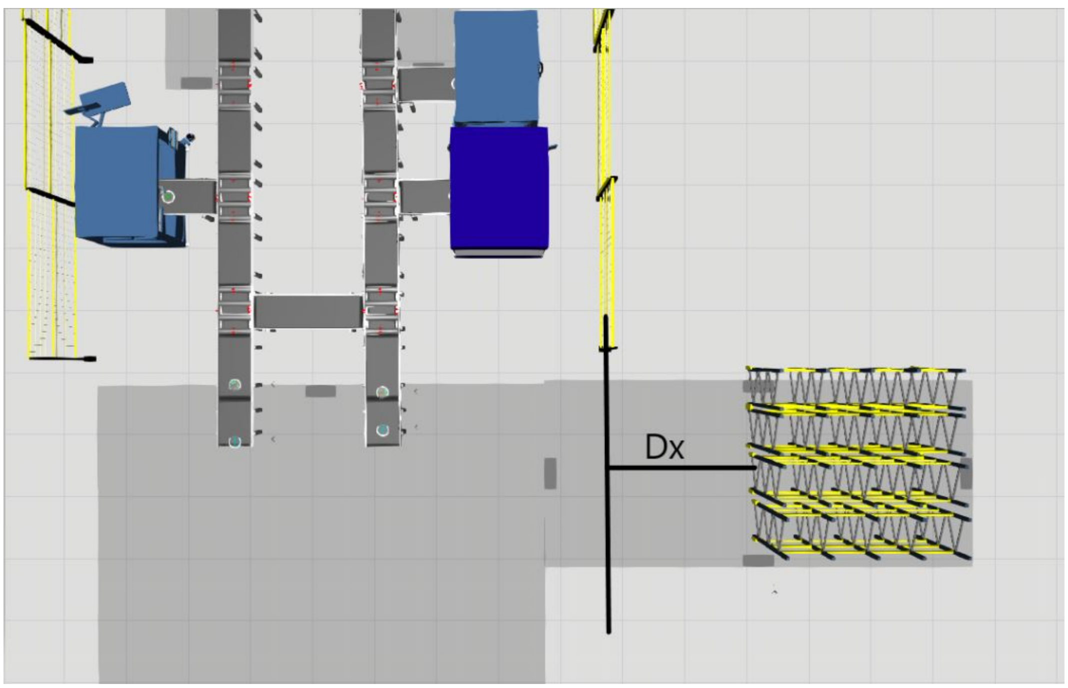

Figure 39: Reference line for change in storage location

a total length of 30m with 1 AGV, that after placing the storage section 30m away from the reference line, the simulation stops because of a choke point resulting in the production of a very limited number of packs. This same trend can be observed in the layout of a total length of 18m with 2AGV where the model was able to produce 23 packs until the storage location is placed 50m away from the reference line after the the production line stops. With the addition of 3 AGVs, in both layouts of 18m total length and 30m total length, the production rate does not stop changing significantly after placing the storage location 100m away from the reference line. Throughout this simulation, the speed of AGVs is constant at 2m/s. Using the theory of constraints, the major constraint has to be improved until its impact on the whole process is reduced

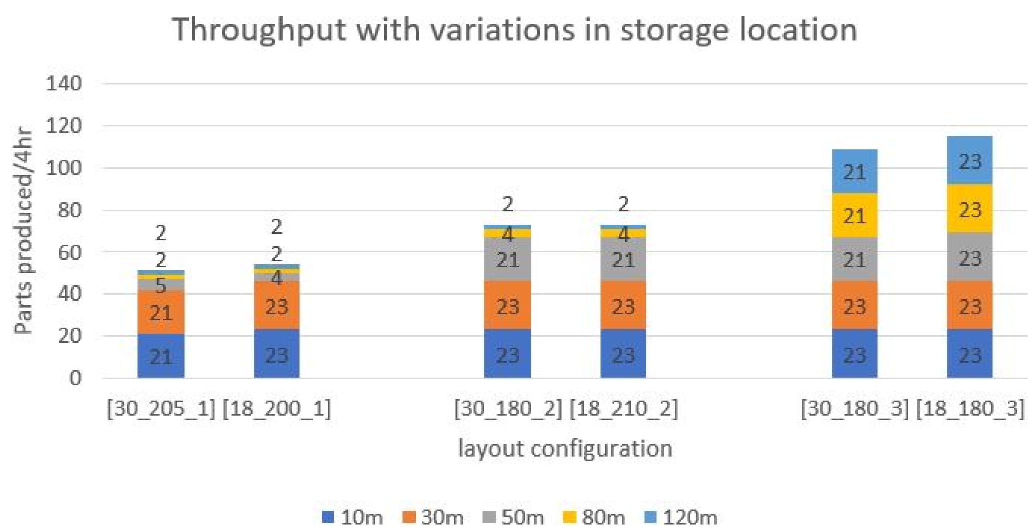

Figure 40: Throughput with variations in storage location, X-axis format is [length of layout_feed rate(s)_number of AGV]

significantly. Further improvement can be done by improving the process that happens in the workstation as mentioned in the section5.2.4

7.3.1 Impact of AGVs speed on production

Let's check how the speed of AGV has an impact on the production rate of battery packs with the 2 developed layouts.
As per the specs of Otto 100 AGV (which is the fixed model of AGV), the maximum speed of Otto 100 is 2m/s. For this simulation, 3 velocities of the AGVs will be considered with the storage location distance set with respect to the reference line is 0.

- v = 2000mm/s
- v = 1500mm/s
- v = 1000mm/s
- v = 500mm/s

from fig 41 and fig 42It can be observed that as the AGV speed is decreased, the number of packs produced, become lower and lower. The 30m long layout with 1 AGV shows the greatest deviation. When the AGV speed goes less than 1500mm/s the number of pack falls from 21 to 18 and a further decrease in speed results in a further decrease of packs produced. The deviation is not high enough in layouts with 2 and 3 AGVs.

In the 18m layout, there is a halt in production (choke point) when the speed of the AGV is set to 500mm/s as shown in fig 42. Since the total area to be covered by AGV is small in an 18m long layout for all the other speed the maximum number of packs produced in 4 hours remain the same.

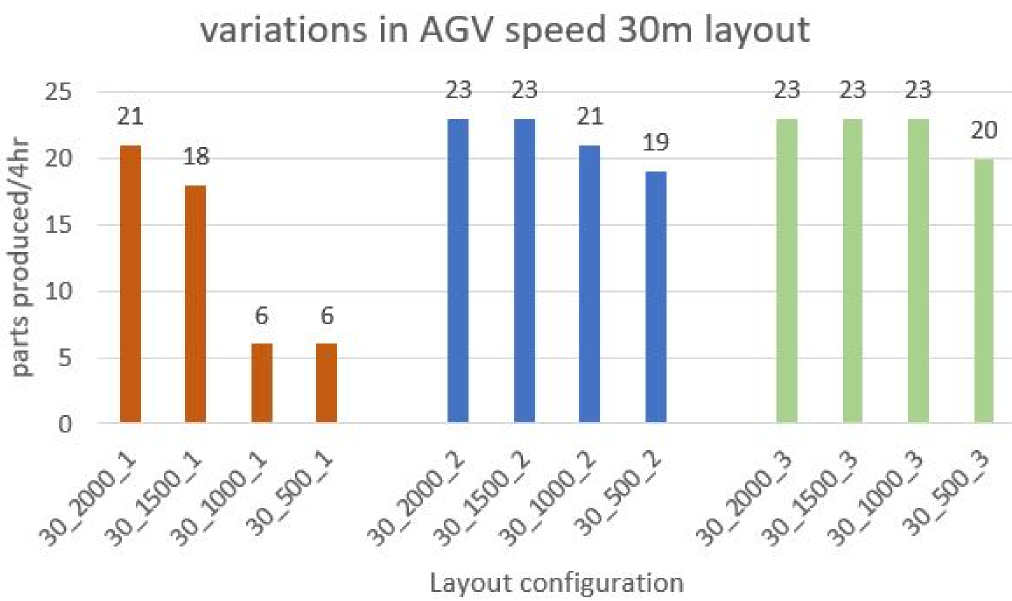

Figure 41: Variations in AGV speed for 30m length layout, X-axis format is [length of layout_speed of AGV(mm/s)_number of AGV]

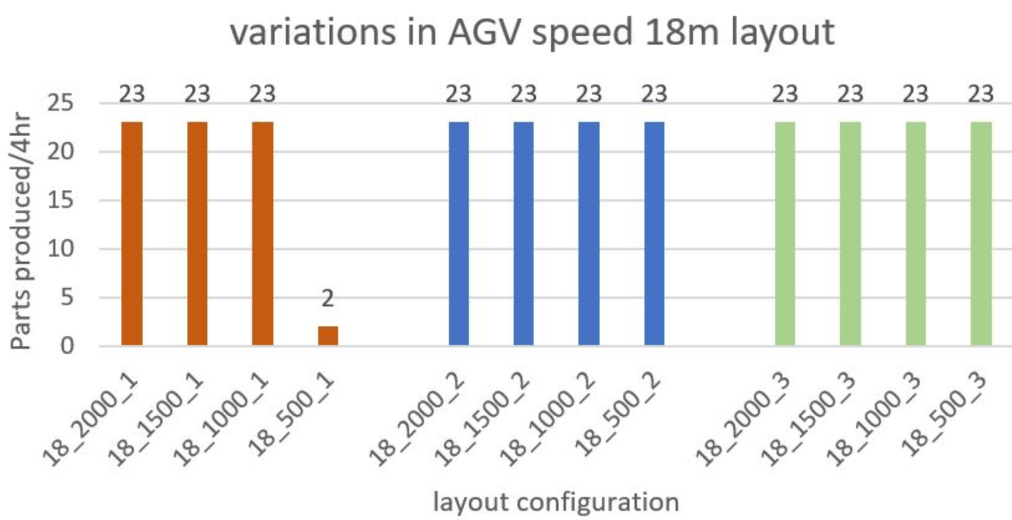

Figure 42: variation in AGV speed in 18m layout, X-axis format is [length of layout_speed of AGV(mm/s)_number of AGV]

7.4 AGV route selection

Route selection of AGV is an important factor for AGV. The route of AGV can determine how efficient, safe, and productive the AGVs are. For this throughput between 2 layouts will be considered.

- 30m length layout with no route change

- 30m length layout with route planning

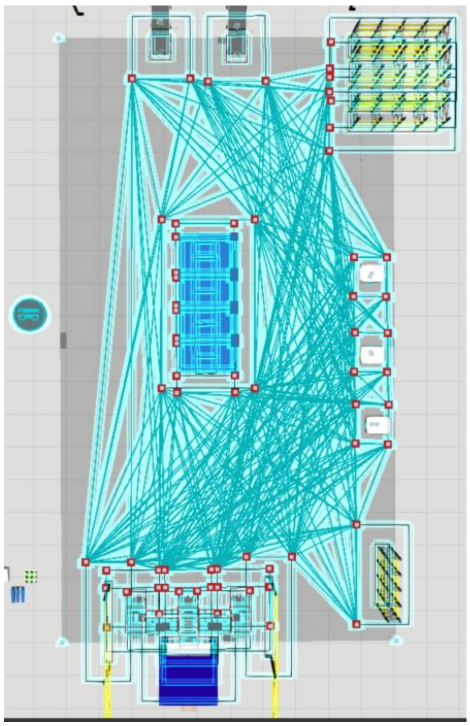

Figure 43: navigation mesh of original 30m layout

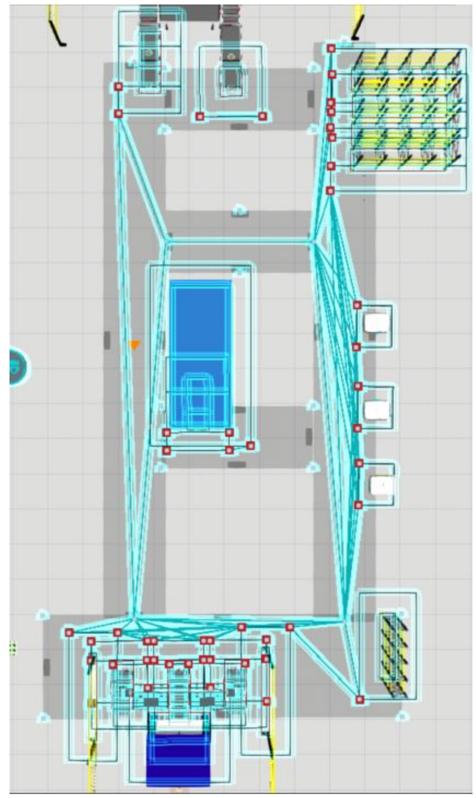

Figure 44: Route changed for 30m layout

Comparing fig 43 and fig 44, the navigation mesh is refined when AGV routes are modified. The navigation mesh here is defined as all the possible paths the AGVs can take. With these 2 variations, the simulation is run. As observed from fig45 the number of packs produced has significantly changed when the same graph is compared with fig 41 as this graph was plotted with the original route. With the new route change, the number of parts produced even with AGV speed as low as 1000mm/s is still 21.
Since the layout of 18m length is too small to create any meaningful route change the simulation was not conducted

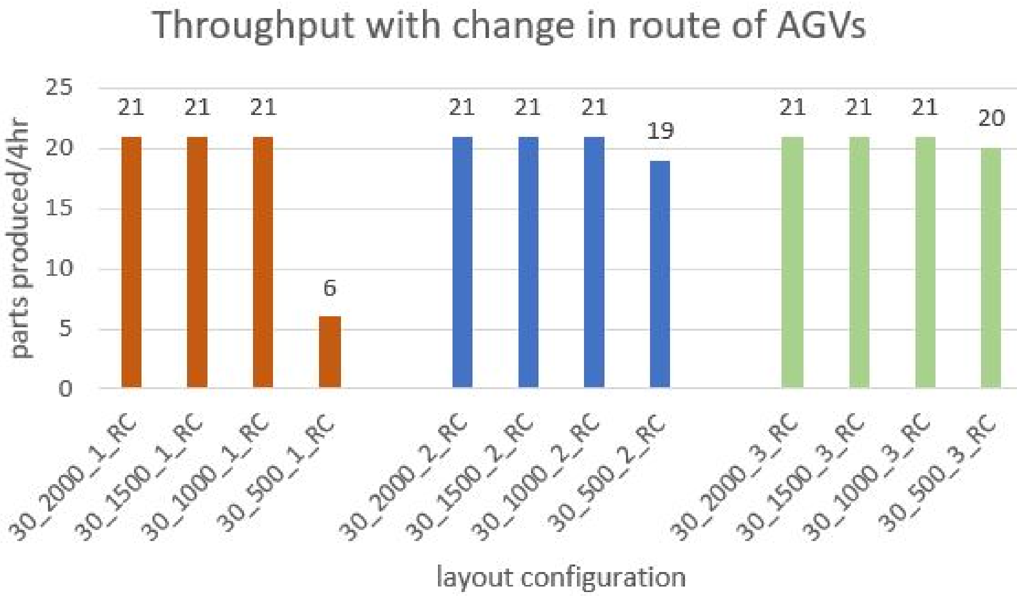

Figure 45: variations in parts produced after route change, X-axis format is [length of layout_feed rate(s)_number of AGV_Route change]

7.5 Pick and place method between conveyor and AGVs

When a component reaches the end of a conveyor belt, it has to be placed onto the AGVs by either a human, a robot, or any other custom placing machine. This process also takes time. In this section, the impact of this pick and place time on the overall production rate of battery packs will be investigated.
In visual components, it can be defined how long it takes to place the component on AGV and how long it takes for the component to be transferred from AGV to the conveyor belt.

when the differences between the number of parts produced in 4 hrs of fig46 and fig47 is compared, it can be seen that when the layouts have 1 AGV it impacts the production rate higher. This can be compensated by adding additional AGV to the production line.

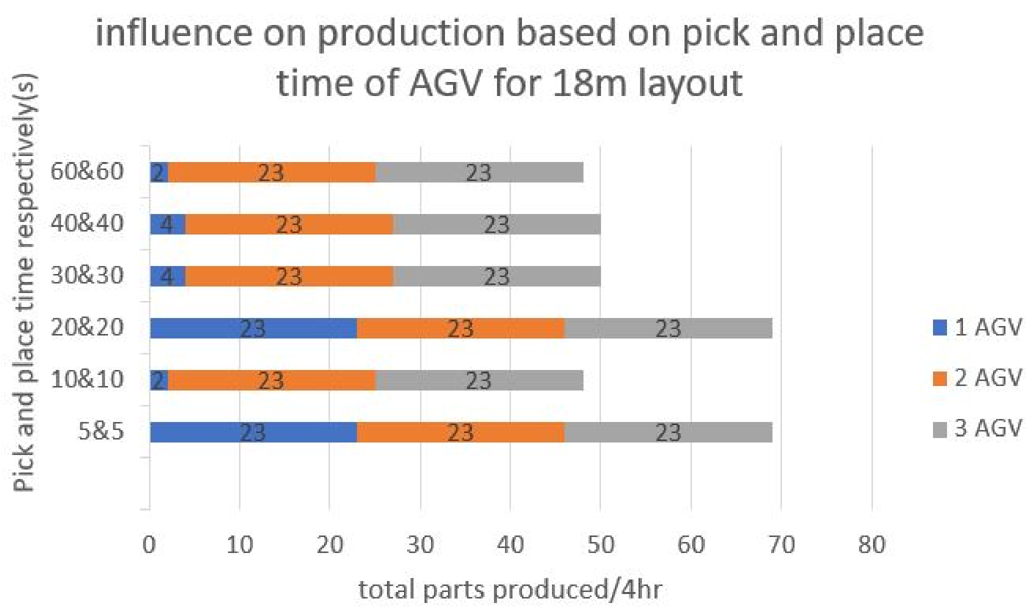

Figure 46: influence of production with variations in pick and place 18m layout. The simulation is run at layouts threshold feed rate

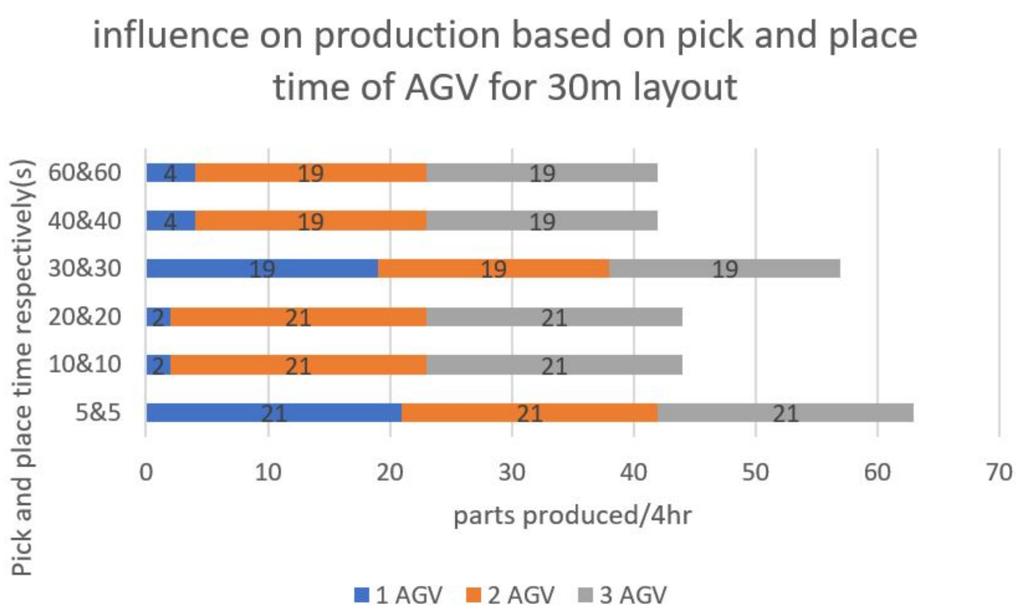

Figure 47: influence of production with variations in pick and place 30m layout. The simulation is run at layouts threshold feed rate

7.5.1 Impact of number of humans

One of the important aspects of lean principles is to introduce automation wherever necessary. In all previous simulations, only 2 humans were considered working at a manual station, and have not considered any other transport solution between the transfer of components from conveyor to AGVs and vice versa was not considered. To simulate the transference of components from the conveyor to AGVs and vice-versa a time delay is added to increase the pick and place time of the AGV. There are other alternate transport solutions to serve the above-mentioned purpose which are as follows:

- Using a robot
- Using humans
- Custom machines

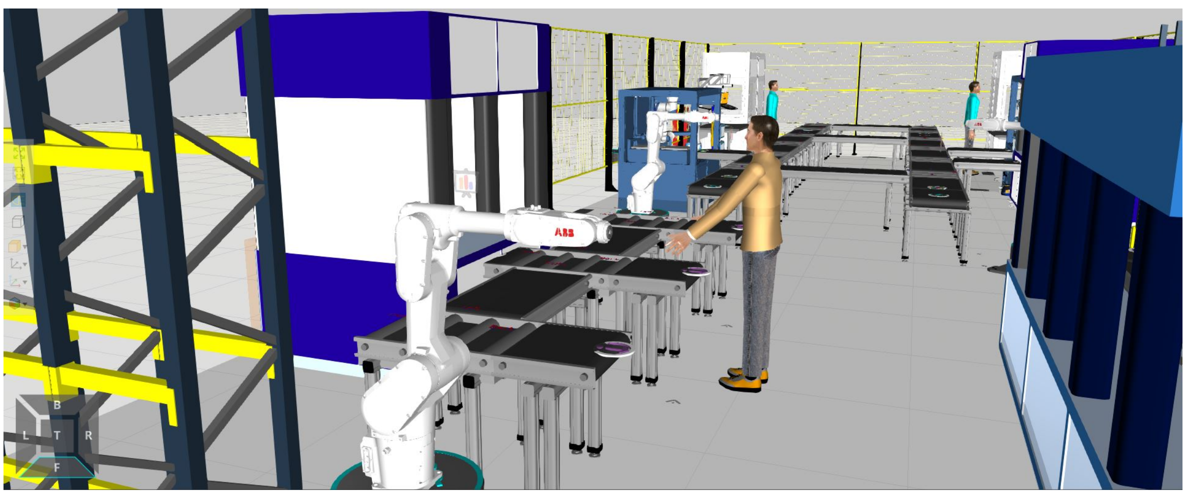

Figure 48: Use of robots and humans as transport links between conveyor and AGVs and vice-versa

In the initial simulation setups, by introducing the above-mentioned delay, the simulation was set up as if there was a custom machine present there. The total production rate when using either a custom machine or a robot will be the same as all the simulations done before. Deviations arise if humans are considered to be the transport solution. Simulation of the process was carried out in the 18m long layout
When the component is at the end of the conveyor, if any human is free at the manual stations, they will become the transport solution and help in the transference of components from conveyors to AGVs and vice-versa. In the above-mentioned sim setup, the throughput decreased to 18, as compared to 23 with the initial setup (initial setup is the simulation parameters set in section7.1), then trying to increase the output in this sim setup by decreasing the batch interval, the human worker is not available when the signal is passed from the conveyor/AGVs, and the humans are walking at the speed of approximately 1m/s. This causes a block in the line which stops production.

Another set of simulations was done, in which the human transport element was only used to transfer the finished pack from AGV to storage. By doing so the total packs produced in 4 hours rose to 20. By this, it can be inferred that to have the max output similar to those of previous simulations at least 2 human workers and either a custom machine or robots as a transport solution between conveyor and AGVs and vice-versa is required. additional simulations considering robots at the conveyor were not conducted, since it is the same as introducing a time delay between the pick and place of components as mentioned in section 7.5.

7.6 impact of variation in flow of components

In all previous simulations, the flow of components from the beginning is In the format of cylindrical cells: prismatic cells: and defects: defects with a quantity ratio of 2:2:1:1. In real-world applications the rejection of cells or a number of cells rejected is not fixed. But in all the simulations conducted, the rejection rate of these cells was fixed and predictable, because if it is unpredictable, for simulation purposes, every time the simulation is running, the output can change. So to create uniformity in simulations the above-mentioned flow of components is considered.
To see the impact on throughput if the order of flow of components is varied, was carried out. For this, 2 other orders, other than the default one is considered.

- P:C:D:D (prismatic:cylindrical:defect: defect)
- D:C:P:D (defect:cylindrical:prismatic: defect)

graph has been plotted with this variation along with changes in the number of AGVs as well. As observed from fig50and fig105, the order of the batch is also a major factor in the production rate. Since prismatic cell battery pack has a lower overall process time than packs with cylindrical cells, feeding this first, results in higher output of the packs.[20]

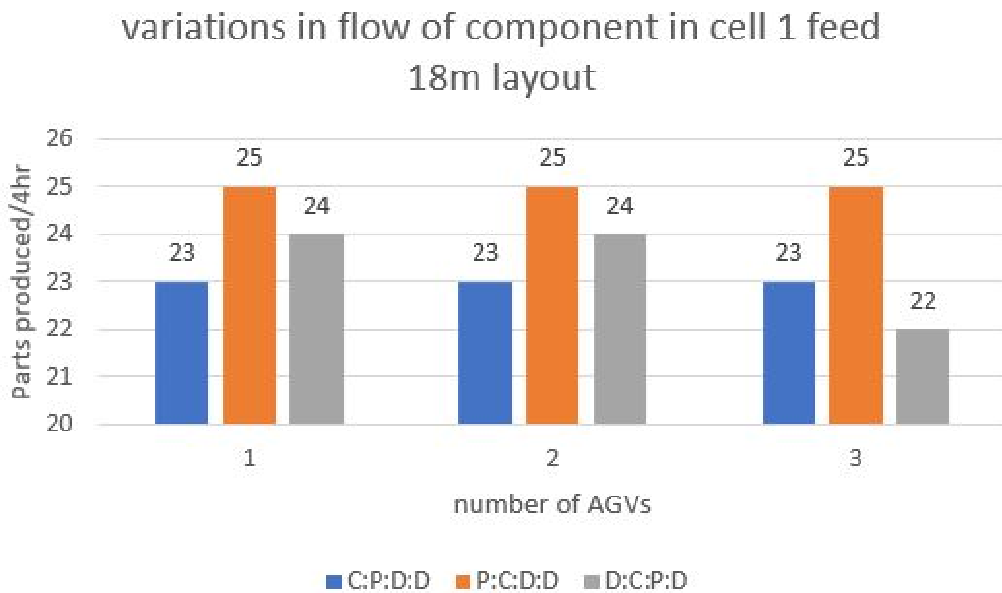

Figure 49: impact on production with respect to variations in batch order 18m layout, where C stands for cylindrical cells, P stands for prismatic cells and D stands for defective cells

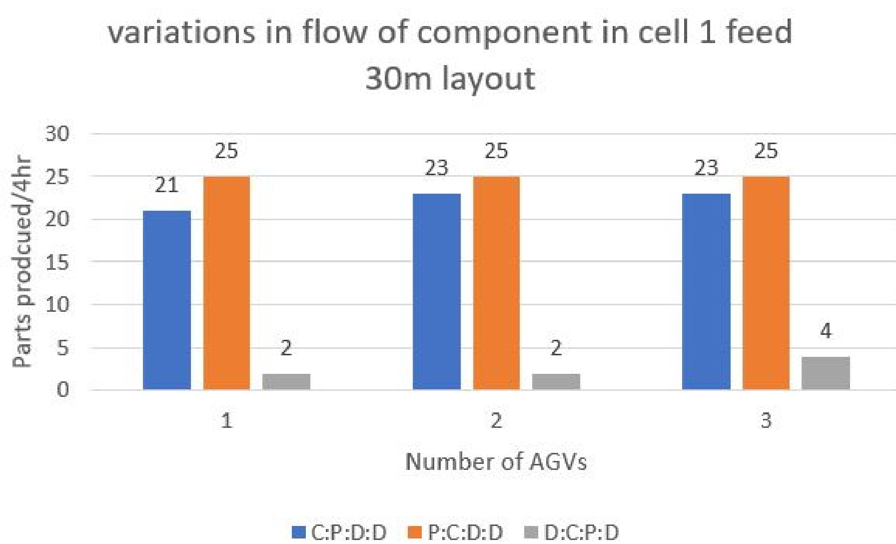

Figure 50: impact on production with respect to variations in batch order 30m layout where C stands for cylindrical cells, P stands for prismatic cells and D stands for defective cells

7.7 Evaluation of factors influencing output and optimizations

From conducting several simulations by varying many factors, certain conclusions can be found.

- The distance between cells was a factor that did not have a large impact on the throughput. Since there is a limitation to a maximum length of 30m for the factory, this small distance can be covered by the AGVs very easily. Since the processing time was very high at manual stations as compared to other processes the Otto 100 has enough idle time to transport all components. There was a slight difference between the output of pack with respect to 1 AGV (output of 21 packs) and 2 AGVs(output of 23 packs) as seen in table 9 and can be inferred from fig 51, but increasing the number of AGVs did not help in increasing the throughput of battery packs.

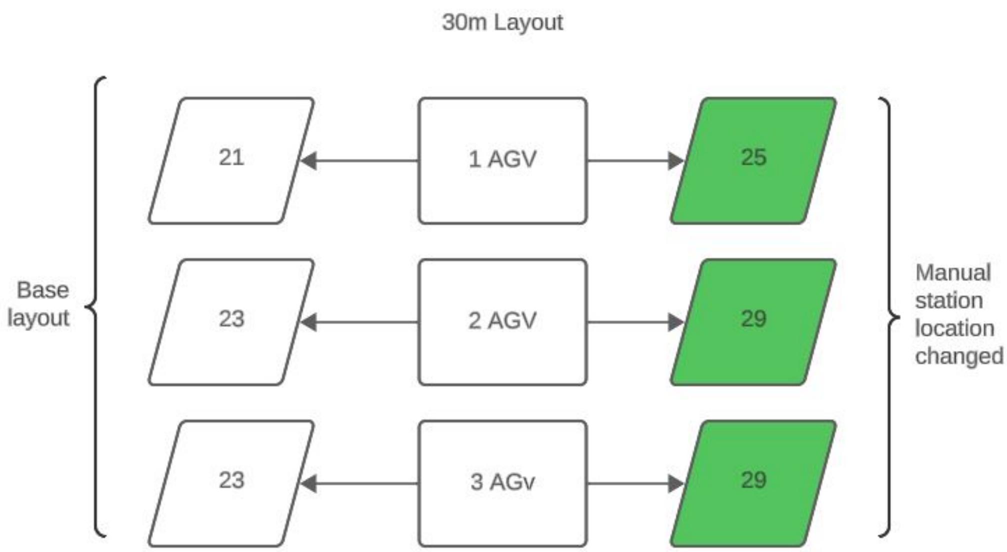

Figure 51: effects of change in location of manual work station in 30m layout

- Station location had a significant influence on the throughput of the pack. The arrangement of the layout was done in such a way that all the high-time-consuming stations were placed on one side of the assembly and the rest of the machines on the other side. The comparison of the output of location changed layouts and the one with no change in location can be seen in table 9. This can also be seen in fig 51 and fig 52. The Green zones indicated an increase in the number of packs produced. All results moving forward are made by using the threshold feed rate before the development of the choke point

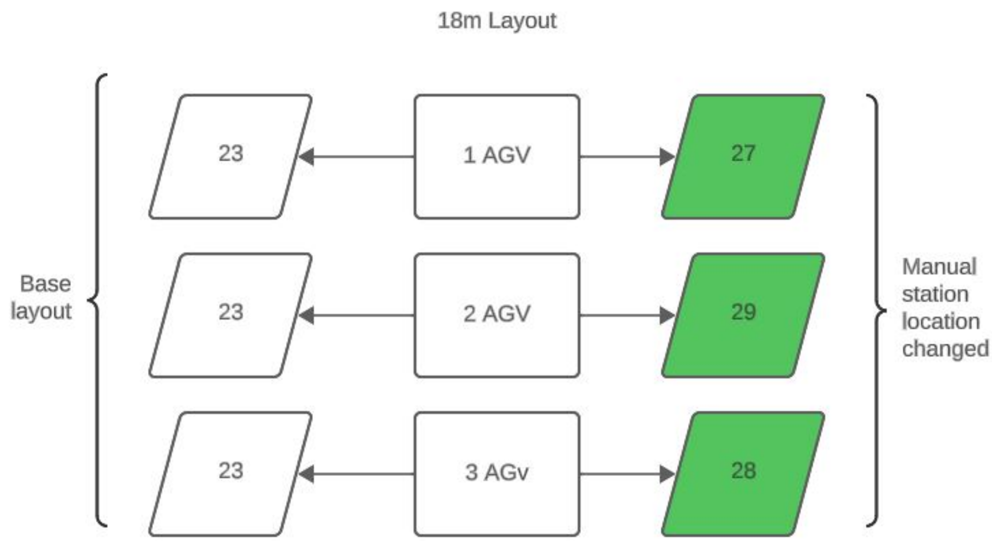

Figure 52: effects of change in location of manual work station in 18m layout

- By increasing the distance of the storage with respect to the cell 3 reference line, the production rate was significantly reduced. Since the exact location of the storage section is not provided, simulating the exact scenario was not possible, but when the graph 40 is observed, there is deviation only after a distance of 20 meters. This is also shown in table 10. The number of packs produced varies based on the number of AGVs used as well. As seen from fig 53, with 1 and 2 AGV when the distance of storage location is under 20 and 50 meters respectively, the production is the same as it would have produced with the storage location at 0m from the reference line. The red zone indicates a drastic drop in the number of packs produced.

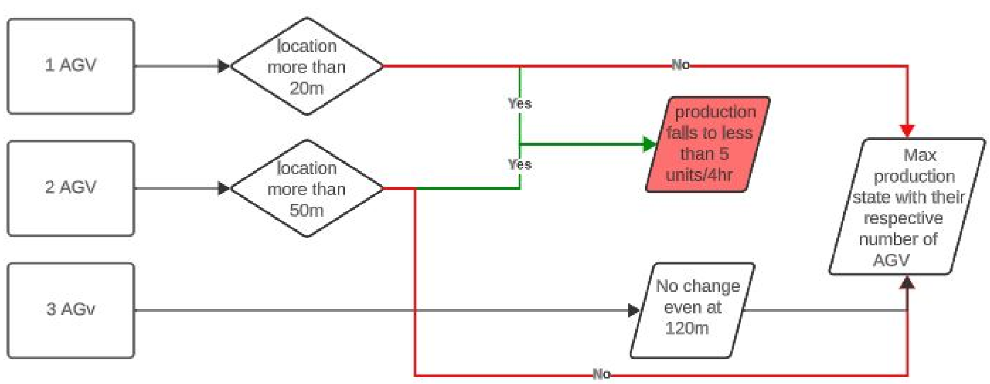

Figure 53: effect of storage location

- Speed of all transport solutions is a very important factor for setting up a facility like this. The number of AGVs and the speed of AGVs have a high influence on each other. This can be seen in table 12, fig 54 and fig 55. With 1 AGV, when the speed drops below 1000mm/s, the production drops drastically as indicated in the red zone. The no-change zone means that there is no change in production rate even after reducing and increasing the AGV speed.

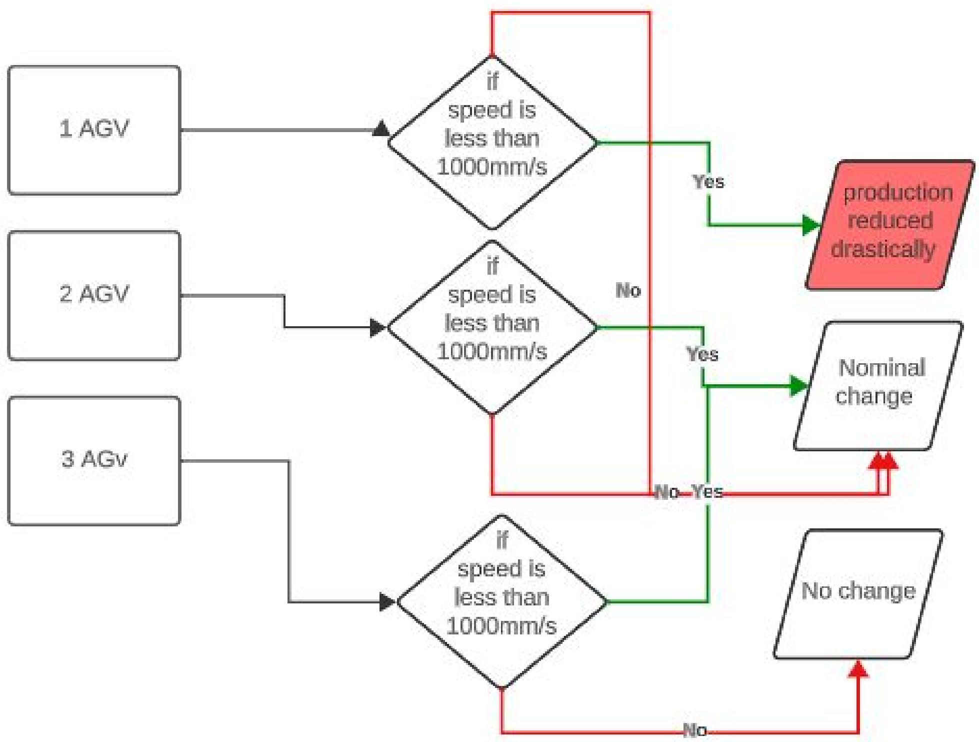

Figure 54: effect of variation in AGVs speed on 30m layout

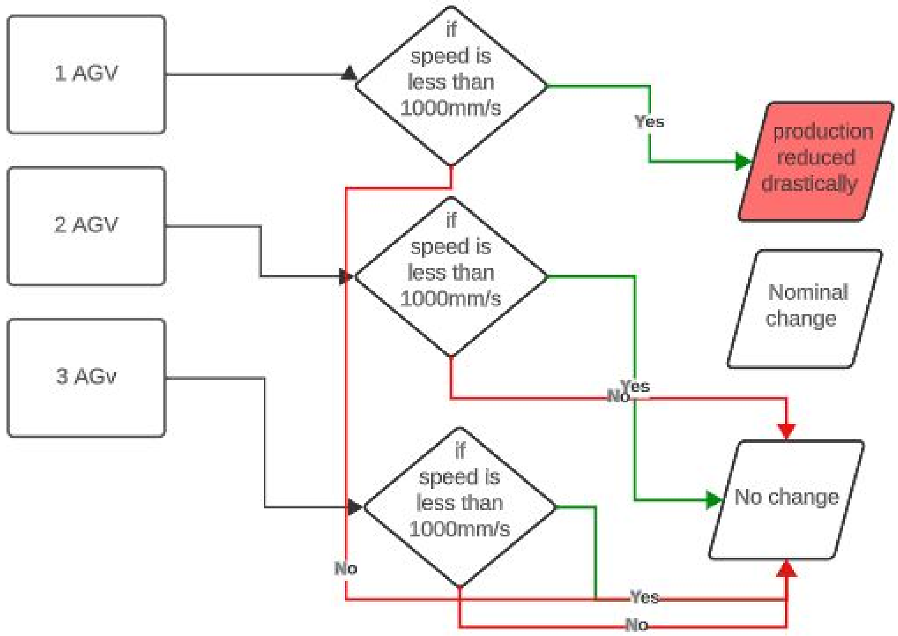

Figure 55: effect of variation in AGVs speed on 18m layout

- The time taken for pickup of components from one station by AGVs and dropping them to another is also an important factor. The red zones in fig 57 and 56 are when production drops drastically.

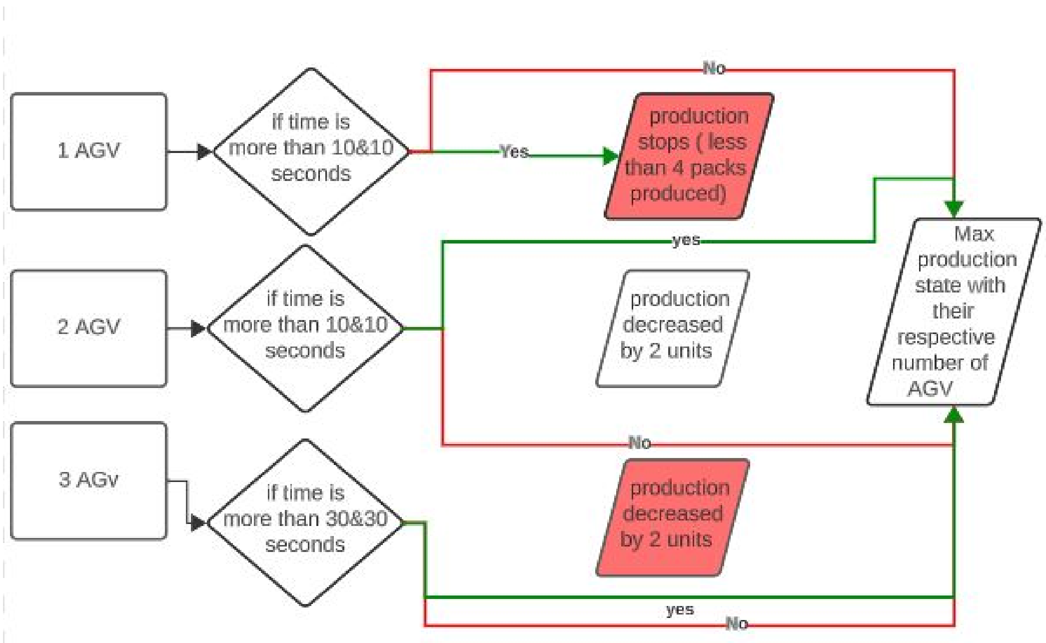

Figure 56: effect of variation in AGVs pick and place time for 18m layout

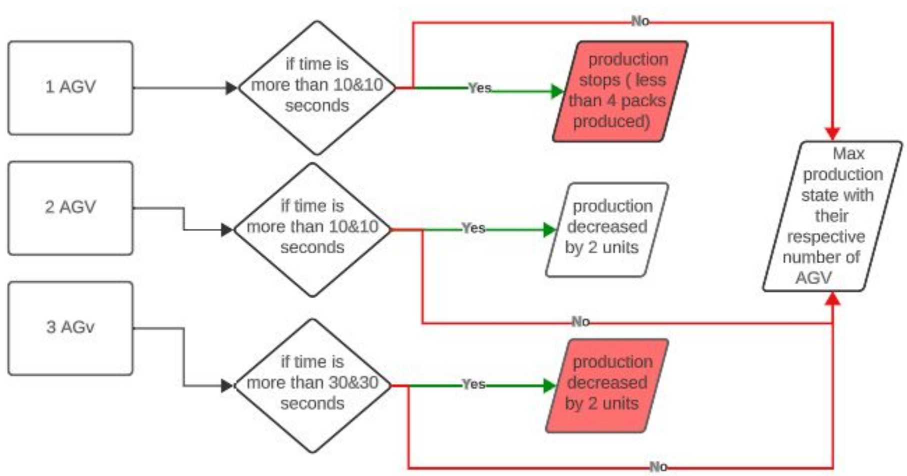

Figure 57: effect of variation in AGVs pick and place time for 30m layout

- The route of the AGV should be planned based on the desired floor layout. The route has to be defined in such a way that the total distance traveled is less and it avoids all obstacles. Reducing the speed does have a huge impact on production as seen in table 13, when the speed of AGV is as low as 500mm/s. The route and speed of AGV should be carefully planned.
- Based on the collected data as shown in table 14, it can be inferred that the flow

of components in the batch and the number of human works/transport solutions present have a significant impact on production. If all the process times are defined, the exact availability of the workers can be found out and validate whether they have time to work on other tasks

These conclusions can be tabulated to understand how each factor is responsible for the production of battery packs

30m lay-out			30m layout location change			18m layout			18m layout location change		
Feed	AGV	Output	Feed	AGV	Output	Feed	AGV	Output	Feed	AGV	Output
205	1	21	200	1	25	200	1	23	180	1	27
180	2	23	140	2	29	210	2	23	150	2	28
180	3	23	140	3	29	180	3	23	150	3	28
1000	1	10	1000	1	10	1000	1	10	1000	1	10
	2	10		2	10		2	10		2	10
	3	10		3	10		3	10		3	10
1500	1	8	1500	1	8	1500	1	8	1500	1	8
	2	8		2	8		2	8		2	8
	3	8		3	8		3	8		3	8
2000	1	7	2000	1	7	200	1	7	2000	1	7
	2	7		2	7		2	7		2	7
	3	7		3	7		3	7		3	7

Table 9: Data of variation between feed rate and number of AGV between both 30m and 18 layout including data when location of stations were changed

30m layout				18m layout			
feed(s)	AGV	distance(Dx)(in m)	Output	feed	AGV	distance(Dx)(in m)	Output
205	1	10	21	200	1	10	23
	1	20	21		1	20	23
	1	50	5		1	50	4
	1	80	2		1	80	2
	1	120	2		1	120	2
180	2	10	21	210	2	10	23
	2	20	21		2	20	23
	2	50	21		2	50	21
	2	80	4		2	80	4
	2	120	2		2	120	2
180	3	10	21	180	3	10	23
	3	20	21		3	20	23
	3	50	21		3	50	23
	3	80	21		3	80	23
	3	120	21		3	120	23

Table 10: Data of variation of storage location distance

30m layout			18m layout		
AGV	Pick and place time(s)	Output	AGV	Pick and place time(s)	Output
1	5,5	21	1	5,5	23
1	10,10	2	1	10,10	2
1	20,20	2	1	20,20	23
1	30,30	19	1	30,30	4
1	40,40	4	1	40,40	4
2	60,60	4	2	60,60	2
2	5,5	23	2	5,5	23
2	10,10	21	2	10,10	23
2	20,20	21	2	20,20	23
2	30,30	19	2	30,30	23
3	40,40	19	3	40,40	23
3	60,60	19	3	60,60	23
3	5,5	23	3	5,5	23
3	10,10	21	3	10,10	23
3	20,20	21	3	20,20	23
3	30,30	19	3	30,30	23
3	40,40	19	3	40,40	23
3	60,60	19	3	60,60	23

Table 11: Data of variation of pick and place time of AGVs

	30m layout			18m layout	
AGV	speed(mm/s)	output	AGV	speed(mm/s)	output
1	2000	21	1	2000	23
1	1500	18	1	1500	23
1	1000	6	1	1000	23
1	500	6	1	500	2
2	2000	23	2	2000	23
2	1500	23	2	1500	23
2	1000	21	2	1000	23
2	500	19	2	500	23
3	2000	23	3	2000	23
3	1500	23	3	1500	23
3	1000	23	3	1000	23
3	500	20	3	500	23

Table 12: Data of variation of AGVs speed

30m layout		
AGV	speed(mm/s)	output
1	2000	21
1	1500	21
1	1000	21
1	500	6
2	2000	23
2	1500	23
2	1000	23
2	500	19
3	2000	23
3	1500	23
3	1000	23
3	500	20

Table 13: Data of variation by changing AGVs route

30m layout			18m layout		
C:P:D:D	1	21	C:P:D:D	1	23
C:P:D:D	2	23	C:P:D:D	2	23
C:P:D:D	3	23	C:P:D:D	3	23
P:C:D:D	1	25	P:C:D:D	1	25
P:C:D:D	2	25	P:C:D:D	2	25
P:C:D:D	3	25	P:C:D:D	3	25
D:C:P:D	1	2	D:C:P:D	1	24
D:C:P:D	2	2	D:C:P:D	2	24
D:C:P:D	3	4	D:C:P:D	3	22

Table 14: Data of variation by changing batch order. Here C refers to cylindrical cells, P refers to prismatic cells, D refers to defects

8 Conclusions, discussion and recommendations

The goal of this project was to find the key factors for designing a flexible battery pack assembly line. However, constructing such an assembly line has its own limitations in the real world and in the simulation world.

8.1 Limitations of the processes and simulation

From the beginning of the simulation, several factors were assumed, the most important being the process times. Since there's no publicly available information on process times accurately modeling the simulation was not possible. Variations in process time can have a significant impact on other factors as well. Comparing all the process in the production of the battery pack, the most time-consuming is the manual process, where testing and certain assembly takes place. In all simulations conducted, it is considered to be 10 minutes, but this can vary depending on the final product intended. One major problem faced during the simulation was how to make the conveyor system smart. If a choke point occurs, the conveyor has to redirect the product to some other available output. Scripting this is a huge task, and if done properly, it can simulate the assembly line more efficiently. But the positive thing is this model can be used again when all the actual process information becomes available, as the process timing can be changed by editing the process node in visual components. In a manual process, there are multiple tasks happening, and the time interval between those tasks, which depicts the availability of the worker can't be well determined because the process times for each of those tasks are undetermined.

8.2 Process improvement

As discussed in the section 8, the biggest bottleneck is the manual station. It is important to introduce more automation in this station. TRIZ can be a great tool in assisting the creation of new processes and machines to reduce the bottlenecks In the assembly line. The theory of constraints can be a very useful tool in the optimization of the layout. The biggest constraint of the designed assembly line which affects the output is the manual stations. constant improvements have to be made on this station to reduce its impact on production as much as possible. Implementation of Montractec system as shown in section5.2.2 should be carefully looked into.

8.3 Simulation improvements

Since the Montratec model was not available in Visual components, a conveyor system that imitates the flow of Montratec system was used. Since the track system of Montratec is superior as compared to a conveyor, more effort has to be invested in trying to develop such a machine in visual components using Python scripting, PLC, etc. Based on the final layout of the factory the path for AGV and humans has to be defined. Since the order of batches of cylindrical and prismatic cells will be fed initially, this may not reflect the real-world case. This input requires data from the proper scheduling of components. Simulation of how certain components reach the workstation following just-in-time principle is not modeled. This simulation can be accomplished by using AGV to feed the components from inventory to stations or by considering the components are already there. It can be observed that in a lot of graphs during the optimization, the production rates drop sharply, this is because whenever there is a development of a choke point, the simulation stops. No addition to the process that intends to resolve this issue is not considered, for example, if a choke point happens in real life, one section of the line is stopped and the problem Is fixed manually.

8.4 Future work

The use of these kinds of models can be extremely beneficial when optimizing or creating new assembly lines. This model can be edited very easily to accommodate the real process times and can be simulated to find areas of optimization. Furthermore, this model can also be integrated with PLC software like Siemens S7 PLC to model advanced process flows and machines. Once the real work assembly line is set up, this model can be used as a first step in designing a digital twin. Recent versions of Visual components also have build plugins like Doosan Dart Studio by which the model in Visual components can connect to its physical counterpart in real world

8.5 Conclusion

A flexible battery pack assembly line is an interesting setup. Because of the flexibility it offers, various products can be made. The factors that were important while designing a flexible assembly line were found and simulated to find their impact on production. The assembly line structure and the transport solutions can be further improved to achieve the production rates required. With the recommendations mentioned above, a full digital copy of the physical model can be created.

Bibliography

[1] VĂSCAN Iulia and SZABÓ Loránd. A brief history of electric vehicles. *Journal of Computer Science & Control Systems*, 15(1), 2022.

[2] Fazel Mohammadi and Mehrdad Saif. A comprehensive overview of electric vehicle batteries market. *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, page 100127, 2023.

[3] Selamat Muslimin, Zainuddin Nawawi, Bhakti Yudho Suprapto, and Tresna Dewi. Comparison of batteries used in electrical vehicles. In *5th FIRST T1 T2 2021 International Conference (FIRST-T1-T2 2021)*, pages 421–425. Atlantis Press, 2022.

[4] Apply for a subsidy to buy or lease an electric car — vehicles — government.nl. https://www.government.nl/topics/vehicles/

apply-for-a-subsidy-to-buy-or-lease-an-electric-car, 2023. Accessed: 2023-09-10.

[5] Ev-volumes - the electric vehicle world sales database. https://www.ev-volumes.com/, 2023. Accessed: 2023-09-10.

[6] Iea report on global sales. https://www.iea.org/reports/global-ev-outlook-2023/executive-summary, 2023. Accessed: 2023-09-10.

[7] E-bike markets. https://straitsresearch.com/report/e-bike-battery-pack-market, 2023. Accessed: 2023-09-10.

[8] Xin Sun, Gang Liu, Han Hao, Zongwei Liu, and Fuquan Zhao. Modeling potential impact of covid-19 pandemic on global electric vehicle supply chain. *Iscience*, 25(3), 2022.

[9] supply chain russia - ukraine war. https://www.ing.com/Newsroom/News/Tightening-supply-shakes-up-battery-metal-dynamics.htm, 2023. Accessed: 2023-09-10.

[10] Tesla battery production is the real bottleneck, not model 3 production, analyst says. https://www.cnbc.com/2018/04/18/tesla-battery-production-is-the-real-bottleneck-not-model-3-production.html, 2023. Accessed: 2023-09-10.

[11] N Lewchalermwong, M Masomtob, V Lailuck, and C Charoenphonphanich. Material selection and assembly method of battery pack for compact electric vehicle. In *IOP Conference Series: Materials Science and Engineering*, volume 297, page 012019. IOP Publishing, 2018.

[12] G Marin-Garcia, G Vazquez-Guzman, JM Sosa, Adolfo R Lopez, PR Martinez-Rodriguez, and D Langarica. Battery types and electrical models: A review. In *2020 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*, volume 4, pages 1–6. IEEE, 2020.

[13] Steffen Link, Christoph Neef, and Tim Wicke. Trends in automotive battery cell design: A statistical analysis of empirical data. *Batteries*, 9(5):261, 2023.

[14] Tesla cells. https://insideevs.com/news/587455/batteries-tesla-using-electric-cars/, 2023. Accessed: 2023-09-10.

[15] AJIT Sharma, PHILIP Zanotti, and LAXMI P Musunur. Robotic automation for electric vehicle battery assembly: Digital factory design and simulation for the electric future of mobility. *IEEE Access*, 7:170961, 2019.

[16] RL Gitzendanner, PG Russell, C Marsh, and RA Marsh. Design and development of a 20 ah li-ion prismatic cell. *Journal of power sources*, 81:847–852, 1999.

[17] Robert Schröder, Muhammed Aydemir, and Günther Seliger. Comparatively assessing different shapes of lithium-ion battery cells. *Procedia Manufacturing*, 8:104–111, 2017.

[18] Georgi Kovachev, Hartmuth Schröttner, Gregor Gstrein, Luigi Aiello, Ilie Hanzu, H Martin R Wilkening, Alexander Foitzik, Michael Wellm, Wolfgang Sinz, and Christian Ellersdorfer. Analytical dissection of an automotive li-ion pouch cell. *Batteries*, 5(4):67, 2019.

[19] Battery module. https://www.laserax.com/blog/battery-pack-design, 2023. Accessed: 2023-09-10.

[20] Iñigo Alonso Fernandez. *Trading Off Between Flexibility and Product Platform Constraints for Effective Technology Introduction*. PhD thesis, Chalmers Tekniska Hogskola (Sweden), 2022.

[21] Xiao-Guang Yang, Teng Liu, and Chao-Yang Wang. Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles. *Nature Energy*, 6(2):176–185, 2021.

[22] Catl launches ctp 3.0 battery "qilin," achieves the highest integration level in the world. https://www.catl.com/en/news/958.html, 2023. Accessed: 2023-09-10.

[23] The next-generation battery pack design: from the byd blade cell to module-free battery pack. https://medium.com/batterybits/the-next-generation-battery-pack-design-from-the-byd-blade-cell-to-module-free-ba 2023. Accessed: 2023-09-10.

[24] Changyong Jin, Yuedong Sun, Jian Yao, Xuning Feng, Xin Lai, Kai Shen, Huaibin Wang, Xinyu Rui, Chengshan Xu, Yuejiu Zheng, et al. No thermal runaway propagation optimization design of battery arrangement for cell-to-chassis technology. *ETransportation*, 14:100199, 2022.

[25] battert sorting machine. https://www.winackbattery.com/products/Battery-Sorter.html, 2023. Accessed: 2023-09-10.

[26] Otto 100 specifications. https://ottomotors.com/amrs, note = Accessed: 2023-09-10, year = 2023.

[27] montratec systems. https://www.montratec.de/en/products/, 2023. Accessed: 2023-09-10.

[28] Abhishek Das, Dezhi Li, David Williams, and David Greenwood. Joining technologies for automotive battery systems manufacturing. *World Electric Vehicle Journal*, 9(2):22, 2018.

[29] Martin J Brand, Philipp A Schmidt, Michael F Zaeh, and Andreas Jossen. Welding techniques for battery cells and resulting electrical contact resistances. *Journal of Energy Storage*, 1:7–14, 2015.

[30] Caihao Weng, Xuning Feng, Jing Sun, and Huei Peng. State-of-health monitoring of lithium-ion battery modules and packs via incremental capacity peak tracking. *Applied Energy*, 180:360–368, 2016.

[31] Is now the time to invest in manufacturing automation? ://www.rmbank.com/business-insights/invest-manufacturing-automation, 2023. Accessed: 2023-09-10.

[32] Flávia Pires, Ana Cachada, José Barbosa, António Paulo Moreira, and Paulo Leitão. Digital twin in industry 4.0: Technologies, applications and challenges. In *2019 IEEE 17th International Conference on Industrial Informatics (INDIN)*, volume 1, pages 721–726. IEEE, 2019.

[33] Hsiang-Hsi Huang, Wen Pei, Horng-Huei Wu, and Ming-Der May. A research on problems of mixed-line production and the re-scheduling. *Robotics and Computer-Integrated Manufacturing*, 29(3):64–72, 2013.

Appendices

A Throughput with variations in feed rate and AGvs

for calculation of a number of packs produced graph was plotted with time and the total parts produced were added together.

A.1 30m layout with variation in feed rates

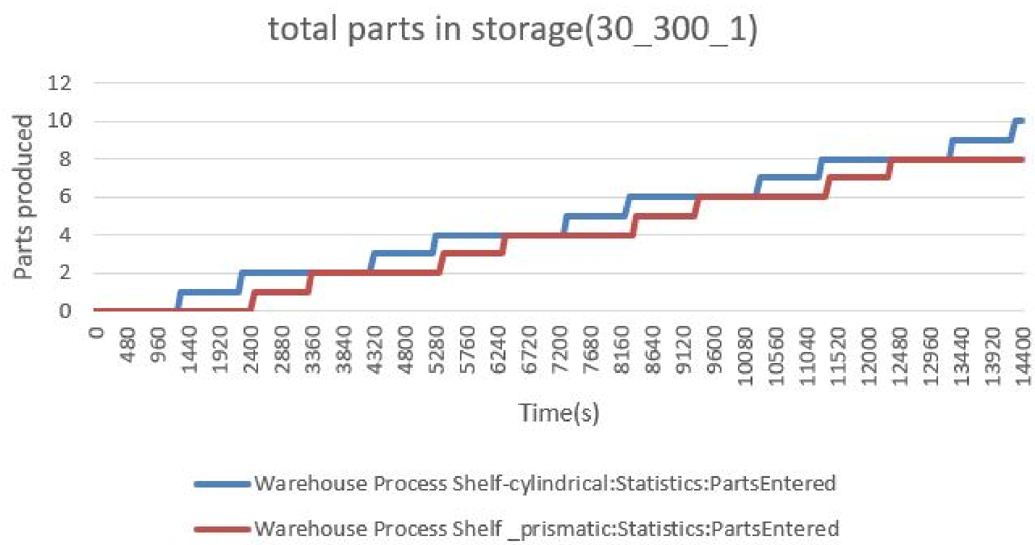

Figure 58: Total packs produced in 4 hours in layout config 30-300-1

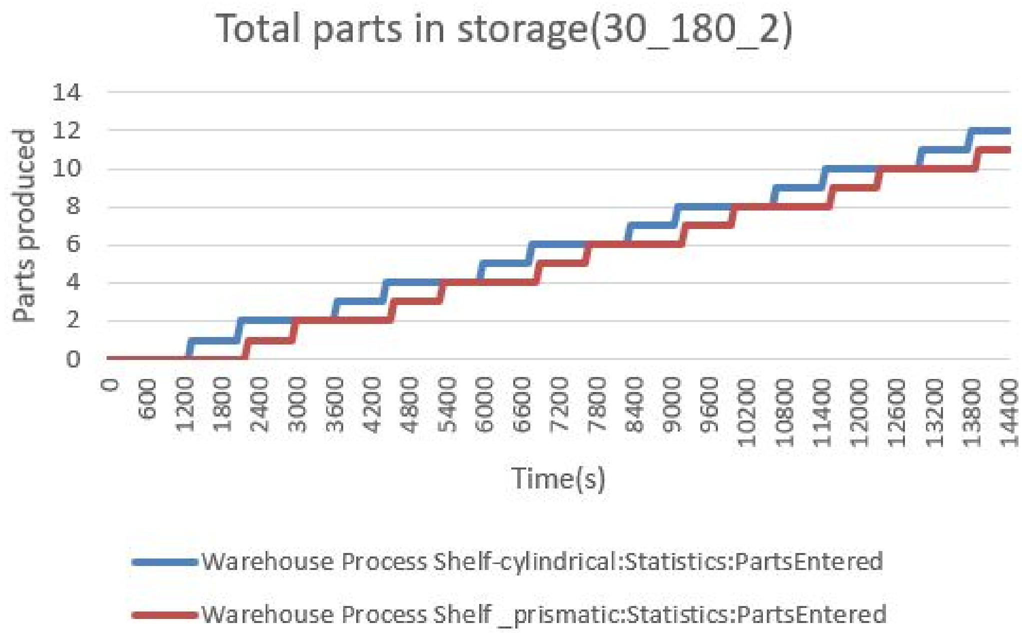

Figure 59: Total packs produced in 4 hours in layout config 30-180-2

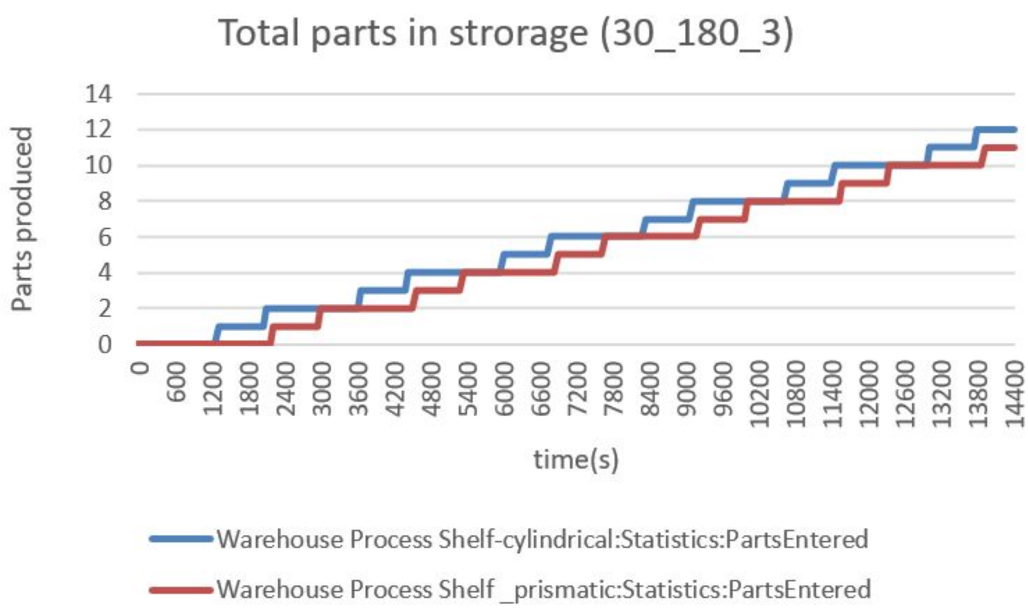

Figure 60: Total packs produced in 4 hours in layout config 30-180-3

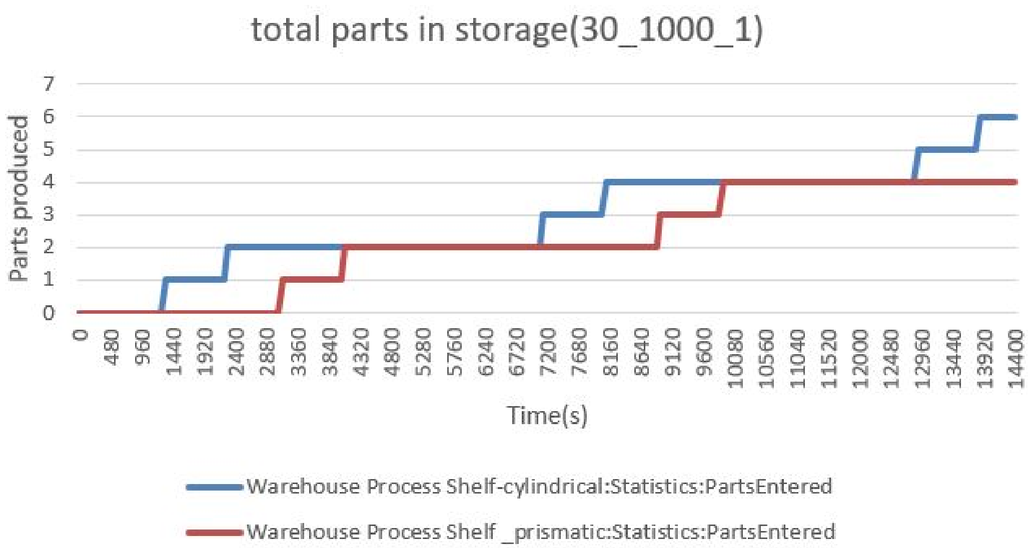

Figure 61: Total packs produced in 4 hours in layout config 30-1000-1

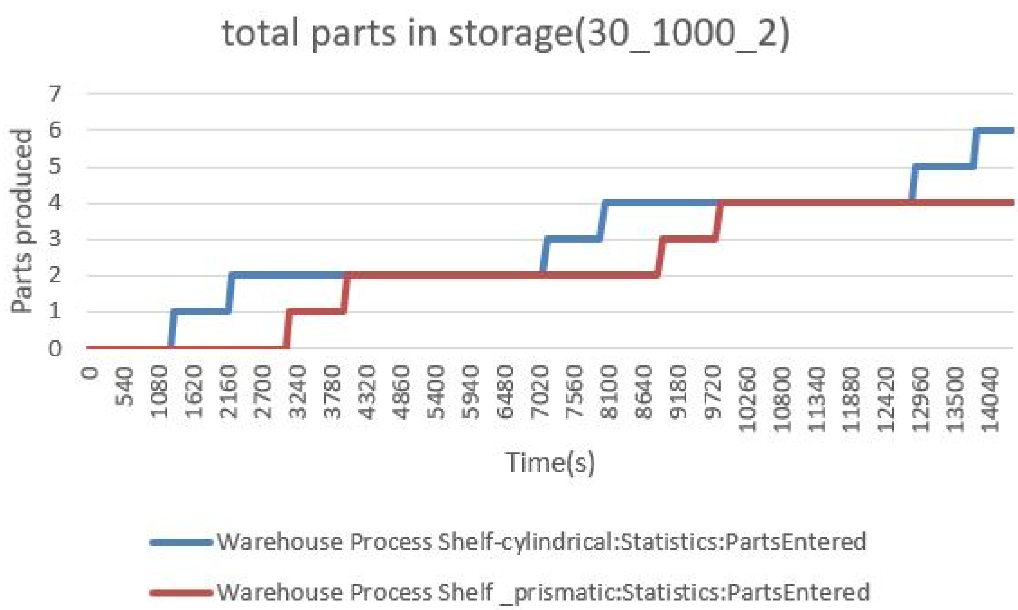

Figure 62: Total packs produced in 4 hours in layout config 30-1000-2

A.2 18m layout with variation in feed rates

A.3 30m layout with variation in feed rate and change in process location

Calculation was done to check how many packs were produced after modifying the base layout to process location(pick and place machine and manual workstation.

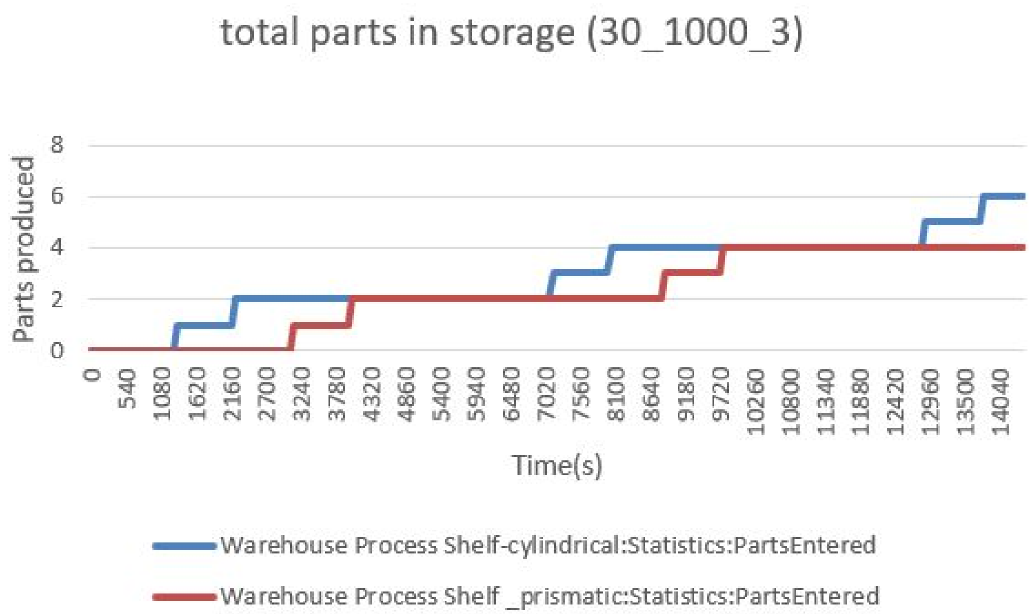

Figure 63: Total packs produced in 4 hours in layout config 30-1000-3

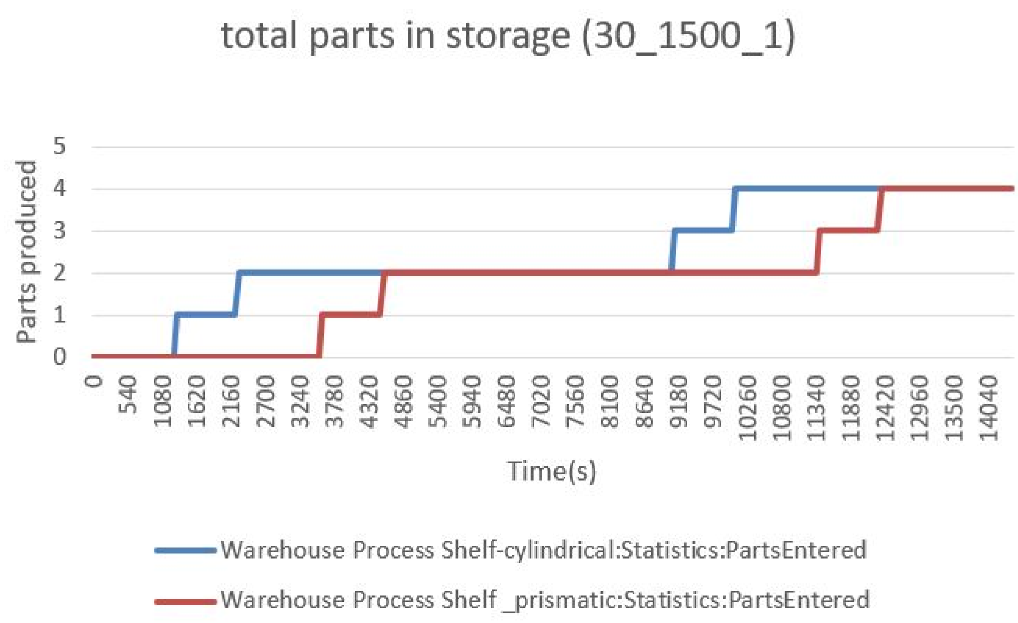

Figure 64: Total packs produced in 4 hours in layout config 30-1500-1

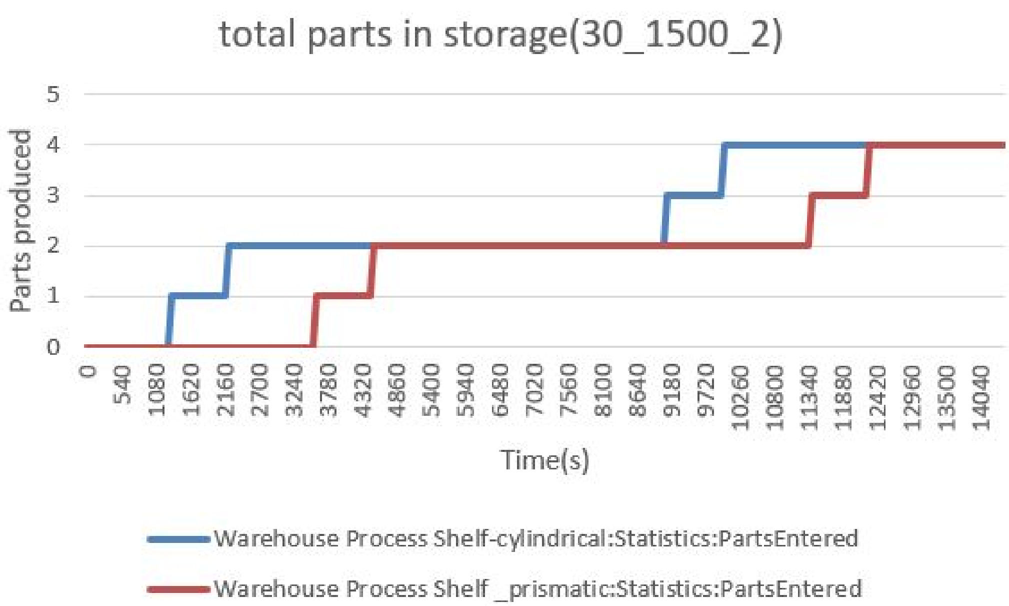

Figure 65: Total packs produced in 4 hours in layout config 30-1500-2

Figure 66: Total packs produced in 4 hours in layout config 30-1500-3

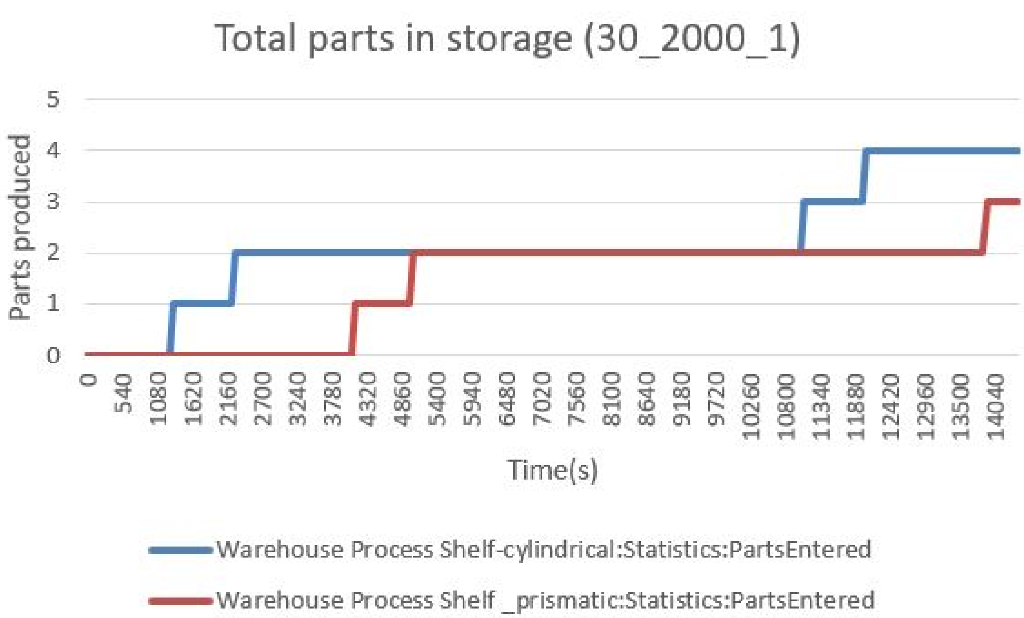

Figure 67: Total packs produced in 4 hours in layout config 30-2000-1

A.4 18m layout with variation in feed rate and change in process location

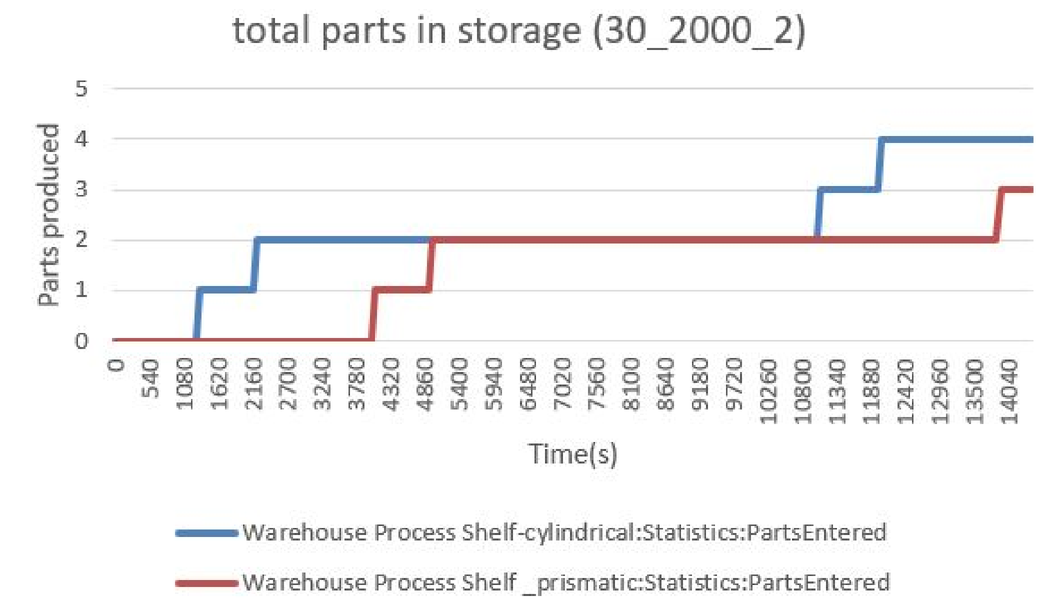

Figure 68: Total packs produced in 4 hours in layout config 30-2000-2

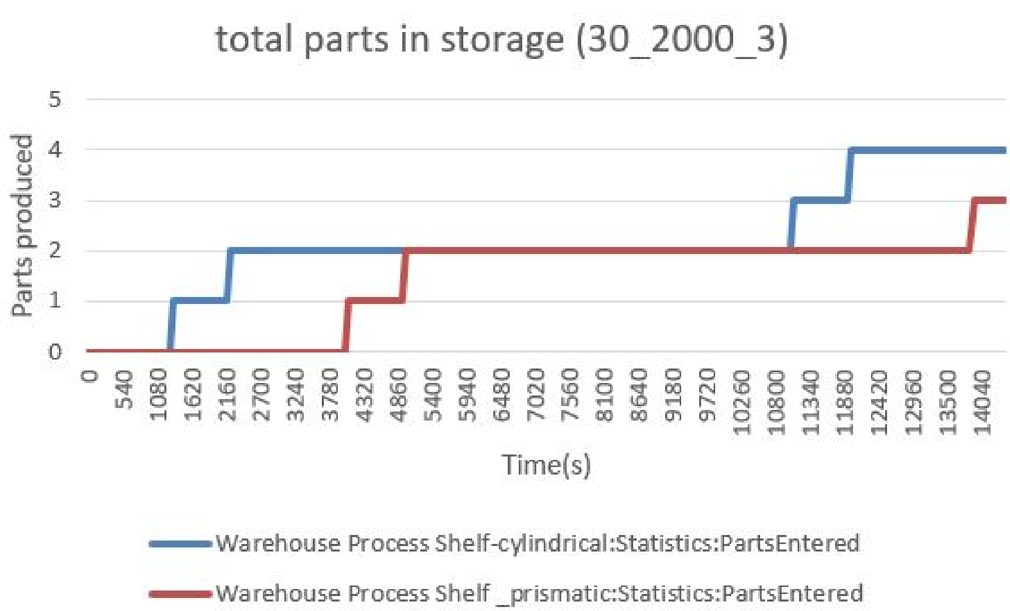

Figure 69: Total packs produced in 4 hours in layout config 30-2000-3

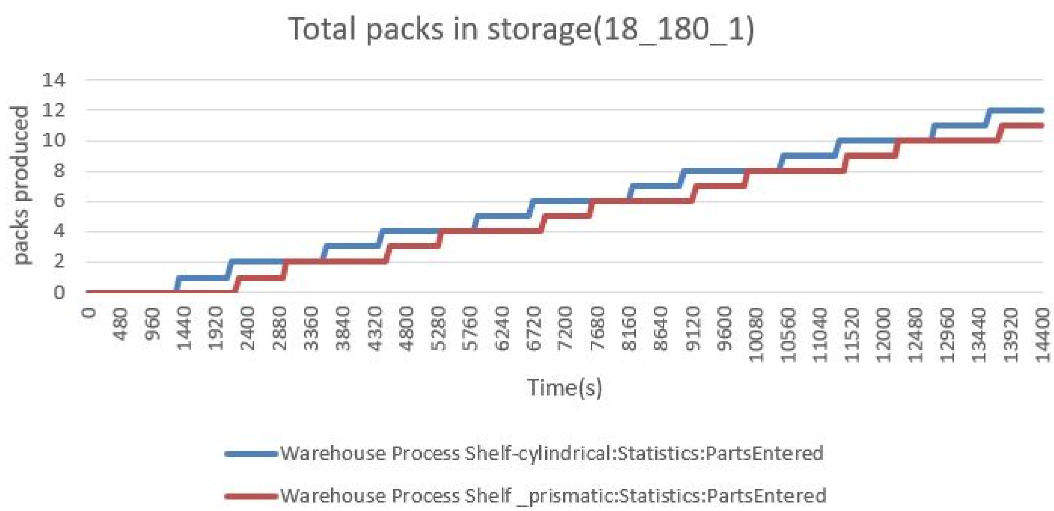

Figure 70: Total packs produced in 4 hours in layout configuration 18-180-1

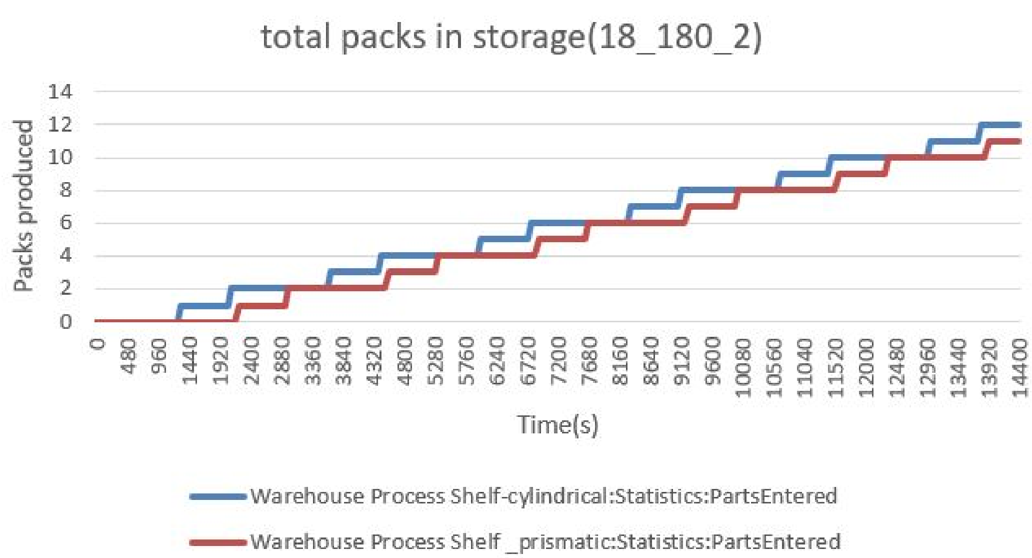

Figure 71: Total packs produced in 4 hours in layout configuration 18-180-1

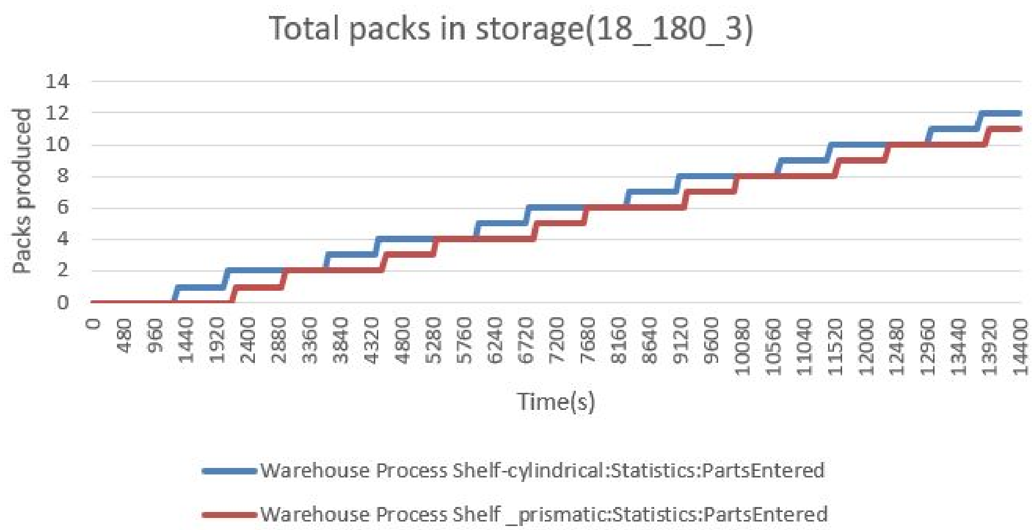

Figure 72: Total packs produced in 4 hours in layout configuration 18-180-1

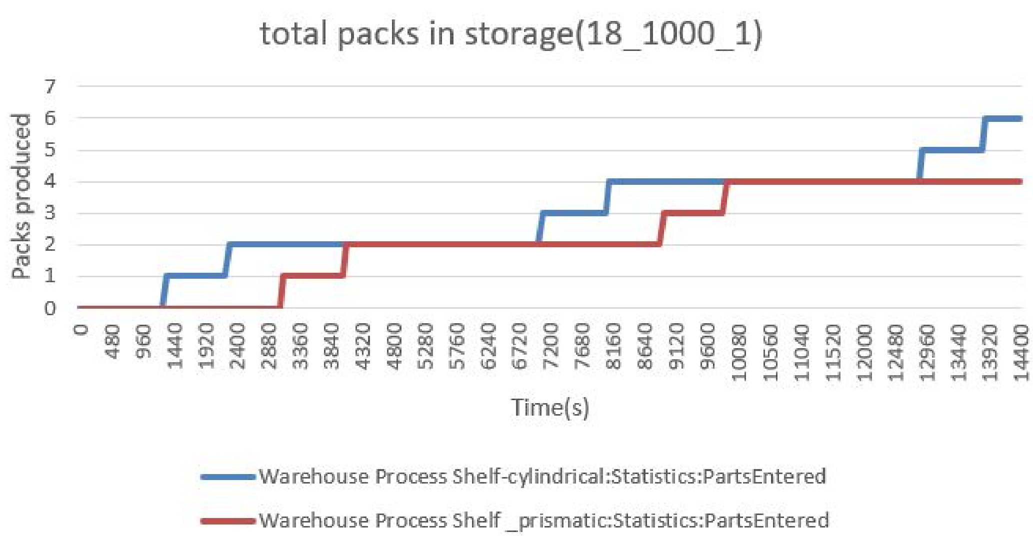

Figure 73: Total packs produced in 4 hours in layout configuration 18-180-1

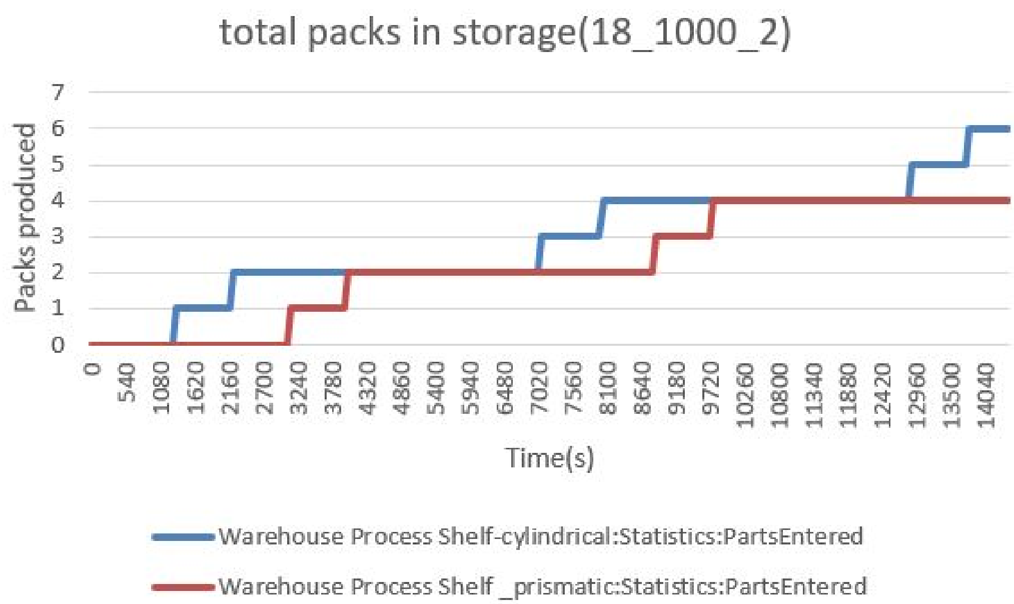

Figure 74: Total packs produced in 4 hours in layout configuration 18-180-1

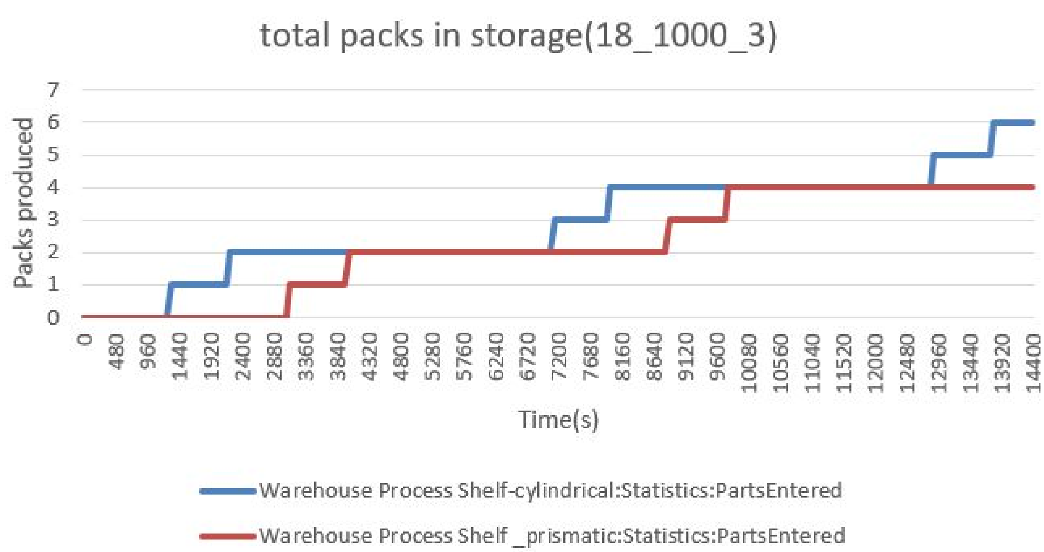

Figure 75: Total packs produced in 4 hours in layout configuration 18-180-1

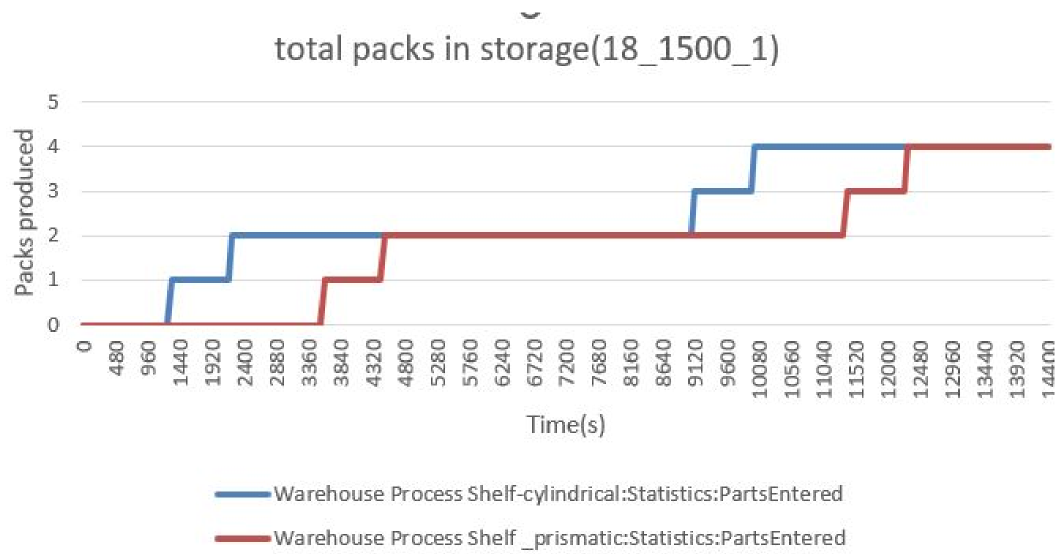

Figure 76: Total packs produced in 4 hours in layout configuration 18-180-1

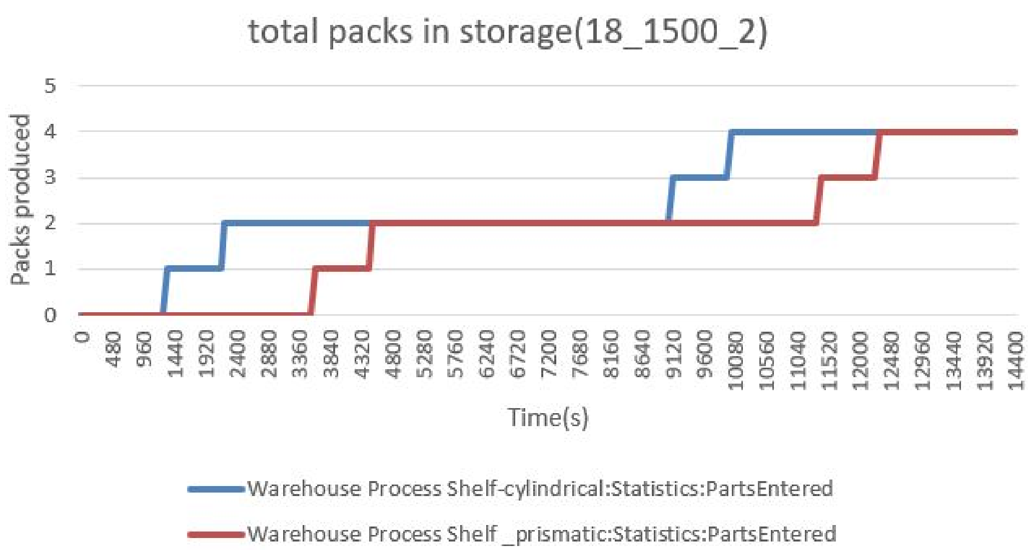

Figure 77: Total packs produced in 4 hours in layout configuration 18-180-1

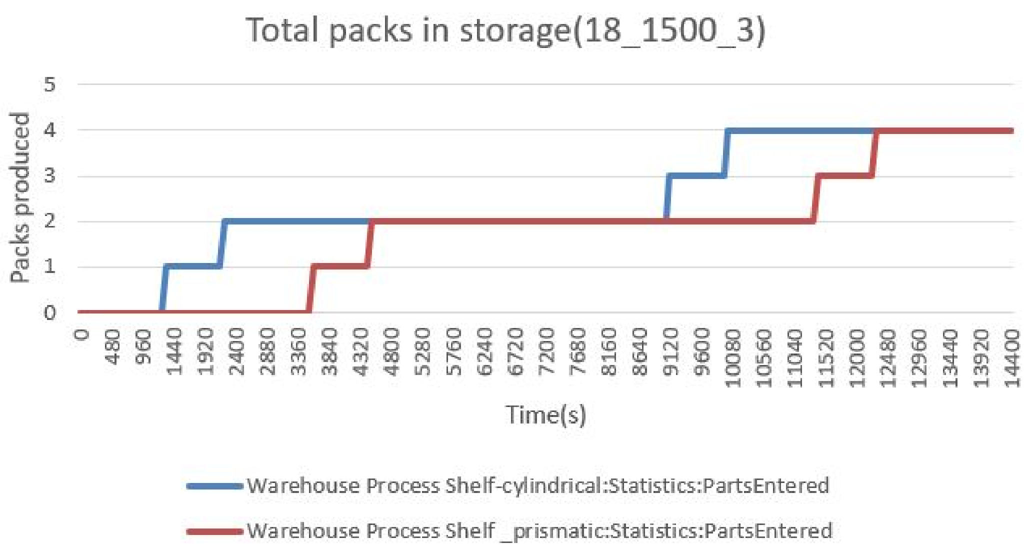

Figure 78: Total packs produced in 4 hours in layout configuration 18-180-1

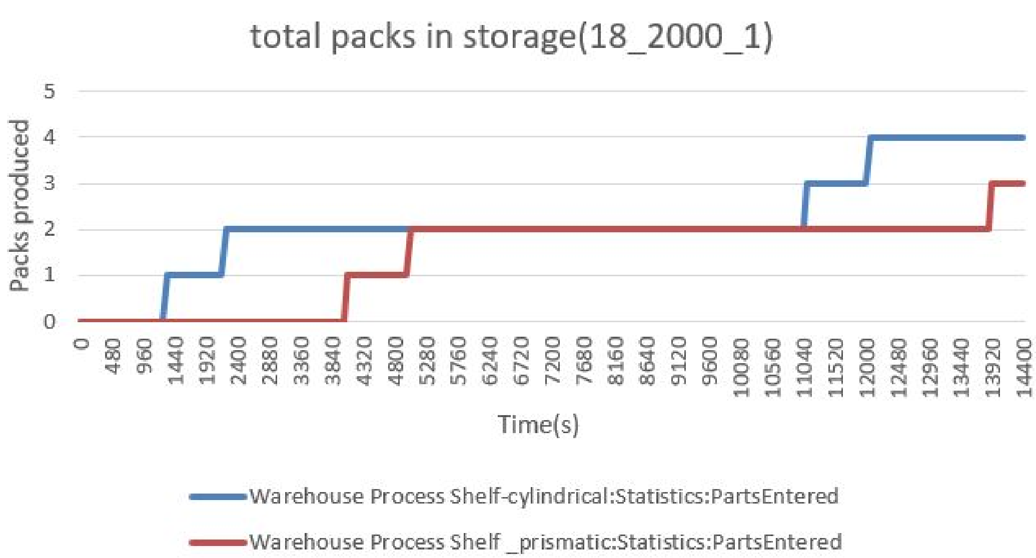

Figure 79: Total packs produced in 4 hours in layout configuration 18-180-1

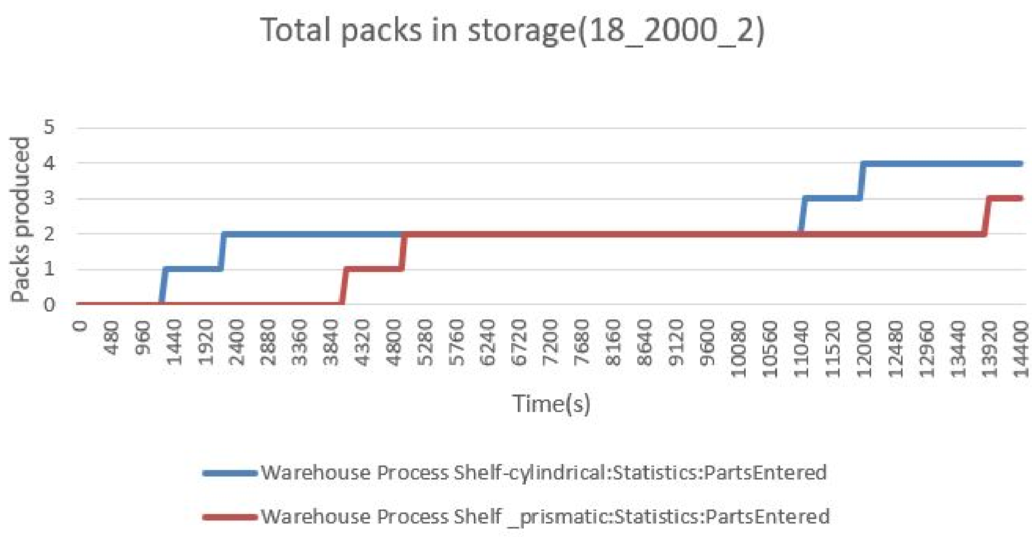

Figure 80: Total packs produced in 4 hours in layout configuration 18-180-1

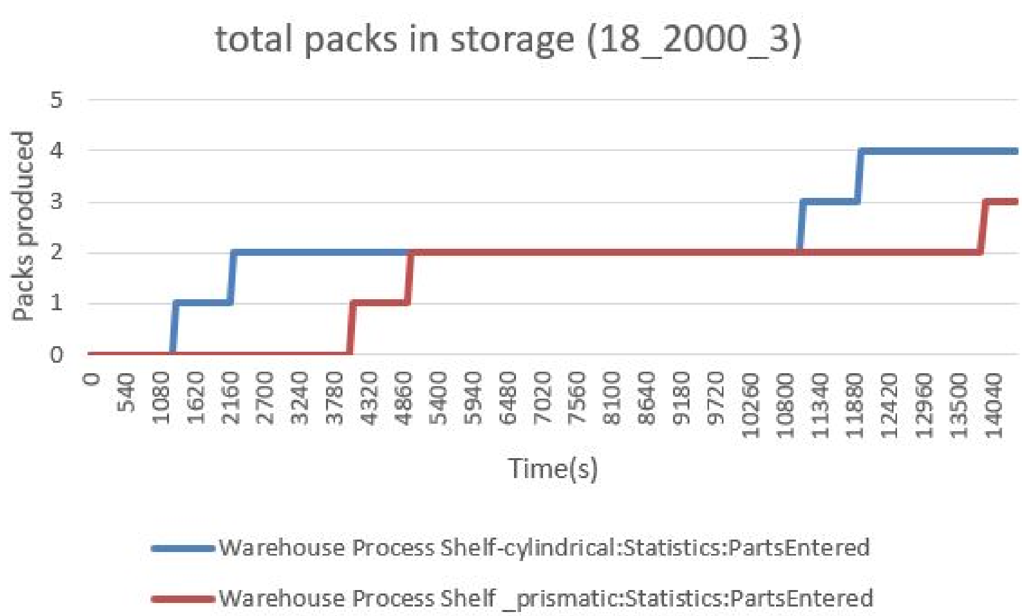

Figure 81: Total packs produced in 4 hours in layout configuration 18-180-1

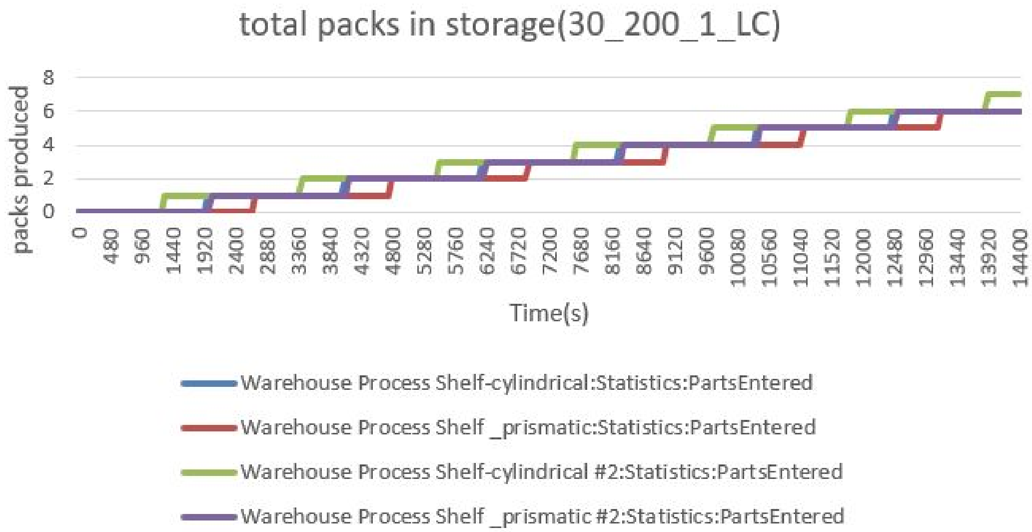

Figure 82: Total packs produced in 4 hours in layout configuration 30-200-1-LC

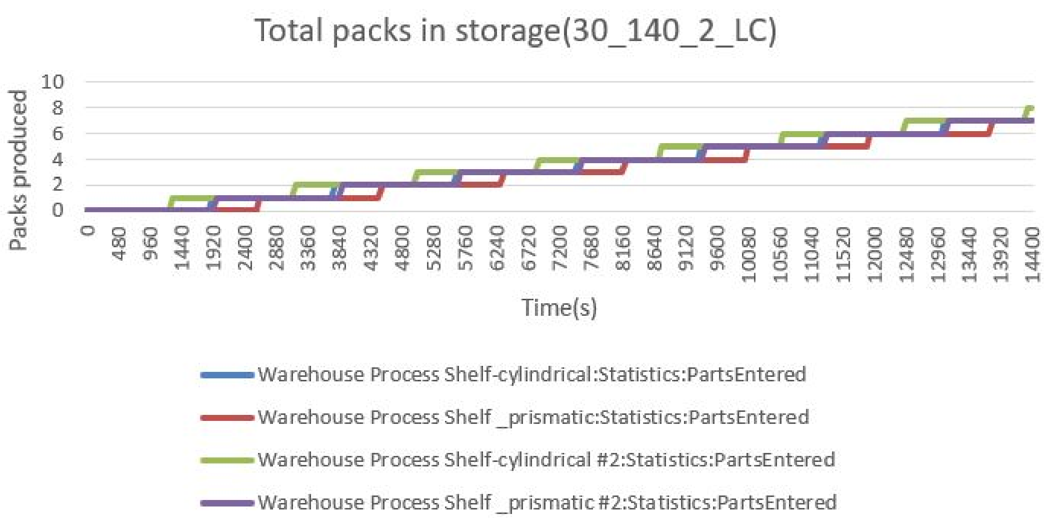

Figure 83: Total packs produced in 4 hours in layout configuration 30-140-2-LC

Figure 84: Total packs produced in 4 hours in layout configuration 30-140-3-LC

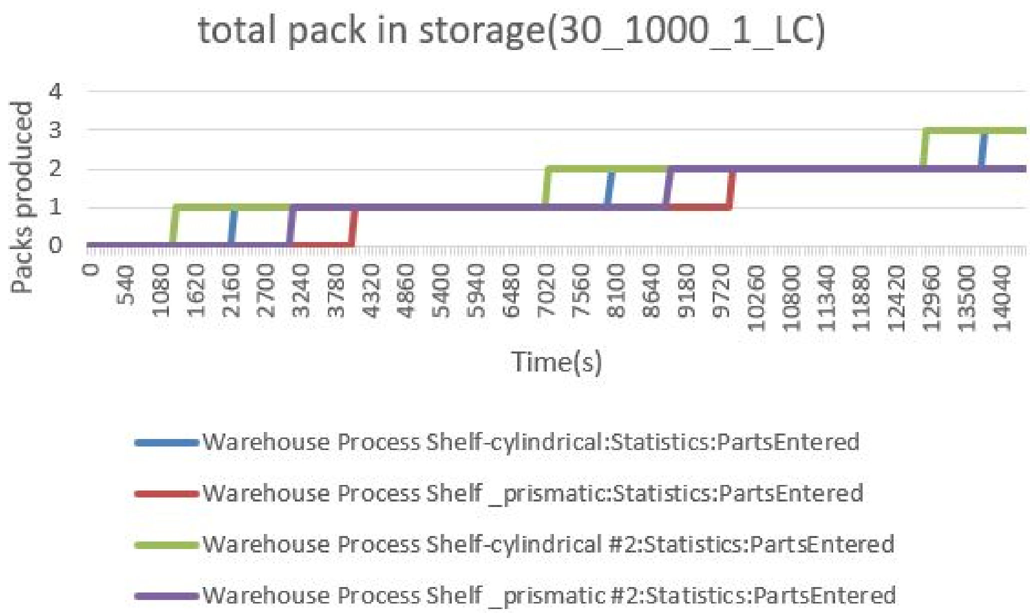

Figure 85: Total packs produced in 4 hours in layout configuration 30-1000-1-LC

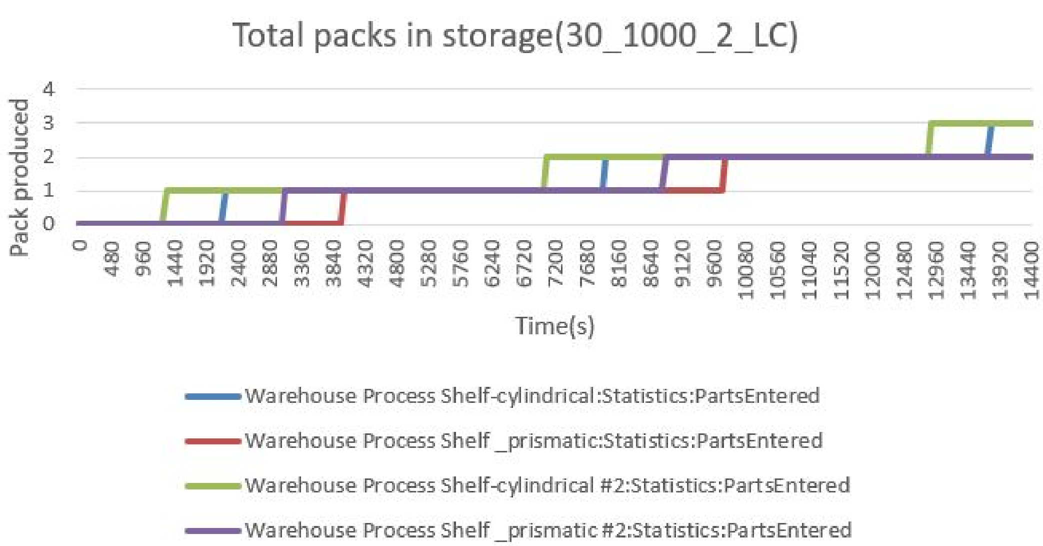

Figure 86: Total packs produced in 4 hours in layout configuration 30-1000-2-LC

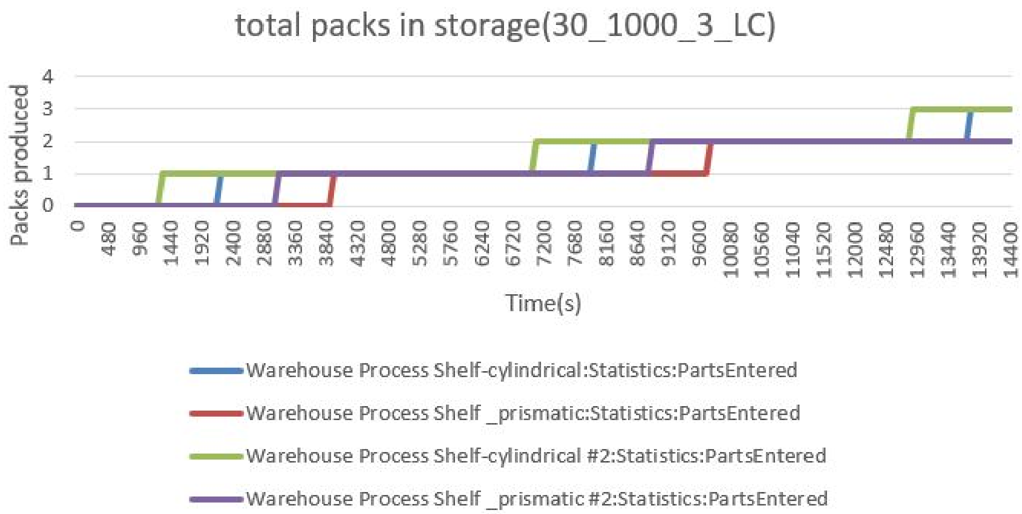

Figure 87: Total packs produced in 4 hours in layout configuration 30-1000-3-LC

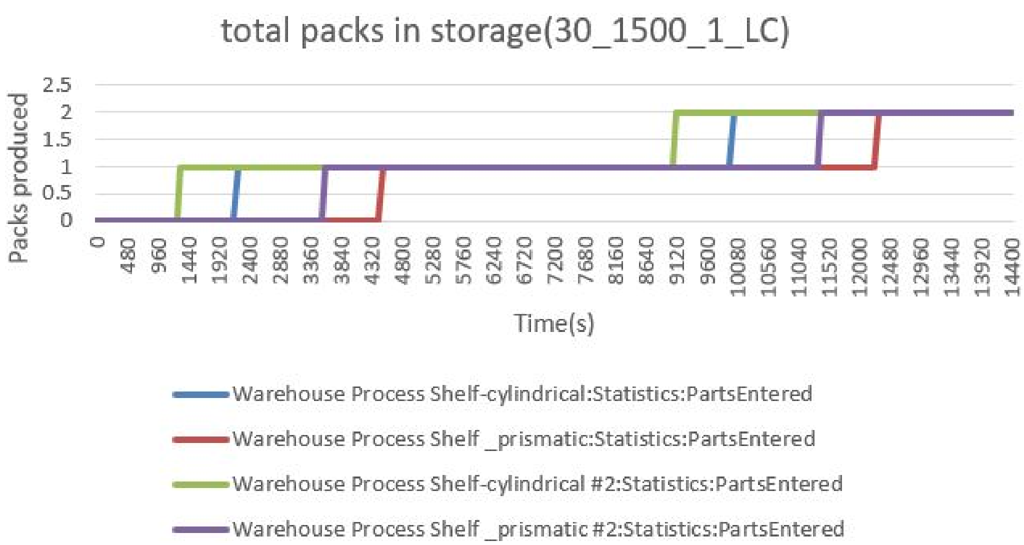

Figure 88: Total packs produced in 4 hours in layout configuration 30-1500-1-LC

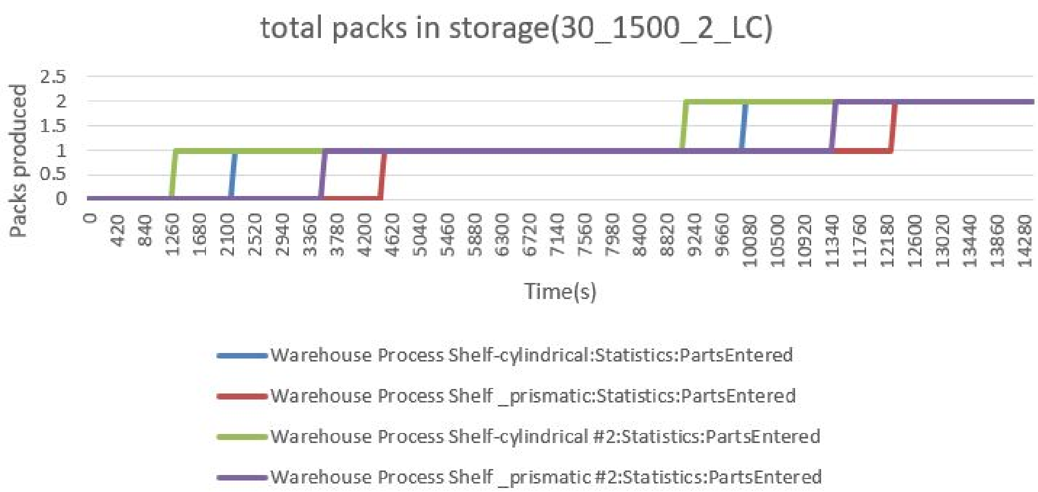

Figure 89: Total packs produced in 4 hours in layout configuration 30-1500-2-LC

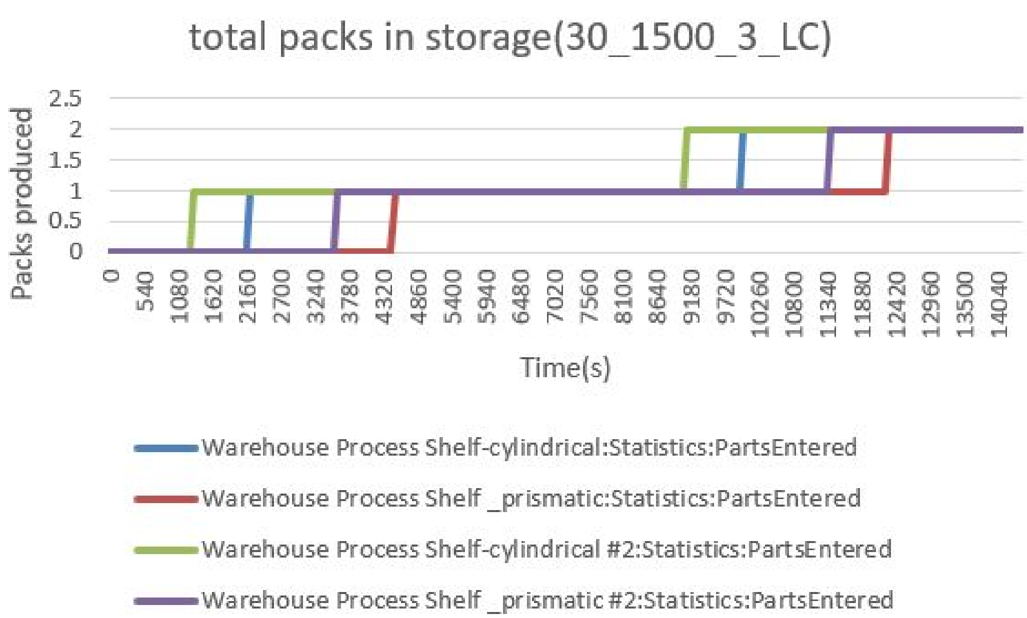

Figure 90: Total packs produced in 4 hours in layout configuration 30-1500-3-LC

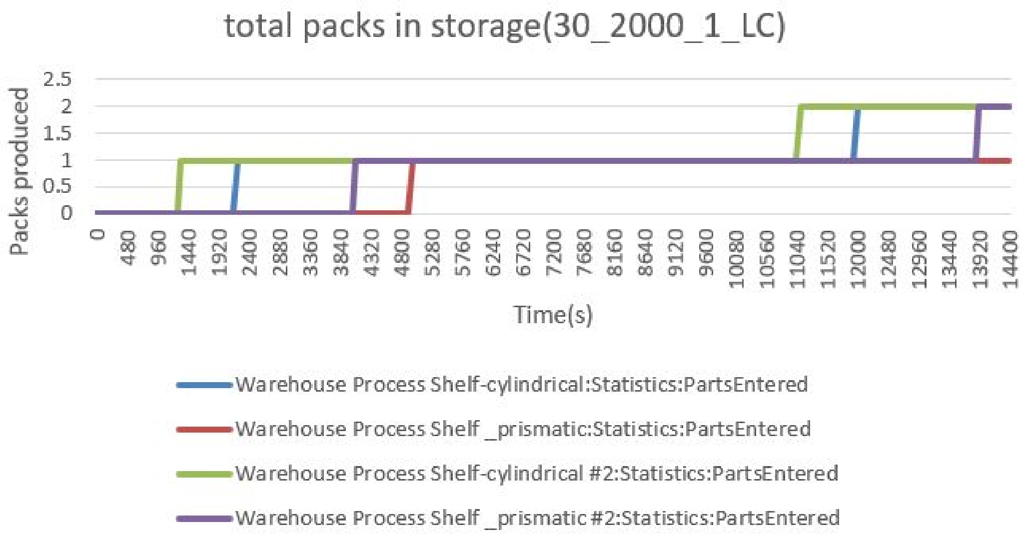

Figure 91: Total packs produced in 4 hours in layout configuration 30-2000-1-LC

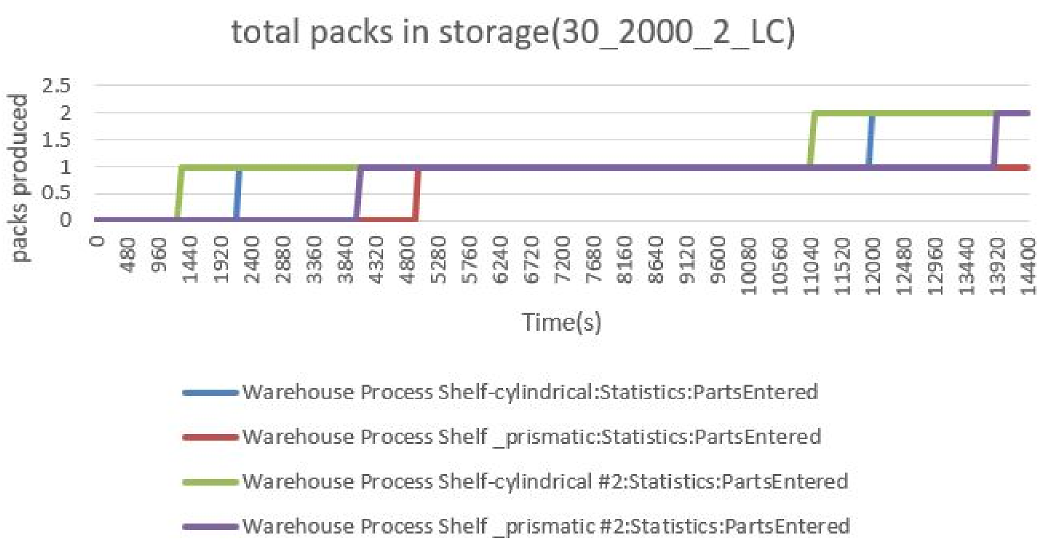

Figure 92: Total packs produced in 4 hours in layout configuration 30-2000-2-LC

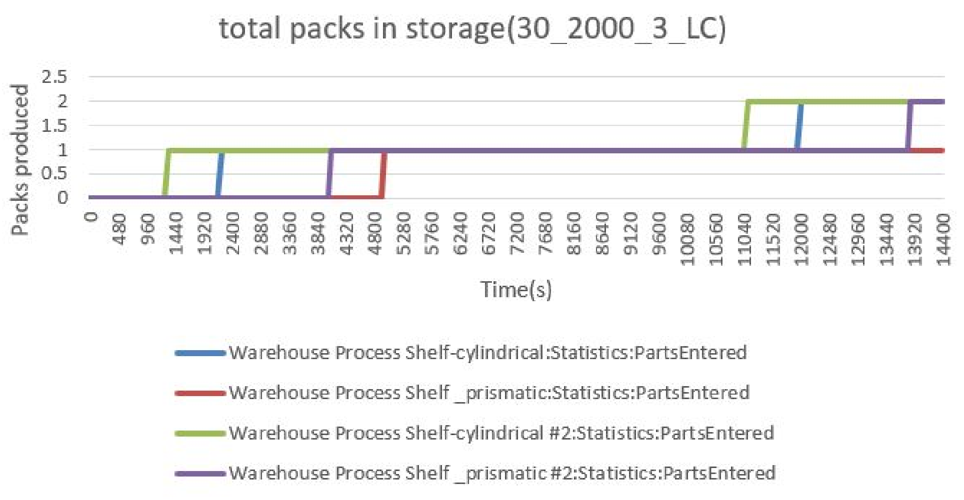

Figure 93: Total packs produced in 4 hours in layout configuration 30-2000-3-LC

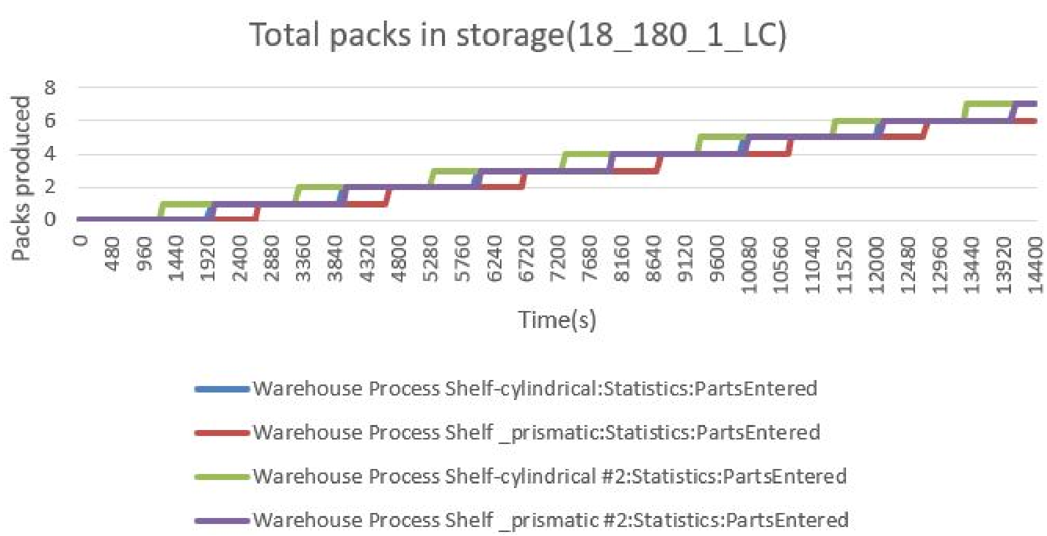

Figure 94: Total packs produced in 4 hours in layout configuration 18-180-1-LC

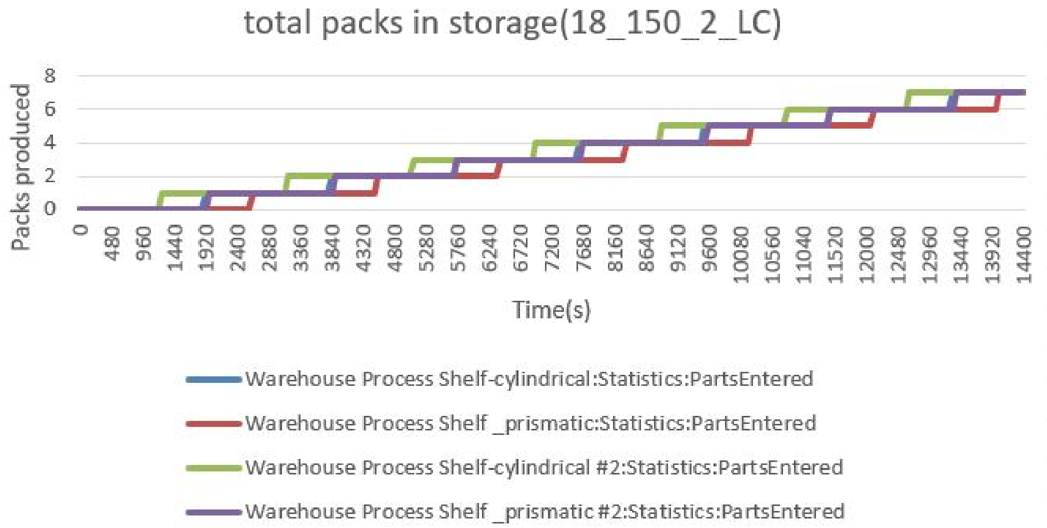

Figure 95: Total packs produced in 4 hours in layout configuration 18-150-2-LC

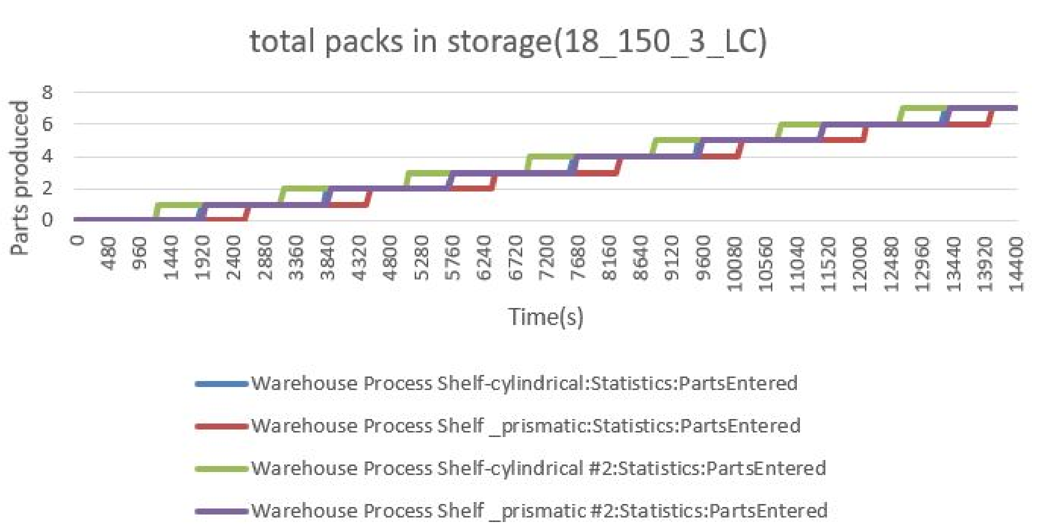

Figure 96: Total packs produced in 4 hours in layout configuration 18-150-3-LC

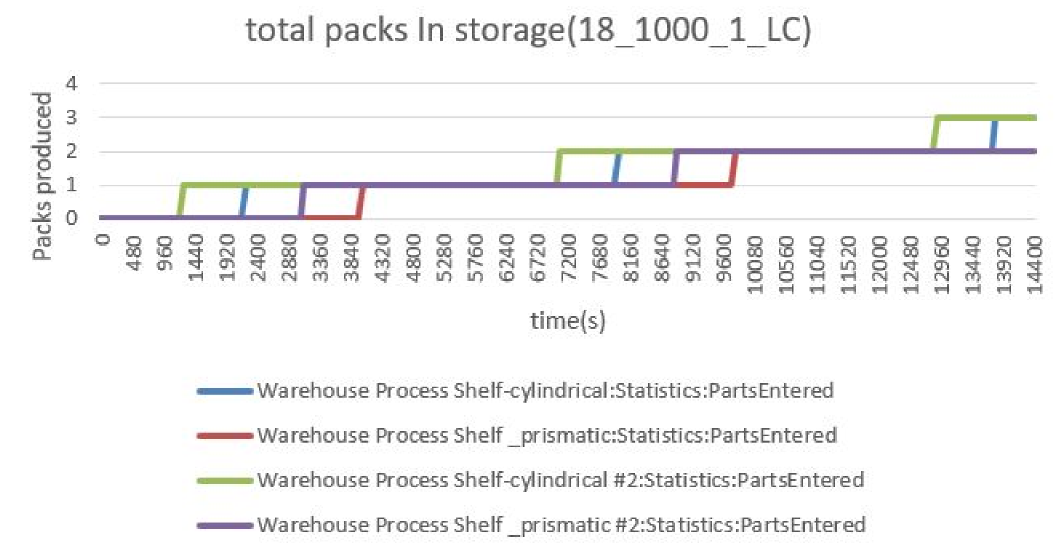

Figure 97: Total packs produced in 4 hours in layout configuration 18-1000-1-LC

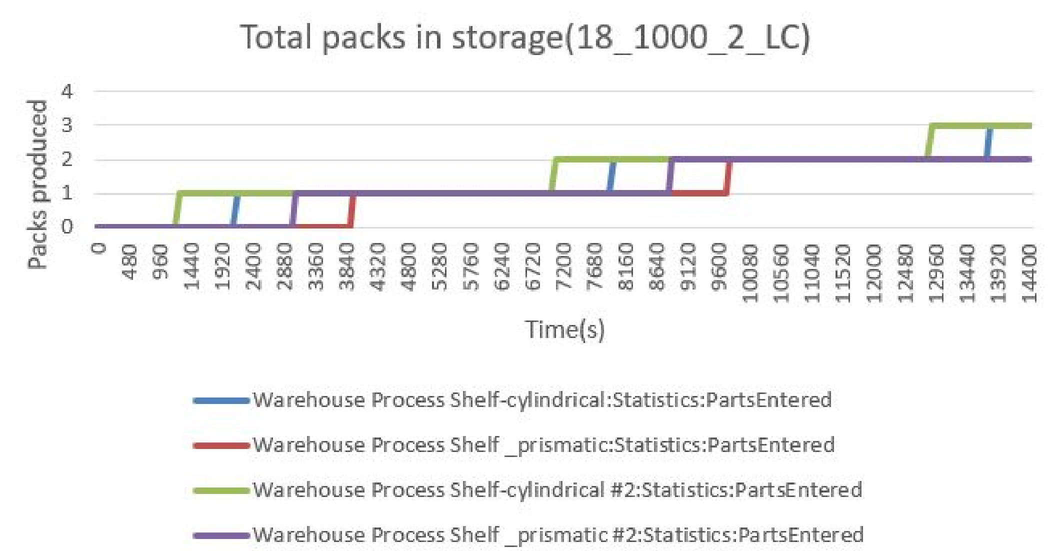

Figure 98: Total packs produced in 4 hours in layout configuration 18-1000-2-LC

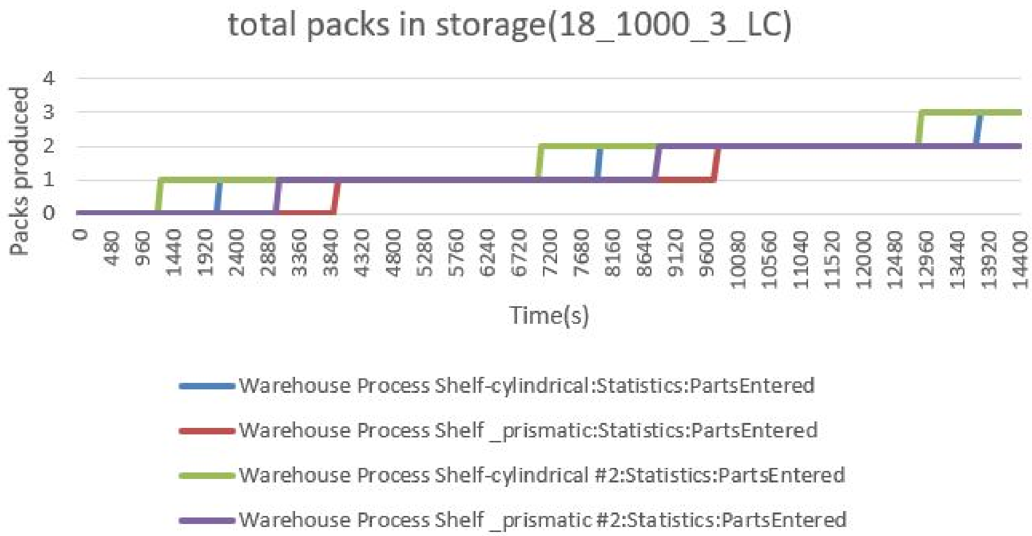

Figure 99: Total packs produced in 4 hours in layout configuration 18-1000-3-LC

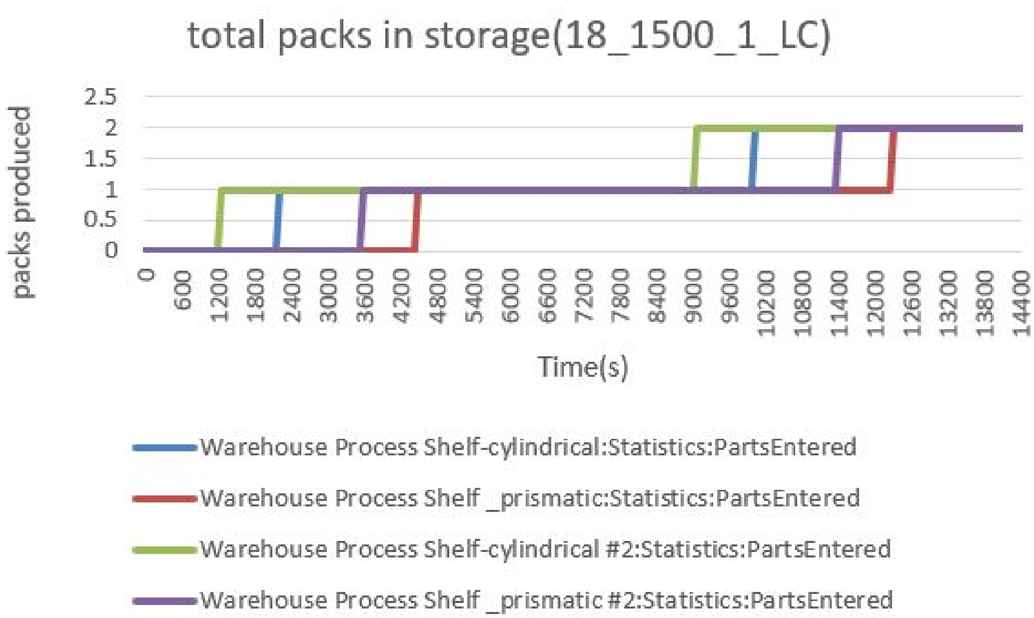

Figure 100: Total packs produced in 4 hours in layout configuration 18-1500-1-LC

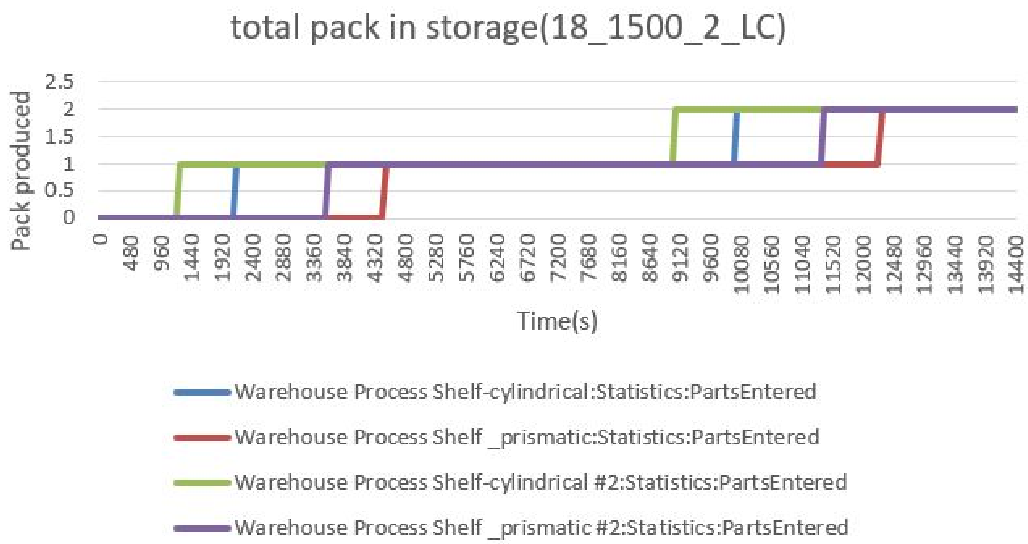

Figure 101: Total packs produced in 4 hours in layout configuration 18-1500-2-LC

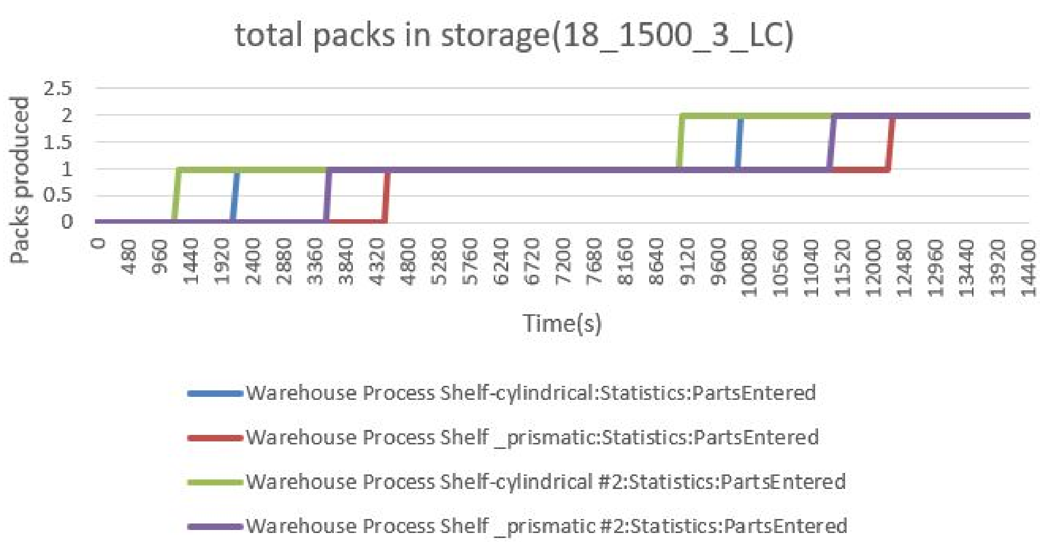

Figure 102: Total packs produced in 4 hours in layout configuration 18-1500-3-LC

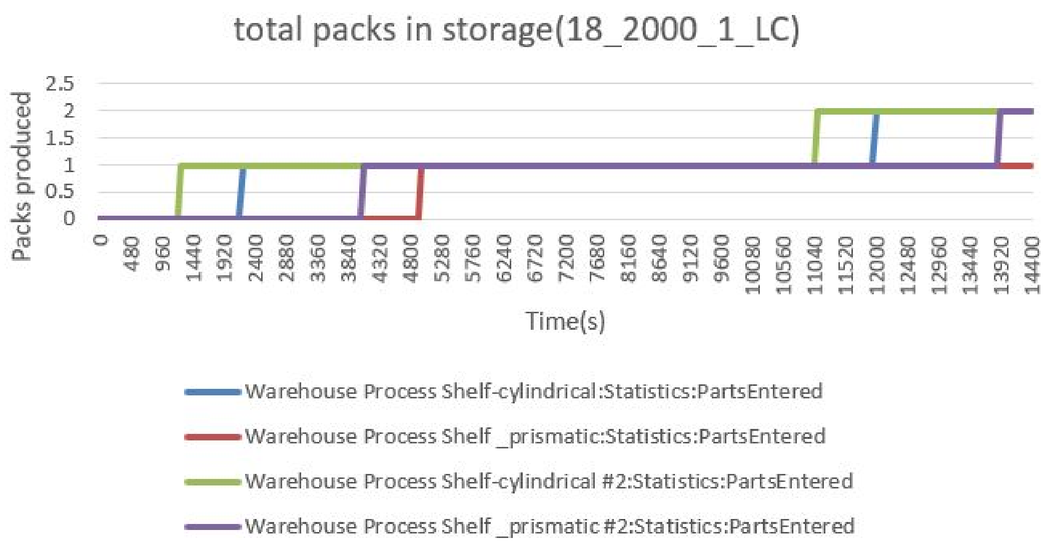

Figure 103: Total packs produced in 4 hours in layout configuration 18-2000-1-LC

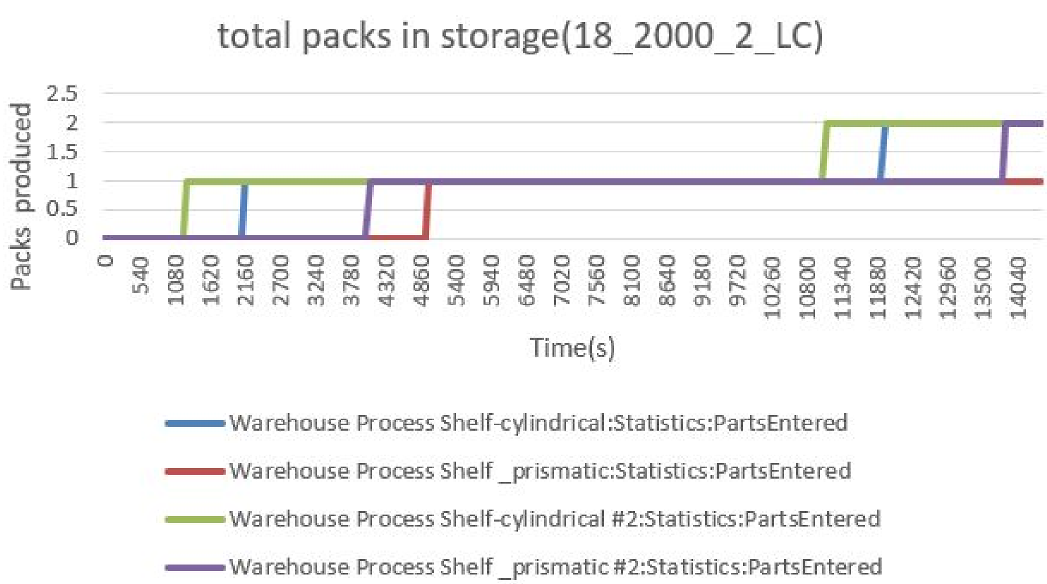

Figure 104: Total packs produced in 4 hours in layout configuration 18-2000-2-LC

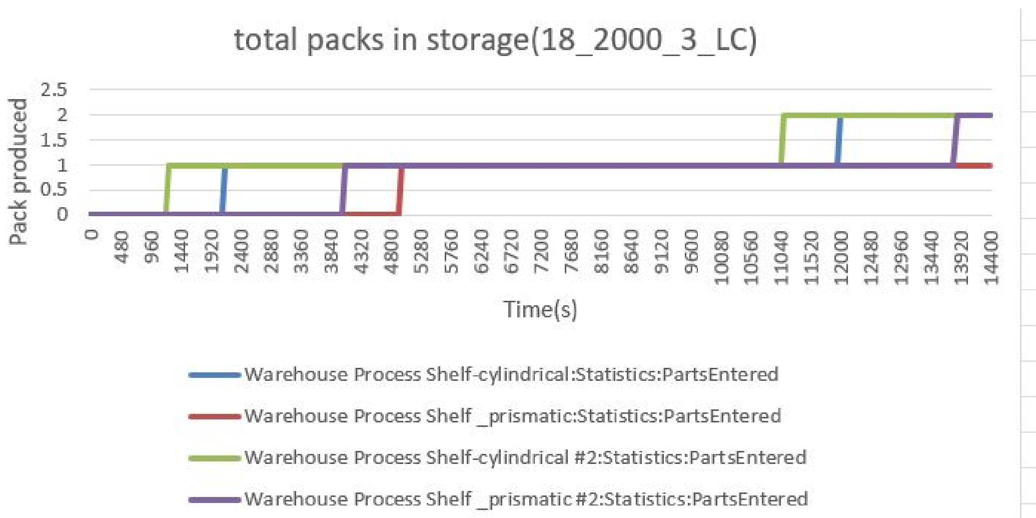

Figure 105: Total packs produced in 4 hours in layout configuration 18-2000-3-LC