SUPER B

PUBLIC VERSION

IMPROVEMENTS IN PRODUCTION LAYOUT AND INTERNAL LOGISTICS

MASTER THESIS INDUSTRIAL ENGINEERING & MANAGEMENT

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SUPER B lithium batteries

Management Summary

This report is the result of a research at Super B to give an advice on redesigning the layout and logistical movements within the production facility. Super B is a producer of lithium batteries. These batteries are used in wide ranges of industries, such as automotive and maritime. Super B has experienced a large growth over the past years, and it is expected that the rapid growth continues. In past expansions of the production environment, stations were duplicated next to the other, material supply got doubled, etc. All without a redesign of layout or production planning. In addition, due to the fast changing market Super B operates in, new product lines need to be operational in the near future.

The goal of the research is to minimize the total travel distance by first determining the layout of the production facility and secondly by redesigning the logistical material flows and practices, while keeping future changes in account. Our objective can be translated into our main research question:

How can Super B redesign its production layout and logistical processes in order to minimize its transport related material handling costs while keeping future expansion into account?

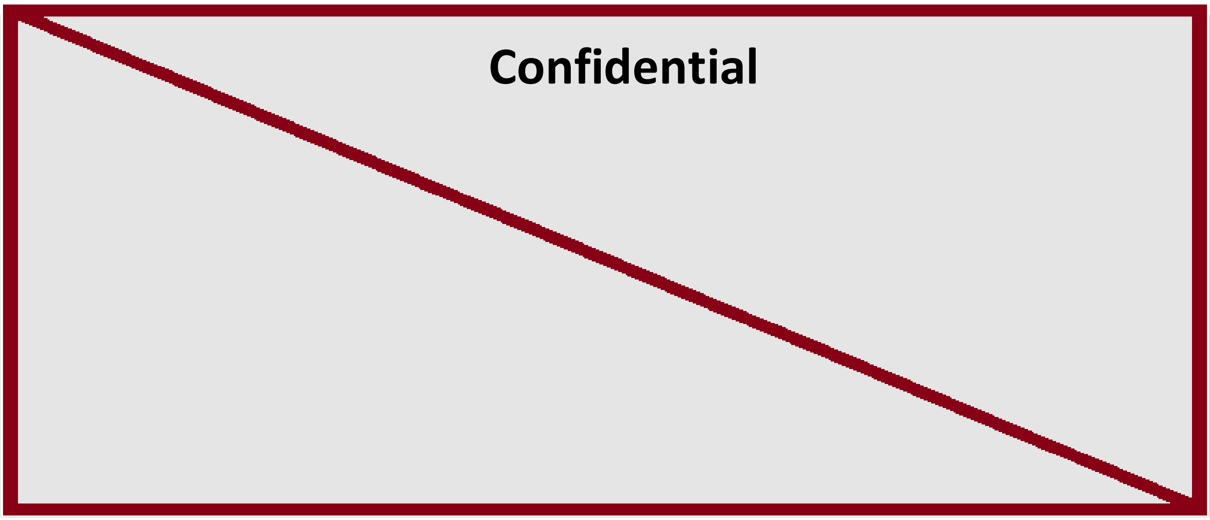
This study offers:

- **Forecasts** of future demand levels for current and new products.
- An extensive research towards **improvements in internal logistics** using Kanban, including:
    - A software program that generates directly implementable Kanban cards containing all necessary information
    - A new material supply method called milk-run
    - A benefit cost analysis
- A future-ready **layout plan**, including:
    - A software program of a unique layout optimization model
    - A detailed layout
    - A benefit cost analysis
- Recommendations, including:
    - A roadmap towards the presented solutions

We decided to set our time horizon at four years, due to the fast-growing market and future moving plans.

Forecast

Super currently produces three main product groups: Starter, Traction and Epsilon. In 2020 Super B launches a new product called the 105E and new models are introduced for the Traction and Starter batteries. In order predict future demand of these product groups, we set up a forecast model. We offer Super B four forecast models representing future demand of their growing product environment. Using the Bass diffusion model we estimated demand levels of current products, new product extensions and completely new products over the next four years:



From our forecast we can conclude that, after 2021, the 105E battery is expected to become Super B's new flagship. We estimate the total demand to grow 22,5% on average per year for the next four years.

Improvements in internal logistics

We did an extensive research on how we could improve transportation waste by changing the planning and control methods of material supply and production. After investigating multiple planning and control methods that ensured a pull system, we selected Kanban as our main method of resupply. We configured every component, by categorising each component based on its size and generality. We created for each category of components an inventory policy (reorder point, reorder amount, reorder bin size, etc.) and constructed a program that generates Kanban cards when entering the component number. The card shows all relevant information regarding the components' inventory policy and destinations.

Next, we introduced a new way of picking, using the *milk-run* concept. With this method we ensure a stable and standardized amount of picking moments. We substantiated this by calculating the average amount of bins needed to resupply production each day for the next 4 years and concluded that all material supply can be fulfilled in a standard one run per day.

These changes result in significantly lower material-picking transport costs, sub-assembly transport costs and NCR transportation costs. This solution requires investments costs of € 19,500. The future benefits results in a Present Value of € 67,884.30 and thus a Net Present Value of **€ 48,384.30**. These are the direct savings in material handling and don't include the indirect savings such as continuation of production when defect components occur.

Layout planning

We followed the *Systematic Layout Planning* procedure by Muther (1961) to design a new layout of the production area. We took into account the logistical improvements of our other solution, which had an effect on flows, unit transportation costs and space requirements. For creating a layout tool we used a combination of two heuristics: *MULTIPLE* and *Simulated Annealing*. MULTIPLE made sure that we could swap departments in the layout and Simulated Annealing made sure we widen our search region to find better solutions. The tool can be used by Super B's planner to create multiple layouts for both the current facility as for new facilities when a moving takes place. For this research, we performed 24 experiments, and selected the layout that performed best during the 4 year period. Next, we detailed this layout. The costs of redesigning this layout is estimated at € 10,320.-. Compared to the Present Value of € 35,657.93, this results in a Net Present Value of **€ 25,337.93**.

Conclusion & Recommendations

In the beginning of our research we focussed on two main aspects: first the internal logistics between production and warehouses and secondly the optimal positions of the departments. During the research of our first solution we found the method milk-run. This method significantly improved our objective function by reducing and standardising the flows. However, this also resulted in our layout solution to become less important, since there are less flows to optimize. Due to the milkrun concept we conclude that, beside grouping the (sub) departments, there are far less significant differences in changing the departments location. So, by finding a better method for first solution (internal logistics), we devaluated our findings researched in second solution (layout planning). Which makes our solution to the internal logistics a higher priority. Nevertheless, we conclude that relocating these departments still provide an optimal layout that significantly add value.

We recommend Super B to follow this roadmap in order to implement the two solutions:

	Action	Week (2019-2020)	Executer(s)
Solution II - Sub-assembly Planning & Control	Install sub-assembly shelves at each department and mark shelf locations	49	Production personnel
	Make Kanban cards for each sub-assembly with the corresponding shelf location	49	Warehouse personnel
	Start storing sub-assemblies (in Kanban-quantities) directly at the corresponding Housing & Electronics department	50	Production personnel

Solution II - Material Planning & Control	Install material shelves and lean workbenches at each department and mark shelf locations (wait with the new workbenches)	51 – 2	Production personnel
	Make Kanban cards for each component with the corresponding shelf locations	51	Warehouse personnel
	Start storing material (in Kanban quantities) at the corresponding departments	2 – 3	Warehouse personnel
Solution I – Layout Redesign	Start building a temporary inventory as a preparation for the move	4-7	Production personnel
	Start with the moving process: - Move shelves - Move workbenches - Move machines	8-9	Warehouse & Production personnel
	Rearrangement of electricity supply, compressed air piping and computer cabling	8-9	Installation company

We advise Super B to invest in equipment and time needed to implement the planning and control methods using our Kanban card tool. Besides, we advise Super B to relocate departments according to the layout plan given in Appendix I.4. Implementing these two solutions should make Super B more efficient and future ready, while directly saving **€ 73,772.23** in material handling costs over the next four years.

Preface

Dear reader,

The master thesis is in front of you is the final step I had to take in order to obtain my master's degree in Industrial Engineering and Management. After being introduced to Super B, I knew that this company was the place I wanted to graduate at. This research was the perfect opportunity for me to put my knowledge into practice.

That is why I want to thank all of the employees at Super B. A special thanks goes to my supervisor at Super B, Paul Beunk, who gave me the opportunity to conduct this research and for being constantly ready to support me with my research. Also, a special thanks to Ramon van der Schaaf and Albert Baan, whom provided me with data regularly.

Above all, I would like to thank my supervisors of the University of Twente, Peter Schuur and Sipke Hoekstra, for the guidance and feedback sessions during my research.

Finally, I want to thank my friends and family for their help and support.

Roy Wichink

2019, December

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SUPER B lithium batteries

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1 Introduction and problem formulation

In order to complete my master's study Industrial Engineering and Management, where I specialized in Production and Logistics Management, I performed a research at Super B in Hengelo to improve the efficiency of the production area.

In this chapter we introduce the company in Section 1.1. In Section 1.2 we discuss the research motivation and in Section 1.3 the problem description is given. In Section 1.4 the research questions are described and subsequently we introduce our research framework in Section 1.5. Next, in Section 1.6 we introduce the research scope and finally, in Section 1.7, the deliverables are given.

1.1 The company

Super B, founded in 2007, is a fast-growing organization that develops and produces lithium batteries. These batteries are used in a wide range of industries and applications, including the automotive industry (car manufactures, recreational vehicles, etc.), maritime sector and energy storage solutions. Super B uses the lithium-iron phosphate technology, which is one of the safest and most durable lithium technology.

Customers

Both companies and private individuals make use of Super B's lithium batteries. However, Super B does not directly sell their products to private individuals, but through external distributors. Well known customers of Super B are Aston Martin and Ferrari in the automotive industry and Beneteau and Jeanneau in the maritime sector.

Facility

Super B has moved twice since the start of the company 12 years ago. Nowadays, Super B operates in two separate facilities, the production site and the head office, both located in Hengelo. The production site of Super B is located at Expolaan 94 in Hengelo. Here tens of thousands of batteries are produced every year and these numbers keep rising. For next decade Super B expects to grow 40% per year. There are currently about 75 employees working at Super B, where 45 employees work at the separate office building and 30 employees work at the production site. At the production site parts such as lithium cells, metal parts and electronics are assembled into batteries. The production process of the batteries is often manual work in combination with automation.

Batteries

When talking about batteries, one would probably recognise conventional lead-acid batteries (best known as a standard car-battery) or lithium-ion batteries (widely used in portable devices and electric cars). Super B, however, uses a different kind of battery cells: lithium-iron phosphate cells.

The main differences between Super B's lithium-iron phosphate batteries and conventional lead-acid batteries are the lifetime, capacity, weight and costs. Compared to lead-acid batteries, the Super B lithium batteries have longer lifetime (3 to 5 times longer); are significantly lighter; charged faster; and are more reliable and stable than conventional lead acid batteries. This not only due to the usage of lithium, but also the result of an integrated smart software that monitors and balances the lithium cells. The costs of a Super B battery, however, are also a lot higher. For example: while a conventional lead-acid battery (with approximately the same dimensions) costs about €150, Super B's cheapest energy battery, the Epsilon, costs currently €1680.

When comparing Super B's lithium-iron phosphate with lithium-ion batteries, it is mainly a difference between, on the one side safety and sustainability, and on the other side electrical performance. Lithium-iron phosphate gets outperformed by lithium-ion in terms of energy transfer and capacity. However, lithium-iron phosphate, which is also a newer version in the lithium family, has an improved chemical balance. This results in a more economical and sustainable battery, which makes the lithium-iron batteries safer to produce, handle and dispose.

The production environment consists of two types of batteries: starter batteries and energy batteries. The starter batteries come in nine different sizes with different capacities and are used to quickly discharge, to start a racing car engine for example. The energy batteries are used for energy storage solutions. The energy batteries can be divided in two types: Epsilon batteries and Traction batteries, see Figure 1.1. The Epsilon battery is specifically made for recreational vehicles. The Traction battery is the best performing battery of Super B: it has the highest capacity in the Super B assortment.

Figure 1.1 - The Traction, Epsilon and Starter battery respectively

1.2 Research Motivation

Super B is a relatively new company, operating in a niche market. Super B's production facility has experienced a large growth over the years, and it is expected that this growth continues. Super B wants to take the next step in their industrialisation process: becoming a mature production company. This is accompanied with a lot of challenges and problems. A main problem is the capacity shortage in warehouse and production. When Super B started producing at their new production site in 2012, they simply installed workbenches and machines to fulfil their current demand. Later when demand and production environment grew, the capacity was simply duplicated: a new workbench next to the other, a new production line next to the other. This continued over the years with minimal changes to the layouts or practices. Super B now believes that, due to these past and future changes in their sales, it is time to take a new look at the layout and internal logistics.

1.3 Problem description

To map the problems that Super B are going through, we use a problem cluster, see Figure 1.2. Super B notices a maximum capacity usage of warehouse staff. This results in high lead times, quality losses and high storage and handling costs. The warehouse staff is under stress for three main reasons: a small workforce, high inventory and too much internal transport. Of these three problems, we focus on the high internal transport. Internal transport can be divided in three problems, so called core problems:

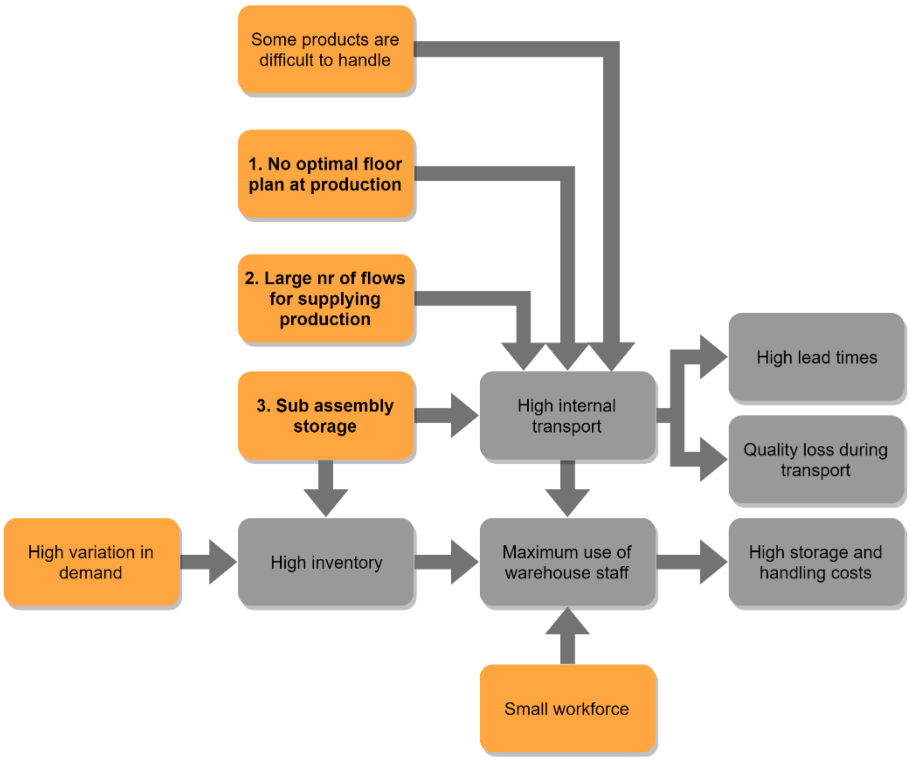


Figure 1.2 - Problem cluster

1. No optimal floor plan at production

In previous expansions of the production line, stations were duplicated next to the original one, without considering an optimal floor plan. This results in a combination of inefficient flows throughout the production site.

2. Large number of flows dedicated to supplying material for production

The production of batteries starts with a production order, which is an order for a batch of 10 or 20 batteries (depending on the type of battery). Each time a new production order takes place, warehouse staff pick a series of new materials for a batch of batteries. Considering that Super B produces on average around 42 batteries per day, this would mean that at least 3 times per day the production line needs new material supplied by the warehouse.

3. Sub-assembly storage

This core problem takes place at the production of Epsilon and Traction batteries. The Epsilon and Traction battery consist of a sub-assemblies which are, after assembly, stored in the warehouse before going to the final assembly of the battery. This results in a high number of flows between warehouse and production.

1.4 Research questions

The goal of the research is to minimize the total travel distance, by first determining the layout of the production facility keeping the expansion into account, and secondly by redesigning the logistical material flows and practices. Our objective can be translated into our main research question:

How can Super B redesign its production layout and logistical processes in order to minimize its transport related material handling costs while keeping future expansion into account?

To answer the main question, we use five research questions, some with sub questions.

RQ1

Which activities does Super B perform and how are they organized?

RQ1 is answered in chapter 2. It describes the current situation using the following sub questions:

SQ1a: What does the main process looks like?

SQ1b: How can future changes be considered?

SQ1c: What are the existing facilities that need to be relocated in the new layout?

SQ1d: What KPIs are already in place?

In order to answer research question 1, we perform multiple interviews and we actively participate in the production and warehouse processes for a whole week.

RQ2

Which literature can be found to further analyse and improve the current situation and which of the literature found is applicable to our problem?

We describe the literature research in Chapter 3 by searching in accepted journals. The search terms used, can be found in the Appendix E.

RQ3

What is *the current performance of the layout and how does it get affected in the future?*

In Chapter 4 we examine the current performance of Super B's layout and make forecasts of future demand with the help of the following sub questions:

SQ3a: *What are the transportation costs of the existing layout?*

SQ3b: *What does the forecast in our time horizon look like?*

In order to answer sub-question 3a we perform calculations of the flows and costs and measure the distances between departments. For sub-question 3b we select a forecast-model from the literature research and interview experts of Super B's sales team.

RQ4

What options can realise the reduction of transportation waste?

In Chapter 5 we explore the logistical improvements between production and warehouse.

SQ4a: *What flows cause transportation waste in the existing process?*

SQ4b: *What methods can we apply to improve the process flow?*

SQ4c: *How are these methods implemented and what are the results?*

In order to answer this research-question we use the methods found in the literature research and modify them if necessary.

RQ5

Which new layouts can we construct to minimize total travel distance for each scenario, while keeping new logistical flows in mind?

In Chapter 6 we construct different models, found in the literature, to improve the layout of the Super B production facility.

1.5 Research framework

Figure 1.3 shows the framework that displays our research plan and approach.

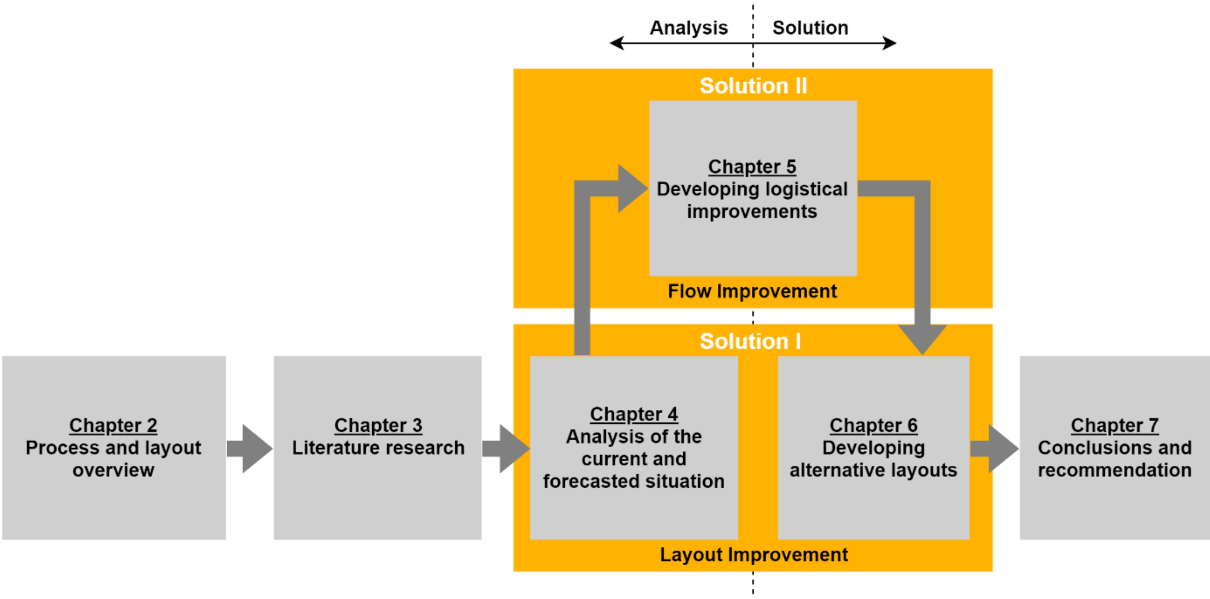


Figure 1.3 - The framework of the research

We start in Chapter 2 with an overview of the current processes and the layout of the production facility. First, we go step by step through the main process, from scheduling to shipping, of the three main types of batteries Super B currently produces. Next, we present the existing layout of Super B's production facility: the shape, floor dimensions and the division of the departments. Third we discuss the future considerations. In Chapter 3 we begin with the literature research. Here we cover three main topics: first the forecasting methods, secondly the methods regarding flow improvements and lastly the layout improvement. Then we divide our research in two solution approaches: Solution I covers layout improvement; and Solution II covers flow improvement. We start with Solution I in Chapter 4 with an performance analysis of the current situation and introduce forecasts of production environment. In Chapter 5 we search for ways to realize the methods, found in Chapter 3, in order to reduce the number of flows. Then in Chapter 6 we develop alternative layouts based on the improved process of Chapter 5. In this chapter we create an algorithm that places each department at the best location. Each department will secondly be detailed with storage areas, workbenches, operator paths, etc. In the last chapter we give a conclusion of our research and a recommendation to Super B.

1.6 Research scope

In this section a list of boundaries of the research are described:

- We focus on the layout design not the facility location.
- We set a time horizon of four years due to Super B's large grow and high uncertainty. In Section 2.4 we explain why, and we elaborate the further future considerations.
- We only focus on the layout and adjustments of the production area. The location of the warehouse and other miscellaneous departments are fixed.
- Only the main (non-specialised) batteries that are produced will be studied in detail, not the production of specialised batteries and accessories.
- Super B only has production data from 2015, which means we have 4 years' worth of data. When needed we use Super B's short-term forecasts (of three quarters) in order to make up for the lack of data.

1.7 Deliverables

In this section we name the deliverables we hand at Super B:

- A detailed floor plan with location of each station and their dimensions regarding multiple scenarios (Solution I).
- Advices on logistical changes that should be made (Solution II).
- A flexible program that constructs layouts, which can be modified when new situations occur in the future.

2 Process and Layout Overview

In this chapter we analyse the current situation. We start off in Section 2.1 with *the process and system description*. Secondly in Section 2.2 we discuss *the future considerations* in terms of time horizon, uncertainty, new products and growth. In Section 2.3 we take a look at *the current design of the production area* and *the division of departments*. In Section 2.4 we focus on *the key performance indicators* currently in use by Super B.

2.1 Process and system description

In this section we go through the main process step by step, see Figure 2.1. The process differs per battery, but in most of the phases there are a lot of similarities.

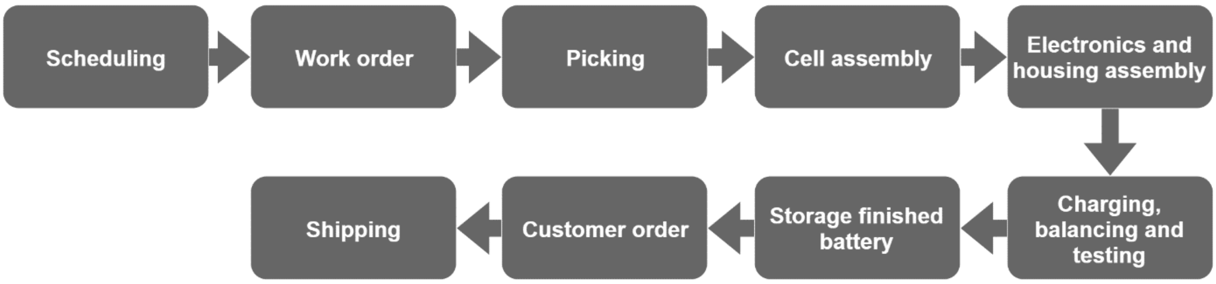


Figure 2.1 - Main process

2.1.1 Scheduling

Scheduling starts every week after customer orders arrive. The customer orders are delivered from stock. Each week the operations manager checks the inventory and determines how much batteries need to be produced to reach the standard stock level again. So, basically, the production quantity for the next period are the orders from the previous period(s). The standard stock levels are determined each year based on the sales forecast and the production capacity. Super B has a normal and a maximum production capacity. Normal production capacity is in use when demand is stable, operators are at their usual stations.

Maximum production capacity means that all necessary stations of the corresponding product group are in use. Super B uses flexible operators that can produce multiple types of products. So, in case of high demand operators switch to produce at other stations. This also means that maximum production capacity can't be reached for multiple product groups at the same time (unless more operators are hired).

2.1.2 Production order

When production quantity is determined it is transitioned to a number of production orders. The production order is saved in the system and new products IDs are created and linked with the production order, such that when failures arise, the problem can be tracked back. Production orders can consist of sub-assemblies as well finished products:

- Sub-assemblies:
  - Sub 1: Cell assembly (Traction battery)
  - Sub 2: Electronics assembly (Traction battery)
  - Battery Lid (Epsilon battery)
  - Printed Circuit Board Support assembly (Epsilon battery)
  - Battery Pack assembly (Epsilon battery)
  - Smart starter electronics assembly (Starter Battery, starts in end 2019)

- Finished product assemblies:
  - Traction battery housing and electronics
  - Epsilon battery housing and electronics
  - Starter battery housing and electronics
  - BIB central battery management system (accessories)
  - 105E (starts in 2020)

2.1.3 Picking (warehouse)

With a production order comes a picklist with the Bill of Materials (BOM). The material is delivered at the corresponding production area. In Figure 2.2, 2.3 and 2.4 the product structure of the Starter, Traction and Epsilon are given respectively.

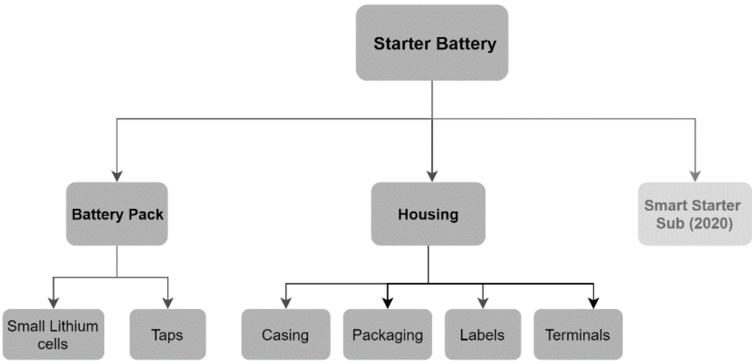


Figure 2.2 - Starter Product Structure

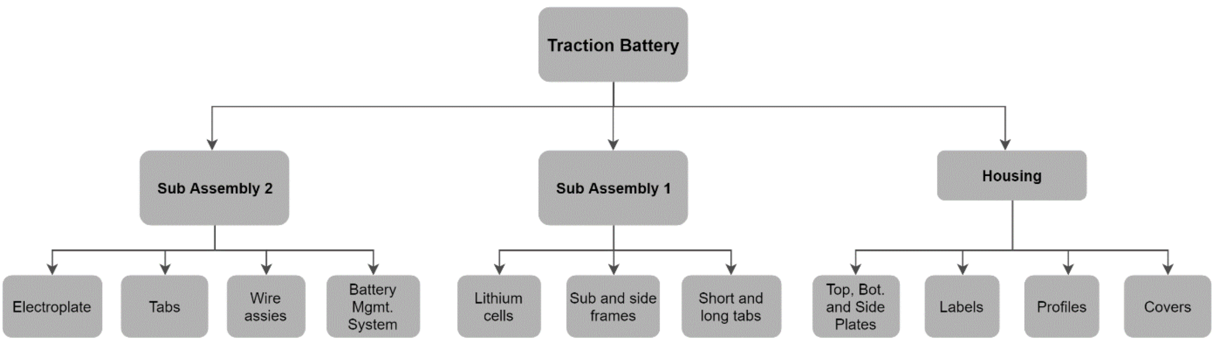


Figure 2.3 - Traction Product Structure

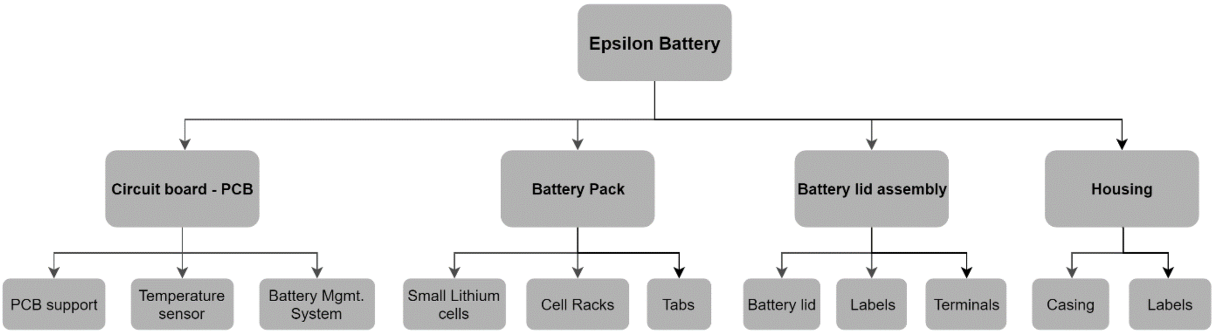


Figure 2.4 - Epsilon Product Structure

2.1.4 Cell Assembly

The production process of all batteries start with the assembly of the lithium cells. The Epsilon and Starter batteries consist of smaller cells, while Traction batteries have four much larger cells, see Figure 2.5. Assembly of the starter cells starts with gluing the cells together in the appropriate form. These cells are available as floor stock at the Starter workstations. The number of cells depends on the type of starter battery that is produced: types with higher capacity need more lithium cells. Next the small lithium cells need to be connected to get the required minimum voltage and amperage output. This is done by manual spot welding the tabs on the cells.

Figure 2.5 - Large lithium cells of the Traction (Tamboli, 2019) and Smaller lithium cells (Lithium Rechargeable Batteries, 2019) respectively

In the Epsilon battery, instead of gluing, the cells are placed in a plastic cell rack. There is only one type of Epsilon battery, so all cell racks are the same and thus have the same number of cells. The joining of the cell rack and the tabs is also done with spot welding, only here it is done automatically with an automatic spot-welding machine. After assembly they're called battery packs, see Figure 2.6 (left). The cell assembly for the Traction battery happens at a separate station and is called Sub 1 Station. This process starts with assembling four cells that are packed together by the supplier. The fact that they are packed together is an important aspect of the process, since each cell is matched with the other three cells at the supplier, which results in a more balanced combinations of cells. The four cells are placed in the internal housing and connected with tabs and bolts such that there is an output voltage of at least 13.5V. The so-called Sub 1 is now complete, see Figure 2.6 (right). When a whole batch of

Sub 1s is complete, they are directly transported to the Traction Electronics and Housing assembly station.

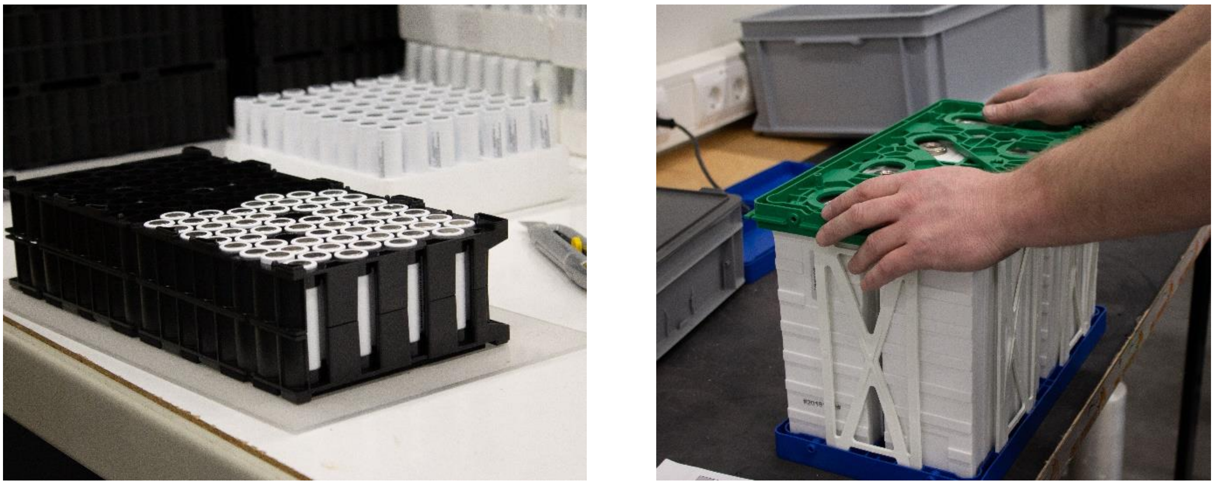


Figure 2.6 - Assembly of the Epsilon Battery Pack (left) and Assembly of the Traction Sub 1 (right)

2.1.5 Electronics and housing assembly

The electronics of each battery type differs a lot. As for now, the starter battery has no smart software. However, there are plans for a new extension of the starter battery in Q1 2020, as will be elaborated in Section 2.4. Currently the starter just has simple electronics that ensures power throughput.

The Traction and Epsilon batteries both do use smart software. The electronics in these batteries function as an integrated battery management system. Due to this system the battery can be monitored and deliver power more efficiently. Both systems work in a similar way at the end-product but are built differently. For the Epsilon the electronics, the Printed Circuit Board (PCB), needs to be attached to two sub-assemblies and the battery pack. These sub-assemblies, the PCB support plate and the Batter Lid, are both made-to-stock items and built at separate stations. These sub-assemblies are picked when a work-order for electronics and housing assembly is released.

The Traction battery has one other sub-assembly, next to the battery pack. The production of this sub-assembly also happens at a separate station, the Sub 2 Station. Here all electronics are attached to a support plate, before it is going to the electronics and housing assembly station. This sub-assembly is called the Sub 2. The Sub 2 is, like the Epsilon sub-assemblies, stored at the warehouse and picked when a work-order for the electronics and housing assembly is released.

The next step at production is similar for all battery types. The picked components (including the sub-assemblies for the energy batteries) are assembled to the battery packs, after which also the housing gets included. For a Traction battery it takes approximately three quarters of an hour to be assembled. For the Epsilon and Starter battery there is an extra step in assembling the housing. The battery is filled with a resin (also called potting) and clammed upside down for several hours for it to get harden, see Figure 2.7. The cover is now fixed and more waterproof.

Figure 2.7 - Potting (left) and the harden process (right) for the Starter battery

2.1.6 Charging, testing and balancing

When fully assembled, the testing balancing and charging takes place. Since the Epsilon and Starter batteries have smaller cells, they are more easily balanced. These batteries only need to be fully charged before they're ready for packaging. The Traction battery, however, also needs to be tested and balanced. The testing and balancing procedures happen at a tooling station. Here the battery is connected to a computer, see Figure 2.8. A software, programmed by Super B, tests the Traction batteries on disturbances and balances each of the four cells by discharging and recharging. When one does not balance the four cells, the battery will have a much lower overall capacity. The four lithium cells are connected in series, this means that when the first cell runs out of power the whole battery runs out of power. Balanced cells is one of the key competencies of the Super B batteries. Depending on how balanced the cells already are, it could half an hour till 4 hours for this process to complete.

Figure 2.8 - Charging & testing station of the Traction

2.1.7 Storage and shipping of the finished battery

After the charging, testing and balancing, the batteries will leave for the warehouse. The starter batteries will first be packaged and then stored, while the Epsilon and Traction batteries will first be stored and packaged later when a customer order arrives. After shipping the process restarts with scheduling new production orders.

2.2 Future considerations

When designing a layout, one would design it for the long term. It is vital to keep in mind future changes in the layout, otherwise it could be the case that the redesigned layout is inefficient after some changes in logistics or production. In the case of Super B, it is even more significant since they are currently experiencing a large growth and changes in the product mix.

2.2.1 Time horizon

The large growth results in the first issue in redesigning the layout: the time horizon. For fast growing companies like Super B the time horizon is of great importance. There are already indefinite plans for Super B moving to a new facility. Choosing a too small time horizon will only cover short term solution and could result in high rearrangement costs. However, a too large time horizon could result in an inefficient layout, since the further you look into the future the more uncertain it gets. Especially in the fast-growing energy market. Hence, in consultation with Super B, we decided to set the time horizon to four years, so from the start of **Q3 2019** up to the end of **Q2 2023**.

2.2.2 New products

In this sub section we go through each new component or product that may have an influence on the redesign of the layout. Super B is introducing a new version of the starter battery, two new variants of the traction battery and a whole new product: the 105A energy battery (105E). The smart starter battery consists of a normal starter battery with an extra component in the lid, a PCB. Just like the Traction and Epsilon battery, the Smart Starter has smart software that can monitor and produce energy more efficiently. The Smart Starter extension is an example of technology push. Technology push implies that a new development is pushed through R&D, production and eventually onto the market. This happens without considering whether or not it satisfies a user need (Martin, 1994). The impact of the Smart Starter on the process and the layout lies in the making of another sub-assembly. In the current plans, the Smart Starter sub-assembly will be produced at a separate sub-assembly station, just like the Sub 2 for the Traction, the Smart Starter station.

Next, we have the new variants of the Traction battery, the 210E. Currently Super B produces only the 100E and 160E Traction batteries. The new variant possesses different lithium cells, one with almost the same exterior properties as the 100E and 160E, but a much higher energy density. Therefore, it has no influence on the current assembly process, other than a change in quantities to be produced.

Finally, Super B wants to introduce a whole new battery, the 105E, which is a waterproof energy battery made for maritime usage. Where the new 210 uses 4 of the new lithium iron cells, the 105E uses 2. The 105E however, is less than half the size of the 210E and thus has a higher energy density than the 210E. The impact of this battery on the whole production facility is much higher. Super B has plans to set up a whole new production line for the new battery. This new production line will consist of three assembly stations and one test station, without sub-assemblies. The 105E is relatively easier to produce than the other batteries, due to smarter outsourcing and its design for manufacturability. Super B expects this model to become the best-selling Super B battery of all time.

2.2.3 Quantities and growth

In order to determine the flow intensity and the required area for departments in our 4 year time horizon, we need to forecast demand. This is an important issue for Super B. Recall that Super B expects a yearly growth of 40% in sales. These numbers suggest a large impact in production. Current departments could grow flow intensity due to rising demand or even decline as new products are taking over demand.

From interviews taken with the Super B's sales team, we discover that Super B has the intention to acquire several large Original Equipment Manufacturer (OEM) contracts in the future. Basically, large OEM ensures a stable and high amount of sales during a long-term collaboration. At this time Super B is very dependent on system integrators and distributors. Super B currently has only one large OEM contract with Lotus Cars Limited, which ensures a large amount of sales of the Starter battery. This makes forecasting in terms of historical data well-nigh impossible in the case of new OEM contracts. Therefore, we make a forecast based on historical data and we construct various scenarios together with Super B that deal with possible new OEM contracts. In this remainder of this section we look at the product life cycle of Levitt (1965) and approximate the current placement of the different battery types, see Figure 2.9.

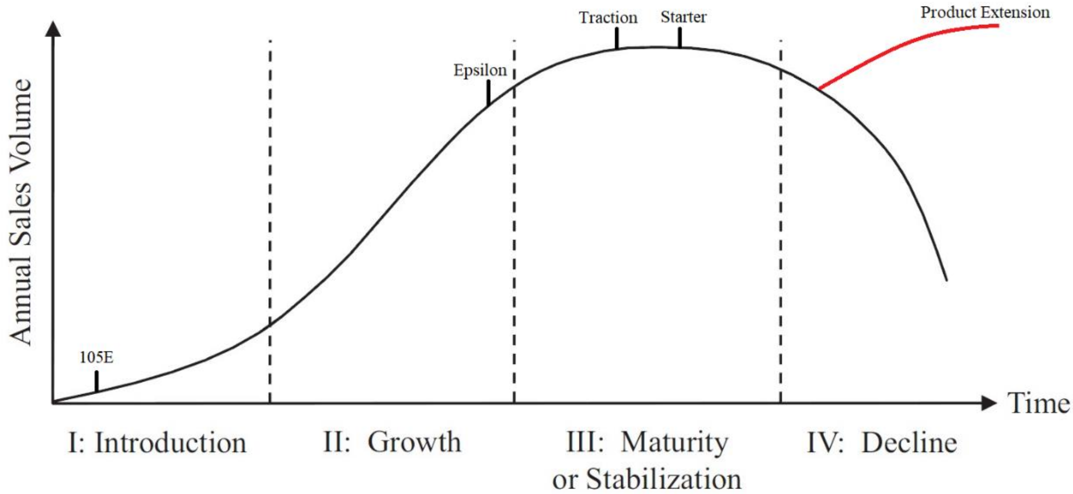


Figure 2.9 - Product Life Cycle (Levitt, 1965)

We approximate the Starter battery to be in the mature phase, since the sales of the past years were stable. This can also be explained by the racing-market. The racing-market provides the largest sales for the starter battery. This is not a growing market, but neither a shrinking market. However, with the introduction of the Smart Starter would mean an extended market and thus a higher growth due to product extension. Besides, the Smart Starter could also be an opportunity for obtaining more large OEM contracts, in that case the sales will promptly go up.

When researching the sales data of the Epsilon battery we estimate that the Epsilon is placed at the end of a steep growth period. This would indicate that the Epsilon battery is entering the Maturity phase. It is expected that it continues to grow for at a year. However, due to the introduction of the new 105E the sales of the Epsilon should decline faster.

As mentioned before the Traction battery is also facing product extensions. Currently the Traction battery is growing about 15% per year. The future of the Traction is questionable. On the one hand it is likely that the new 105E would have a negative impact on the sales of the Traction, since both can be used in the maritime sector. On the other hand, the Traction receives a serious capacity upgrade in the near future.

Finally, the new product, the 105E gets introduced in the beginning of 2020. The 105E starts, clearly, in the introduction phase. Super B expects the 105E to become the bestselling product in Super B's history, by far.

In Section 4.2 we make forecasts of all batteries above. As stated in Section 1.6, the accessories Super B also produces, like the BIB, are not taken into account in forecasting.

2.3 Current layout of the production

In this section we introduce the current floor layout of the production site and its separate departments. In Figure 2.11 an overview of all departments is given.

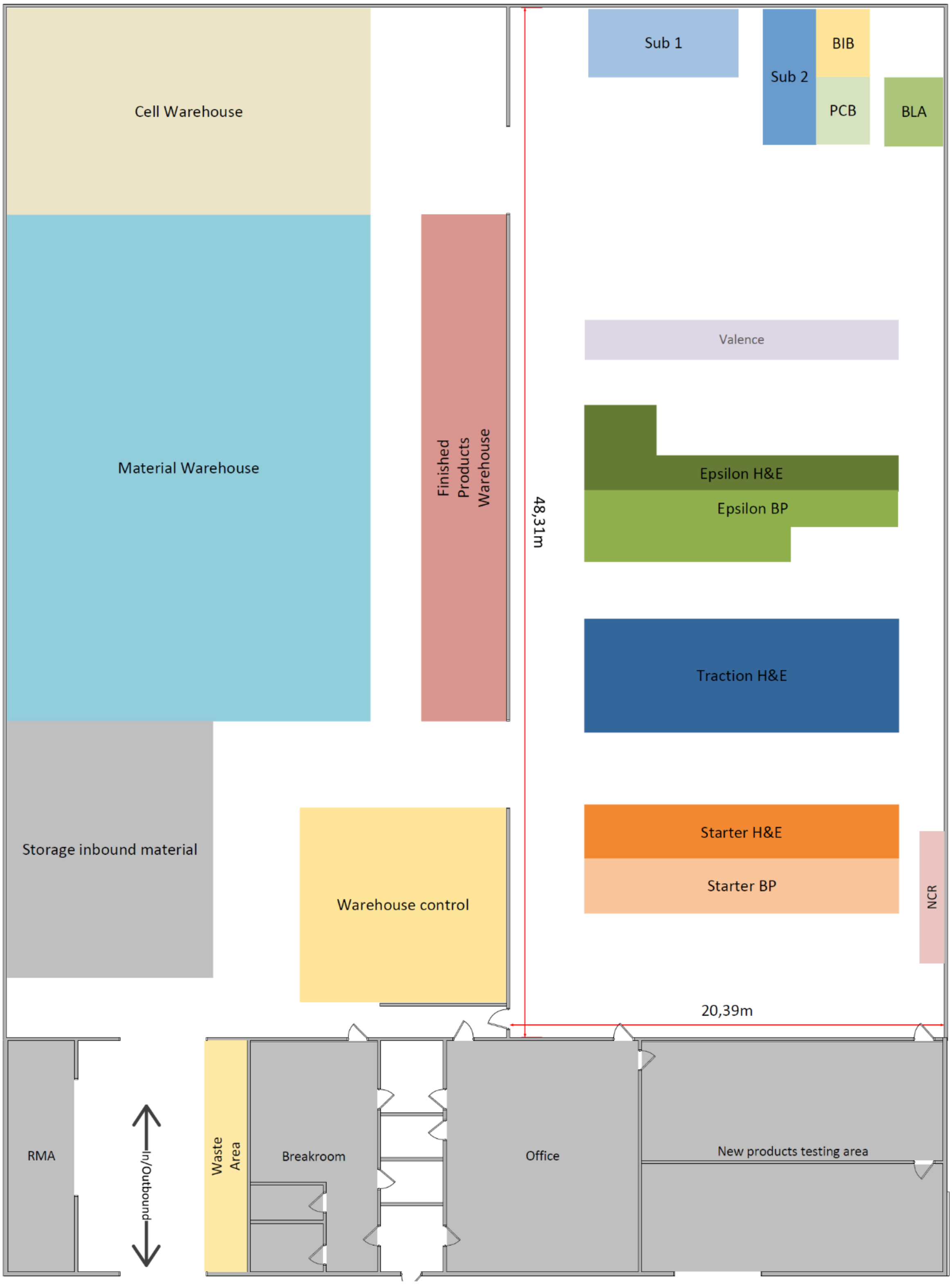


Figure 2.10 – The current layout of Super B's production facility

A detailed layout of super B's production facility can be found in Appendix I.6 (with a corresponding legend in Appendix I.1).

Next, we divided the departments in 4 categories in Table 2.5:

A. Departments that have to be reorganized.
B. Departments that have influence but are fixed.
C. Departments that will be introduced in the future
D. Departments that are out of scope and will be ignored.

Department	Abbreviation	Category
Sub 1 Station	Sub 1	A
Sub 2 Station	Sub 2	A
Batter Lid Assembly	BLA	A
PCB Support Assembly	PCB	A
BIB Assembly	BIB	A
Epsilon Battery Pack Assembly	Epsilon BP	A
Epsilon Housing and Electronics assembly	Epsilon H&E	A
Traction Housing and Electronics assembly	Traction H&E	A
Starter Housing and Electronics assembly	Starter H&E	A
Starter Battery Pack Assembly	Starter BP	A
NCR Rack	NCR	A
Material Warehouse	M-WH	B
Finished Product Warehouse	FP-WH	B
Cell Warehouse	Cell-WH	B
Waste Area	-	B
Smart Starter Station	Smart Starter	C
105E Assembly	105E	C
Warehouse Control & final packaging	WH-C	D
Valence Station	-	D
Storage Inbound Material	-	D
In-/Outbound Warehouse	-	D
RMA Station	-	D
Breakroom	-	D
Office	-	D
R&D Testing Area	-	D

Table 2.1 – Categorisation of the departments

2.4 KPIs currently in place

In this section we study the KPIs Super B make use of in their production facility. Beside our objective function we need to take into account other factors that can be affected positively or negatively by our research. Currently Super B uses 5 KPIs in the production facility, see Table 2.2.

KPIs
Capacity utilization
First Pass Yield
Cycle time
Inventory turnover
Work in Process

Table 2.2 - KPIs of Super B's production facility

2.4.1 Capacity utilization

The Key Performance Indicator capacity utilization is of great importance in terms of production. The KPI gives a percentage of time that the station is active. The capacity utilization could be measured on each level of the production facility: station, department or the whole facility. Super B measures this on department level. A utilization too low would indicate that station are unused which results in unnecessary costs. A utilization to high would indicate that Super B is in under capacity resulting in larger inventories.

2.4.2 First Pass Yield

The First Pass Yield (FPY) is defined as the number of units that go all the way through the production process without the need for rework divided by the total number of units that went through the production process in a certain period of time. The FPY is a good indicator of the yield of a process. The KPI shows how good the process is in producing defect-free products.

2.4.3 Cycle time

The cycle time is simply the total time elapsed to complete one or multiple operations. This, clearly, should be as low as possible.

2.4.4 Inventory turnover

Inventory turnover is the ratio of Sales divided by the Inventory. Inventory turnover is the number of times the company sells products and replaces its stock. This KPI provides an insight on how effective sales efforts has been and how the company manages its costs. A high inventory turnover shows that a company is fast in selling their goods and/or a high demand exists.

2.4.5 Work in process

Work in process (WIP), or work in progress, is the amount of goods that are waiting for completion. These items are already in production but not finished yet. They may be fabricated or are waiting in a buffer. The WIP requires space for storage and represents capital that cannot be used for investments.

2.5 Conclusion

In this chapter we started with explaining the general route an order takes that results in of the three main battery types. In the second paragraph we investigated the difficulties of future uncertainties Super B experiences. We conclude that difficulties consist mainly of the forecasting the quantities of current and new products and components. Therefore, we perform a literature review about forecasting (with limited data) in the next chapter. Finally, we listed multiple KPIs that are currently in use by Super B and could, next to our objective function, also be affected by our research proposal.

3 Literature Review

In the previous chapters we introduced Super B, gave the problems at hand and presented an overview of the current situation. Next, in this chapter, we perform a literature review related to three main subjects. In Section 3.1 we start with *the forecasting*, such that we can make a good approximation of future flows and expansions. In Section 3.2 we search literature for *the improvement of flows* using the lean philosophy. In Section 3.3 we start with researching *layout planning*. Within this section we discuss five topics: definitions in layout planning; Muther's Systematic Layout Planning method; approaches within the change of layouts; the different metaheuristics; and finally, the calculation of the layout performance.

3.1 Forecasting

In production planning, decisions will almost always involve managing resources in the presence of demand uncertainty. Capacity, for example, must be allocated to certain products in anticipation of future sales. These decisions require accurate forecasts of the demand in the future periods.

In this section we focus on forecasting models that we can use to calculate the required space and flow intensity for each department in different periods in the future. Finding the right model depends on:

- Demand intermittency
- Required amount of data
- Time horizon
- New products and products extensions capabilities

The products of Super B differ in these aspects, so multiple models will be discussed. Literature gives a number of models, but for this research we reduced them to three types of demand models: Time series demand model, intermittent demand model and the diffusion model.

3.1.1 Time series demand models

In Time Series Analysis we use mathematical models to statistically forecast the 'basic' demand. Time Series Analysis focuses on short term demand forecasting. We set x_t as the demand in period t in our forecast model. According to Silver, Pyke and Thomas (2016) any time series can be composed of four components: level (a_t), trend (b_t), seasonal factor (F_t) and the irregular random fluctuations ($\mathcal{E}$). The level of a model captures the scale of the forecast. When only the level is present in a model, the forecast would be a constant with time. The second factor, trend, identifies the linear growth. The third factor, the seasonal factor, identifies seasonal patterns in which alterations in demand level occur, which is more of a short-term parameter. The last factor is the random error that always occurs, which cannot be predicted. As mentioned before, TSA uses mathematical models which requires relatively much past data. In formula 3.1 the basic TSA formula, the multiplicative tend-seasonal model, is given.

$$\hat{x}_t = (a_t + b_t t) * F_t + \mathcal{E}_t \qquad (3.1)$$

The TSA models are specialised short-time forecasts.

3.1.2 Intermittent demand models

Intermittent demand can be defined as occurrences of infrequent demand. A simple but effective method is the Croston model (Croston, 1972), see formula 3.2.

$$x_t = y_t * z_t \qquad (3.2)$$

Where y_t is the probability of an order occurring and with z_t we express the quantity of the order. The probability of y_t is determined by dividing 1 with the average in-between period of past occurrences, which results in a simple uniform probability distribution y_t. The Croston model is primarily intended to forecast slow moving items but can also be effective in forecasting the occurrence of OEMs. As mentioned in Section 2.2.3, OEMs could have a major impact on sales. However, when Super B obtains an OEM contract (which happens sporadically like in Croston), the sales go up, but other than in Croston, they stay on approximately the same level for a long period of time, see Figure 3.1 for a conceptual demand period.

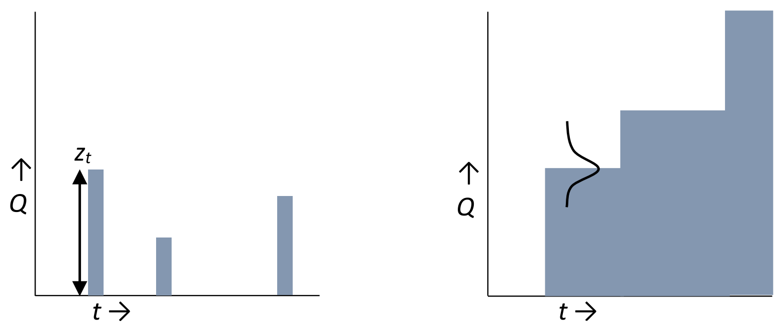


Figure 3.1 - Intermittent demand vs OEM demand

Therefore, we make a small adjustment to the Croston model, see formula 3.3. When a new large OEM contract occurs, the demand fluctuates around a certain level until a new OEM wants to get involved, which then adds up to the previous demand level. This results in a cascading demand curve.

$$x_t = y_t * z_t + x_{t-1} \qquad (3.3)$$

The intermittent demand model could be combined with the TSA model in order to successfully forecast different types of demand within each product group.

3.1.3 Bass diffusion model

The Bass diffusion model is rather different from the TSA and Croston models. The diffusion model consists of a difference equation that presents the sales curve of new products. It can be seen as the model to forecast the product lifecycle of new products. This means BASS uses long term forecasting. The Bass diffusion model uses either the sales data of the first few periods after the start of the new product or the past sales data from similar products. In the Bass model there are two groups of customers: innovators and imitators. The moment that the product is available is communicated through members of a social system, where a little group is interested and actually buys the product:

the innovators. The other group will follow after the word gets out. This second group is called the imitators. Figure 3.2 shows the conceptual graph of the Bass diffusion model.

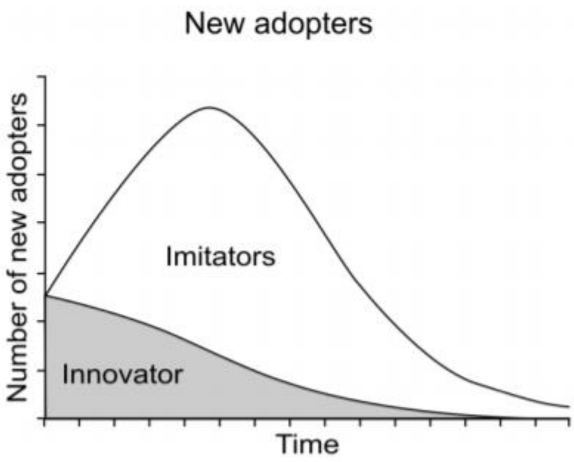


Figure 3.2 - BASS diffusion model (F. Bass, 2004)

The Bass diffusion model is a conditional probability function *f(t)* in which the probability is an event that will occur at a certain time *t* given that the event has not occurred before, or in this case the adoption of the product. Next, we define *F(t)* as the fraction of possible customers adopted at a certain time *t*, see formula 3.4. According to Bass (1969) "the probability of adopting by those who have not yet adopted is a linear function of those who had previously adopted." This quote is mathematically formulated in formula 3.5. In these formulas the *p* and *q* parameters are the coefficient for innovation and the coefficient of imitation respectively. The coefficient of innovations signifies the strength of advertisement, the higher this *p*-value the sooner one would reach the peak sales, it does not affect the overall shape of the adoption curve. The coefficient of imitation signifies the strength of word of mouth processes. This parameter has an influence on both the shape, size and timing of the peak of the adoption curve. A higher *q*-value results in a higher peak that is achieved earlier in time. Increasing the coefficient of imitation, or contact rate, can be achieved by arranging conferences, workshops or by creating an environment where current adopters and potential adopters could come in contact.

$$f(t) = p + (q - p)F(t) - q[F(t)]^2 \qquad (3.4)$$

$$\frac{f(t)}{1 - F(t)} = p + q * F(t) \qquad (3.5)$$

Solving for *F(t)* and *f(t)* gives us formula 3.6 and subsequently formula 3.7.

$$F(t) = \frac{1 - e^{-(p+q)t}}{1 + \left(\frac{q}{p}\right) * e^{-(p+q)*t}} \qquad (3.6)$$

$$f(t) = \frac{(p+q)^2}{p} * \frac{e^{-(p+q)t}}{(1 + (\frac{q}{p} * e^{-(p+q)t})^2} \qquad (3.7)$$

By differentiating formula 3.7 we can calculate the moment of peak sales, this is done in formula 3.8. Here t^* is defined as the moment of peak sales (Bass, 1969).

$$t^* = \frac{1}{p+q} \ln(\frac{q}{p}) \qquad (3.8)$$

Next, we introduce a new parameter *m* as the ultimate market potential. The market potential can be seen as the upper limit on sales for each period of time. The number of sales can now be defined as *S(t)*, see formula 3.9 and subsequently we implement the peak moment of sales in formula 3.10, resulting in S^*.

$$S(t) = mF(t) = m\frac{(p+q)^2}{p} * \frac{e^{-(p+q)t}}{(1 + (\frac{q}{p} * e^{-(p+q)t})^2} \qquad (3.9)$$

$$S^* = \frac{m(p+q)^2}{4q} \qquad (3.10)$$

In order to make a precise forecast we need to estimate the parameters *p*, *q* and *m*. First, the parameters *p* and *q* can be estimated by analysing historical data of similar products. For this we create two other variables: *N(t)* and *n(t)*, which are the cumulative sales and the sales in period *t* of a similar product(group) respectively. Quadratic non-linear (polynomial) regression N(t) is then applied under *N(t)* and *n(t)*. This results in formula 3.11. From this formula we gain the parameters *a*, *b* and *c*.

$$n(t) = \boldsymbol{a} + \boldsymbol{b} * N(t) - \boldsymbol{c} * (N(t))^2 \qquad (3.11)$$

Next, with the values of the known parameters a, b and c, the innovation and imitation coefficient can be determined. These values can be calculated using the *a*, *b*, *c* and *m* parameter, see formula 3.12 and 3.13. The ultimate market potential parameter of the new product, *m*, could be chosen in consultation with the company's management or experts. The parameter *m* could also be calculated from the used similar products, then formula 3.14 should be applied.

$$p = \frac{a}{m} \qquad (3.12)$$

$$q = p + b \tag{3.13}$$

$$m = \frac{-b - \sqrt{b^2 - 4ac}}{2c} \tag{3.14}$$

With these parameters one could calculate the expected sales of the new product for each period with formula 3.9, the graph of these values should resemble the product life cycle of Levitt (1965).

In 1987 Norton and Bass created an update of the Bass diffusion model. Recall that in Section 2.2.3 we explained that some products could have new extensions (like the Smart Starter Battery) that give sales a boost and extend the life cycle. These extensions could also be forecasted with the Bass diffusion model (1987). In Figure we see the amount of stock for different generations of cell phones which indicates the amount of sales. Here G2 represents a new extension of G1 and G3 as a second extension.

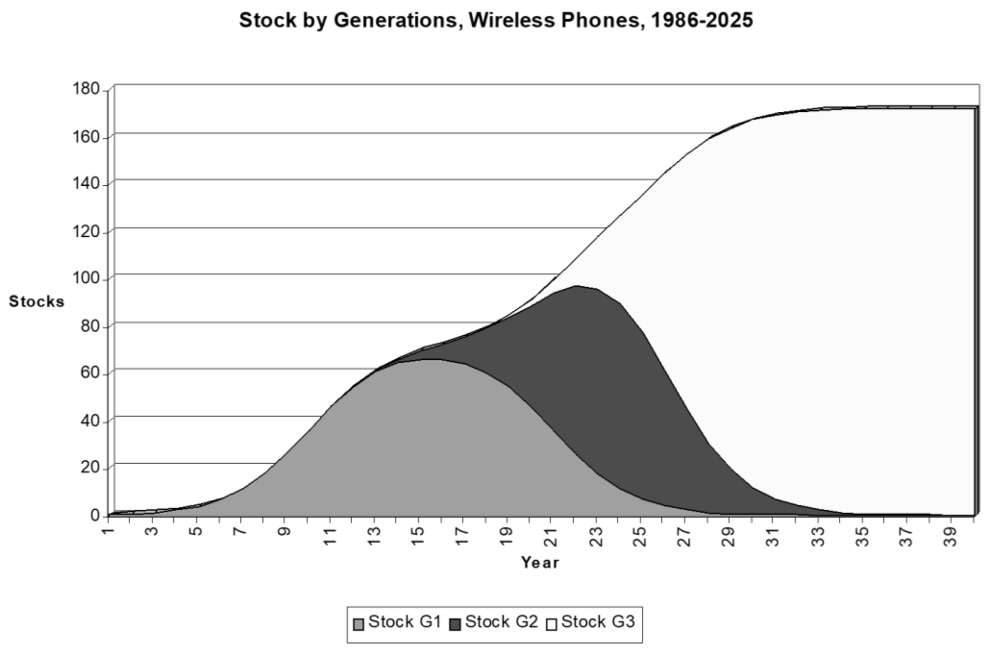


Figure 3.3 - Storage numbers of Wireless phones (solvinnov.com, 2019)

The extensions are modelled using formulas 3.15 and 3.16.

$$S_{1,t} = F(t) * m_1 * (1 - F(t - \tau_2)) \tag{3.15}$$

$$S_{2,t} = F(t - \tau_2) * [m_2 + F(t) * m_1] \tag{3.16}$$

Where τ_i is the time since introduction of the i^{th} product extension and m_i the ultimate market potential of the i^{th} product extension.

3.1.4 Model overview

In Table 3.1 an overview of each forecast model is given. In Section 4.2 we make a selection between these models.

Characteristics	Time Series Demand model	Croston Intermittent demand model	Bass diffusion model
Demand interval	Non-intermittent	Intermittent	Non-intermittent
Required amount of data	3-5 years	High number of orders	At least 3 'periods' or data of similar products
Time horizon	Short term (weeks-months)	Medium term (months-years)	Long term (years-decades)
New products and products extensions	Not included	Not included	Included

Table 3.1 – Overview of forecast models

3.2 Reduction of flows

Now that we have examined which methods we could use for forecasting, we search for options to improve the efficiency of the layout. The efficiency of a layout is generally expressed in terms of material handling costs. These costs are directly related to the distance material has to travel and how often it has to travel. So, in reducing the total travel distance two aspects can be reduced, either the distance, or the number of flows. In this section we focus on reducing *the number of flows*. In Chapter 2 we concluded how two of the core problems of this research explain the high total travel distance super B was experiencing. This was due to a large number of flows from sub-assembly and to production. In this section we look at what kind of flows there are.

3.2.1 Backtracking and bypassing

Backtracking and bypassing, see Figure 3.4, are two movements in flow-line layouts. These flows negatively impact the flow of the products. Bypassing occurs when a part skips one or multiple facilities during its move towards the flow line arrangement. Backtracking is the movement of a Work In Process (WIP), from one facility to another preceding in the sequence of facilities in the flow line arrangement (Drira, Pierreval, & Hajri-Gabouj, 2007). So, these number flows, whose direction is contrary to the global sequence, has to be minimized. Or in other words: maximize the number of directed flow paths. A directed flow path is an uninterrupted path of flows that experiences no backtracking or bypassing and creates no congestion or unwanted intersections with other flow paths.

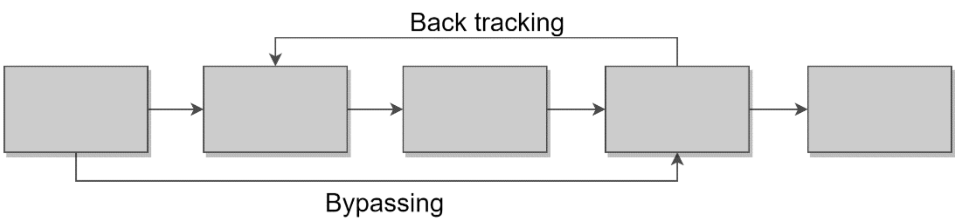


Figure 3.4 - Backtracking and bypassing

3.2.2 Lean philosophy

In this subsection we search for methods to counter backtracking and bypassing. We start with considering the lean philosophy. The lean philosophy can contribute to three aspects: the philosophy to run operations; the method of planning and controlling operations; and the improvement of operations performance. In our research we focus on the method of planning and controlling operations, in particular layout and the lean planning methods. In this section, the search is dedicated to lean planning methods that reduce (or even eliminate) the backtracking and bypassing flows, such that we improve our primary objective function, as well as our secondary objectives (the KPIs given in Section 2.4).

Transportation waste

According to Slack (2013), backtracking and bypassing contribute to the third form of waste in lean philosophy: transport. Waste can be defined as any activity that does not add any value (Slack, 2010). Moving items around the operation, together with the double or even triple handling of the WIP, does not add value. In fact, it can even decrease quality of the product. These sorts of wastes can be eliminated through a smooth streamlined flow. The smooth flow of information, people and information is one of the essential ideas in the lean philosophy. Long process routes appear it is accompanied with large inventories and delay, which in turn slow down throughput time and add no value. Basically, there two contributions in lean to a smooth streamlined flow. The first contribution to a streamlined flow is change in layout, which we will discuss in the next sections, and secondly, in which we focus in this section, planning and control methods which promote smooth flows.

Just-In-Time

A well-known planning and control method in lean management is the Just-In-Time (JIT) methodology. JIT was introduced in Japan before the term was expanded and called lean manufacturing. The key focus in JIT is that each process only produces what is needed for the succeeding process, in a continuous stream. The supply of material and information exactly matches the demand, both in quantity and in time. JIT results in an uninterrupted flow, which will result in shorter lead times, better quality and lower costs. Basically, JIT consists of three elements: takt time, flow production and a pull system.

Takt time

Takt time is the time needed to produce products in order to meet the pace of customer demand. The Takt time is calculated by dividing the average available work time by the average rate of customer demand. 1

Flow production

Flow production, or one-piece-flow, is a production method that focuses on processing in items in small quantities in sequential steps, rather than mass production. In flow production products flow from one process to another without waiting and only acceptable quality products are accepted by the succeeding process.

Pull system

To understand the pull system, we first introduce the push system. In a push-controlled production environment each workstation will push out work to the next operation, without taking into account if the next workstation can make use of it, see Figure 3.5. Each workstation is controlled by a central operation planning and control system. However, there can be many reasons why actual conditions are different from those that were planned. This result in larger queues, idle time and inventory. The planning method in use, is the Material Requirements Planning (MRP), which is a demand driven system that determines when each part is required.

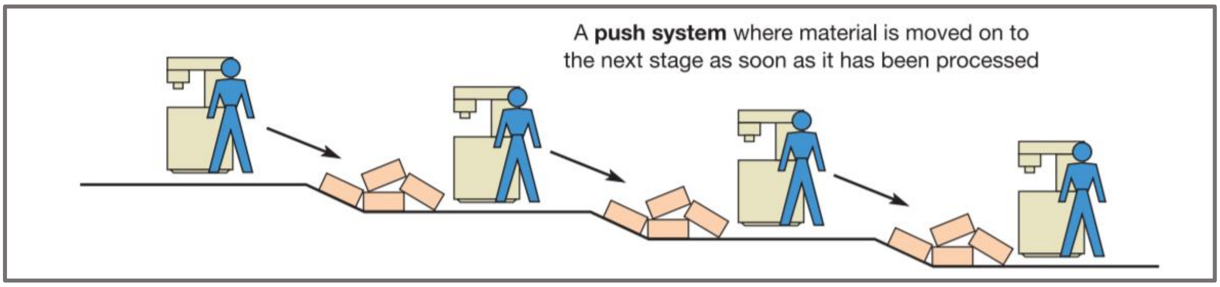


Figure 3.5 - Push production (Slack, 2013)

Completely in contrast is pull production. In pull production the pace and variety are determined by the last workstation, which, gets triggered by the customer. This means that each workstation is pulling work from the preceding workstation. The preceding workstation can't operate when there is no request from the succeeding workstation. This system is far less likely to result in large inventories. Figure 3.6 shows that in parts can't flow uphill, only when pulled from the next station, resulting in a smaller WIP inventories. Literature consists of many conflicting definitions of pull systems. Pull system is frequently classified in literature as a make-to-order production, while push systems refer to make-to-stock production. However, we prefer the definition composed by Hopp and Spearman (2004), who distinguish both puss and pull-systems on whether or not the systems enforces a limit on WIP. A Pull system is a system that forces a hard limit on WIP (or inventory), while a push system does not enforce a hard limit.

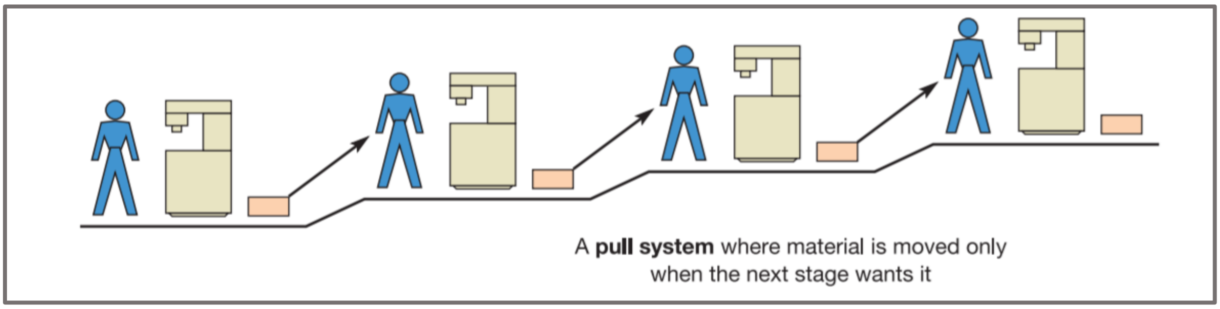


Figure 3.6 - Pull production (Slack, 2013)

Finally, there exists a hybrid system: the push-pull system. In a push pull system, a succeeding station makes an order request (pull), while the preceding notes reacts by replenishing from a certain stock, that is filled up by warehouse (push). The advantage of a push-pull system is that one could base the inventory levels of individual components on forecasts and the production on actual demand.

Note that in this research we focus on improving the production facility of Super B and don't take into account the improvement of the planning of incoming and outgoing goods. Thus, we don't research the implementation of pull production throughout the whole process.

Planning and control methods

In order to operationalise the three elements of JIT we explore three planning and control methods. The first method is **Kanban**. Kanban is a card-based system that controls items between operations. In the common form Kanban is a card that is sent back to the previous workstation as a signal to send more item(s). The idea of Kanban can be implemented in multiple ways like the two-bin system or POLCA. The two-bin system is perhaps the easiest way to introduce a Kanban system into a production facility. One would place two equally sized bins with material next to a workstation. When one bin is empty the production starts with the second bin. The first bin is then used as a signal and send back to the previous workstation. The empty bin is filled and brought back next to other bin, this process goes on and on.

POLCA, our second method, is more extensive and difficult to implement. The downside of a simple Kanban system is the lack of production variety. In Kanban is a high quantity, low variety system. Therefore, there is a material control system developed, called POLCA, that can handle a larger variety of products. POLCA stands for Paired cell Overlapping Loop of Cards with Authorization. With POLCA workstations are linked to one or more workstations downstream and form a loop. Within this loop a number of POLCA cards circulate. If the receiver finished his work, he sends a released POLCA card, that belonged to his predecessor, upstream as a signal that it has the capacity to start a new order. What products this order consists of does not matter. An ERP system then indicates which orders are authorized, or which products may be produced. The number of cards in a loop represents the WIP. POLCA comes out best when each product type have different routes in a production process. For example, when part 1 has to go through stations A-B-D-F and part 2 has to go through stations A-C-D-E (and so on), it is difficult to implement a simple Kanban card system to properly route each part.

The last common method in literature for operationalising a Pull System is Constant Work in Process (CONWIP). CONWIP is also a form of Kanban. CONWIP follows a simple procedure. An order with the highest priority (based on a priority rule) is released for a production line when the WIP of a production line becomes lower than a WIP limit (Lödding, 2011). It differs from Kanban, since with Kanban a separate set of cards is dedicated to each workstation, instead of the whole line. This results in setting more parameters with Kanban (multiple stations) than with CONWIP. Kanban is also specific for each type of products, while in CONWIP the next order is based on the priority rule, which, in addition, also results in a better cope with variation of product and volume.

With these methods one would not only reduce the WIP, but also gives the opportunity to reduce certain backtracking and bypassing flows. With pull production, backtracking flows, like flows from production towards temporary storage can be eliminated by keeping the WIP in production, which subsequently also eliminates the flows from temporary storage towards production, the bypassing flows.

3.3 Layout planning

In the previous Section we presented two ways of improving the efficiency of a layout, either by reducing the number of flows or by reducing the distance of the flows. In this section we focus on *reducing the distance of flows*. We divided this section in five main subsections: definitions in layout planning; Muther's Systematic Layout Planning method; approaches within the change of layouts; the different metaheuristics; and finally, the calculation of the layout performance.

3.3.1 Definitions in layout planning

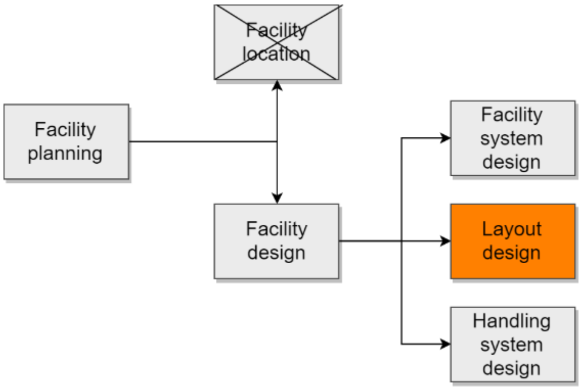


Figure 3.7 - Facilities planning

Facilities planning determines how tangible fixed assets can be in best support of achieving the activities objective. In manufacturing context this means that facilities planning supports production. It is important to realise the difference between facility planning, facility design and facility layout. The planning of facilities can be divided two major tasks: facility location and facility design, see Figure 3.7. The design of a facility layout is known to have a substantial effect on manufacturing costs, work in process, lead times and productivity (Drira, Pierreval, & Hajri-Gabouj, 2007). Good facilities design planning can contribute to a reduction of 10% to 30% of the material handling expenses, which is about 20% to 50% of the total expenses. The facility design is subdivided in facility systems design, the facility layout and handling system design. The facility system design includes environmental, lighting/electrical and safety systems. Layout design consists of all production(-related) areas, support areas and personnel areas within the building's envelope. The handling system design consist of all handling equipment, personnel, material and information that supports production. As discussed in Section 1.6, we focus on the facility layout, while taking the facility and handling system design in mind.

3.3.2 Systematic Layout Planning

In 1961 Richard Muther introduced the Systematic Layout Planning (SLP) method to systematically address layout problems. SLP is a simple step by step procedure and has three main phases: the analysis phase, the search phase and the selection phase, see Figure 3.8.

Analysis phase

In the first step of the analysis phase, a series of input data is required. This is generally obtained by using a PQRST analysis, where the product, quantity, routing, supporting activities and time are examined.

The flow of materials is analysed in the second step. This is generally accomplished with the use of a flow-to chart. The flow-to chart is a matrix in which flows between all departments are quantified.

In step 3, the activity relationships, the non-quantifiable relations are identified. This is done by rating the necessity of closeness in an activity relationship chart. The activity relationship chart is of more importance when an adjacency-based objective is used.

In step 4 the previous two steps are combined into a relationship diagram. A relationship diagram exposes a good relative positioning decision among the functional areas. It provides a quick overview of the potential closeness relationship (Yang, Su, & Hsu, 2000).

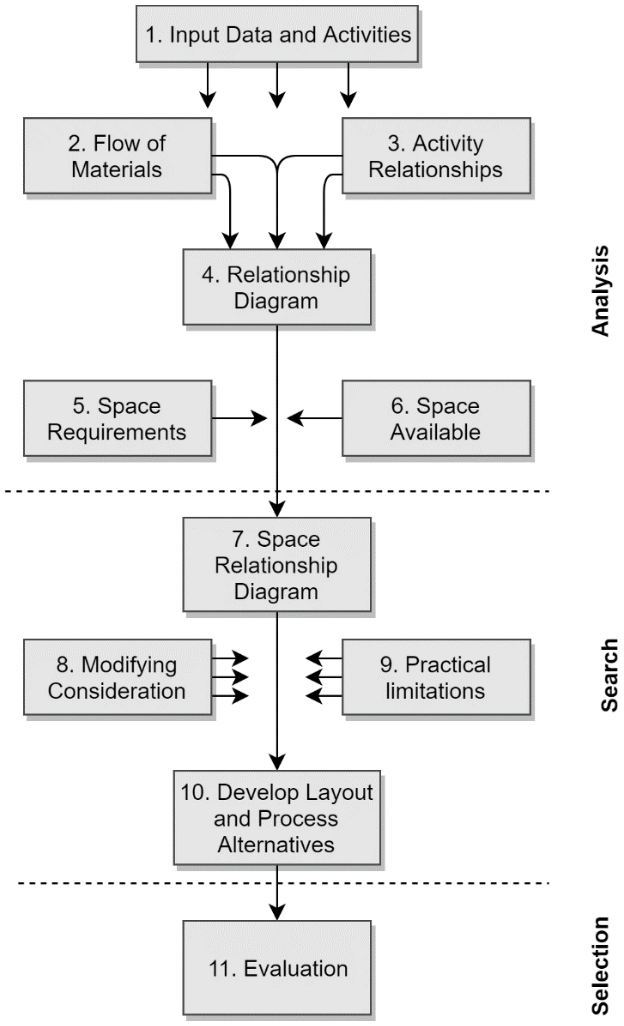


Figure 3.8 - Systematic Layout Planning by Muther (1961)

Step 5 and 6 are space related and the last of the analysis phase. In step 5 the required space for each department is calculated, which is one the more extensive steps in SLP. We determine the required space by first determining individual workstations, next, departmental requirements should be determined based on the collection of workstations in the department and the main aisles.

According to Tompkins (2010) the required space for each individual workstation is mainly determined by:

1) Equipment
    a) Workbenches
    b) Machinery
2) Material
    a) Inbound material storage
    b) In-process material storage
    c) Waste and scrap storage
    d) Tools

3) Personnel
    a) Operator work area
    b) Material handling (within workstations)
    c) Operator ingress and egress

After the workstation space requirements, we specify the departmental space requirements. To determine the departments space requirements, we won't just sum all individual workstations, we also need to include aisle space, material handling within the department and other details, like information boards. Aisle spaces within departments cannot be determined exactly, since the setup of within the department is not yet known, however, it can be estimated. Finally, we need to determine the main aisle space requirements. Aisles can be divided in department aisles and main aisles. The main aisles are the aisles between departments in the facility. Planning aisles to narrow would result in a congested facility with a lot of damage and safety problems. On the contrary, planning the aisles to wide would result in a waste of space. Volume and the material handling equipment are decisive factors when determining the aisle width.

In the final step of the analysis phase we determine the available space. This is simply the area where the departments can be placed.

Search and selection phase

In the search phase we start with step 7: the space relationship diagram. In this step the relationship diagram is converted into a space relationship diagram by mapping the area of each department. Department pairs with a high flow intensities or closeness relation are favoured to be placed in proximity. In step 8, 9 and 10 we construct layout alternatives considering modifications (step 8) and practical limitations (step 9). These steps convert a space relations diagram into a block layout. The different layout design algorithms will be explained in section 3.5. Finally, we detail further such that each the layout of the facility is completely redesigned.

3.3.3 Approach comparisons

In this subsection we take different aspects in consideration that will help us choose the right designing procedure.

Continuous or discrete approach

Following SLP one would have to construct a block layout. This block-layout can either be continuous or discrete. Most layouts are optimized with a discrete approach. This allows computer to store and manipulate the layout as a matrix. With this representation the area is rounded to the nearest integer. The grid size determines the resolution of the layout: a smaller grid results in a finer resolution, which result in more flexibility of the departments shapes. However, this also results in a larger number of grids, which considerably enhances the computational time (Tompkins et al., 2010).

The alternative representation is the continuous approach where one won't use a grid structure. In Figure 3.9 the two options are visualized (the grid in the continuous representation is only for comparison purposes). The continuous approach can be seen as a discrete approach with infinite number of very small grids. This means that the continuous approach is much more flexible but also takes more effort to compute. The continuous approach becomes easier to implement on a computer if it consists of strictly rectangular departments and a rectangular building. Then the only information needed to pinpoint the exact location and its shape are the area; *x, y*-coordinate of the centroid and the length of either the north-south direction or the east-west direction of the department.

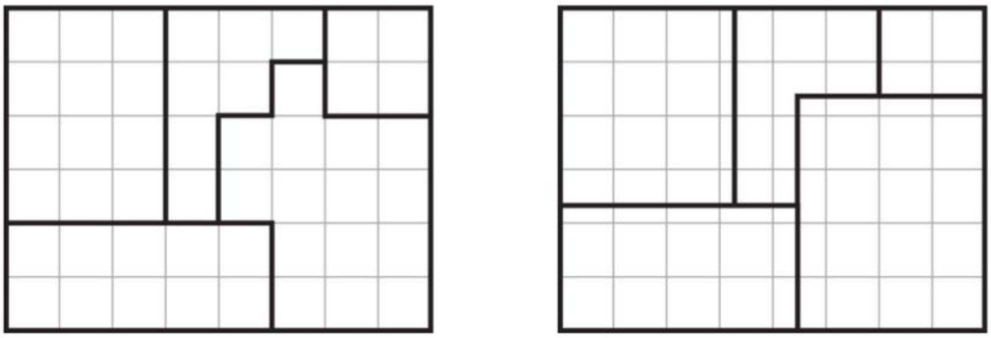


Figure 3.9 - Discrete (left) versus continuous (right) layout representation (Tompkins, 2010)

Exact or heuristic approach

Facility layout problems can be solved by using exact approaches and heuristic approaches. In the exact approach the optimal solution is provided, but (depending on the problem) it can take some time to get there. A heuristic is an approach to solve problems, not in guarantee of finding an optimum, but to find a sufficient solution that is capable of reaching the immediate goal (Michalewicz, 2013). Facility layout problems are NP-hard problems, which means that using an exact approach takes quite some time and might even be impossible to solve. Heuristics can be used to speed up the process of finding an acceptable solution. In layout problems there are several improvement heuristics that are constructive.

Static, dynamic or robust approach

Nowadays manufacturers must be able to quickly respond to changes in demand, product mix and product volume. Page (as cited in Drira, 2007) reported that, on average, around 40% of company's sales are gained thanks to the introduction of new production. However, the changes in yield will also mean changes in layout. This brings us to the third choice we must make within our model. Do we choose a static, dynamic or robust model?

In static approaches one would base the layout on a single moment in time with a certain product mix. In the history of layout planning most redesigns where made using the static approach. Until the last period more and more companies switch to a dynamic approach. The dynamic approach considers more than one timeframe, while considering the effects of the product mix and the rearrangement costs, in order assure a long-term solution. The objective of a dynamic approach is defined as the minimization of total costs, material handling costs for multiple static layout problems and additional rearrangement costs between periods. The static layout problem that is used can either be the best static layouts, random layouts or a mix between both. This results in formula 3.1.

$$Min(Dynamic\ Layout\ Problem) = \sum_{t=1}^{T} Static\ layout\ problem\ (t) + \sum_{t=1}^{T-1} Rearrangement\ cost_{t,t+1}$$

(3.17)

The rearrangement costs occur between the change of period *t* and period *t+1*.There are multiple approaches to calculate the rearrangement costs for the dynamic approach. Rearrangement of departments may lead to production loss or may require specialised labour and equipment. Therefore, rearranging a production facility consist of labour costs, equipment costs, out-of-pocket moving expenses and the costs of operational disruptions (Suo, 2012). We consider these costs as fixed costs. If the rearrangement costs are relatively low, the layout configuration will tend to change more often in order to attain the material handling efficiency. Same principle is true for the other way around. If the rearrangement cost is high, the layout configurations tends to be more static.

Viewing multiple periods will also lead to larger computational problems. While static layout approaches would have $N!$ (where N is the number of departments) solutions, a dynamic layout problem would have $(N!)^T$ (where T is the number of time periods) solutions. Logically the more periods you chose, the better the results become, but more calculations it requires.

According to Rosenblatt (as cited in Suo, 2012) robustness is defined as the frequency that a layout falls within a pre-specified percentage of the optimal solution for different sets of production scenarios. In a robust layout one would also consider a wide variety of products and demand scenarios (as in the dynamic approach), but one would only choose one layout, even though this layout may not be optimal under any specific demand scenarios. Therefore, the robust method does not take into account rearrangement costs in the objective function, it only consists of minimizing the material handling costs as in the static approach.

For this research, since Super B is a fast-growing company, it is of great importance to ensure that future products won't go unnoticed. However, in our time horizon of 4 years it is illogical to think that Super B will change its layout multiple times. Therefore, we choose the robust approach.

Adjacency- or distance-based objective

In this section we compare the distance-based objective to the adjacency-based objective. Recall that the distance-based objective is formulated as in formula 3.2. The adjacency-based objective can be seen in formula 3.3.

$$\textit{Distance-based objective}: \ \min z = \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij}\, c_{ij} d_{ij} \qquad (3.18)$$

$$\textit{Adjacency-based objective}: \ max\ z = \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij} x_{ij} \qquad (3.19)$$

The distance-based objective is very similar to the classical combinatorial optimization problem called Quadratic Assignment Problem (QAP) objective. The problem follows the following real-life problem where a set of *n* facilities and a set of *n* locations need to be paired. Each pair of locations would have a weight or flow and a distance between each other. The problem is to assign all facilities to the different locations, with a goal to minimize the sum of the distance times the corresponding flows.

The adjacency-based objective is to maximize the adjacency score. The adjacency score is calculated by the sum of all flows or relationship values (step 3 in SLP). The adjacency-based objective is mainly used to arrange facilities based on their qualitive characteristics, which is not possible with the distance-based objective. The X_{ij} value can either be 1, which means department *i* and *j* are adjacent (i.e. relatively close to each other, share a border, etc.), or 0 otherwise.

Our objective in this research is to minimize the overall distance that has to be travelled. Besides, we don't make use of activity relationships (qualitive data); therefore, we select the distance-based approach.

3.3.4 Specific heuristic algorithms

Optimal block layout in production facilities is critical to the cost effectiveness in these facilities. Hence, a lot of different algorithms and computer programs has been developed over the past years. In this section we study different heuristics in order to select the one that matches best with the considerations made in the previous section.

CRAFT

CRAFT stands for Computerized Relative Allocation of Facilities Technique and has a distance-based objective function. CRAFT applies two- or three-way exchanges to an existing layout and identifies the best exchange. In CRAFT in/out points are located at the centre of the non-fixed department. Basically, CRAFT exchanges the centroids of the non-fixed departments. CRAFT exchanges only the departments that share a border or are at the same size. In Figure 3.10 an example of a CRAFT model is given. Here each number and colour represent a department. An iteration could be the exchange of department 6 with department 5 (same border) or an exchange with department 2 (same size). CRAFT searches for the best exchange, once it is found it updates the model and searches for the next best exchange and does this until no further reduction in layout costs can be obtained.

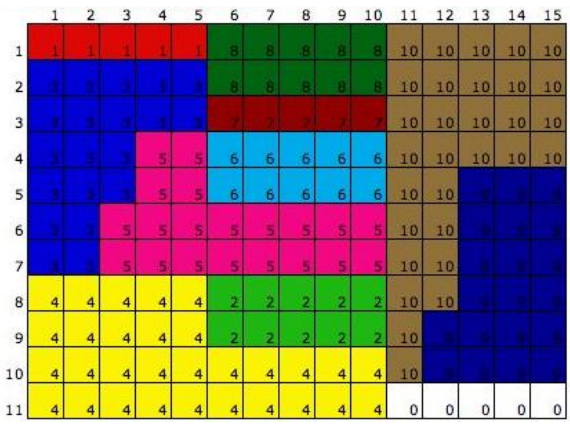


Figure 3.10 – A CRAFT Model (Utexas.edu, 2019)

Graph-based

According to Tompkins (2010) the graph-based method is a construction-type layout algorithm. The graph-based method is often used with an adjacency-based objective. We describe this heuristic procedure below and in Figure 3.7 using an example of Tompkins (2010).

Step 1:

In the first step a relationship chart is created with numerical weights. From this chart we select the pair departments with the highest mutual connection. In this case dep. 3 and 4.

Step 2:

Next, we list the remaining departments and their relation to departments 3 and 4. We select the department that has the highest total connection and add them in a chart. In this case department 2.

Step 3:

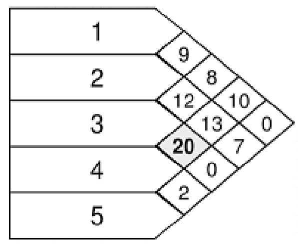
Now we have a face in the graph. We will denote this face as 2-3-4. We now choose between department 1 and 5 to be placed within this face. The value for adding department 1 and 5 is 27 and 9 respectively. Again the department with the highest value is selected and placed in the graph.

Step 4:

The last task is to determine on which face we place the fifth and last department. Department 5 can be paced in faces 1-2-3, 1-2-4, 1-3-4 and 2-3-4. Here the best faces are 1-2-4 and 2-3-4. We arbitrary select face 1-2-4 as the face where we place department 5.

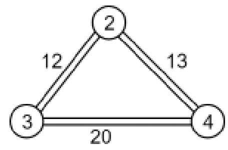
Step 5:

In the final step we construct a block layout based on the final graph of step 4. Note that when constructing a block layout with the graph-based method, it is likely that one would need to alter the original department shapes in order to satisfy the requirements. In practise it may not be possible to make these alterations.



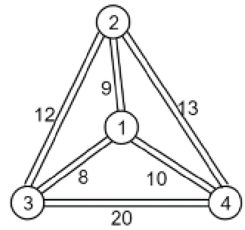
Step 1

	3	4	Total
1	8	10	18
2	**12**	**13**	**25**
5	0	2	2



Step 2

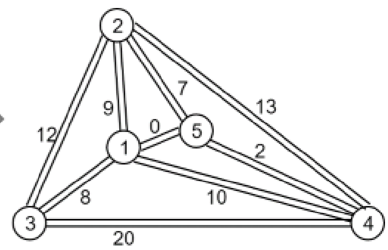
	2	3	4	Total
1	**9**	**8**	**10**	**27**
5	7	0	9	16



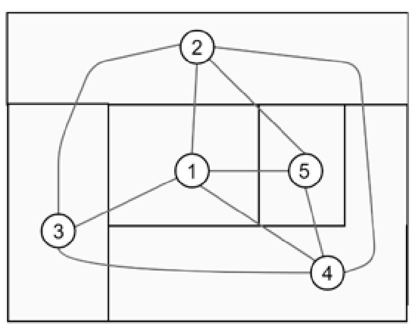
Step 3

	1	2	3	4
5	0	7	0	2

Faces	Total
1-2-3	7
1-2-4	**9**
1-3-4	2
2-3-4	**9**



Step 4



Step 5

Figure 3.11: Graph-based method

MIP

A continuous approach is the Mixed Integer Programming (MIP) problem. MIP can only be used when all departments are assumed to be rectangular. The MIP model requires only the centroid, area and length (or width) to fully show the shape and location of the department. MIP model is primarily used as a distance-based model. Although different methods of using MIP to layout design problems can be used, we focus on the model of Montreal (1990). Let us first consider the parameters of the model. Let

B_x	be the length of the building (using *x*-coordinates),
B_y	be the width of the building (using *y*-coordinates),
A_i	be the area of the department *i,*
$L^u{}_i$	be the upper bound of the length of department *i*,
$L^l{}_i$	be the lower bound of the length of department *i*,
W_i^u	be the upper bound of the width of department *i*,
W_i^l	be the lower bound of the width of department *i*,
M	be a large number.

Next, let us consider the decision variables. Let

α_i	be the x-coordinate of the centroid of department *i*,
β_i	be the *y*-coordinate of the centroid of department *i*,
$x_i^{'}$	be the *x*-coordinate of the left side of department *i*,
$x_i^{''}$	be the *x*-coordinate of the right side of department *i*,
$y_i^{'}$	be the y-coordinate of the bottom side of department *i*,
$y_i^{''}$	be the y-coordinate of the top side of department *i,*
z_{ij}^x	be equal to 1 if department *i* is strictly to the east of department *j*, and 0 otherwise,
z_{ij}^y	be equal to 1 if department *i* is strictly to the north of department *j*, and 0 otherwise.

The *z*-variable is created to ensure that no overlap takes place between the departments. Note that z_{ij}^x should be 1 when $x_j^{''} \leq x_i^{'}$, thus when the *x*-coordinate of right hand side of department *j* is smaller or equal to the *x*-coordinate of the left hand side of department *i*. The same principle goes for the z_{ij}^y variable, department *i* would be strictly above department *j* if and only if $y_j^{''} \leq y_i^{'}$. The departments are not overlapped when either one of the departments is east of the other (z_{ij}^x=1 or z_{ji}^x=1) or one of the departments is north of the other (z_{ij}^y=1 or z_{ji}^y=1) and, of course, no overlap exists when departments are separated on both axes.

$$Min\ z = \sum_i \sum_j f_{ij} c_{ij} \left(|\alpha_i - \alpha_j| + |\beta_i - \beta_j| \right) \qquad 3.20$$

Subject to	$L_i^l \leq (x_i'' - x_i') \leq L_j^u$	for all *i*	3.21
	$W_i^l \leq (y_i'' - y_i') \leq W_j^u$	for all *i*	3.22
	$(x_i'' - x_i')(y_i'' - y_i') = A_i$	for all *i*	3.23
	$0 \leq x_i' \leq x_i'' \leq B_x$	for all *i*	3.24
	$0 \leq y_i' \leq y_i'' \leq B_y$	for all *i*	3.25
	$\alpha_i = 0.5x_i' + 0.5x_i''$	for all *i*	3.26
	$\beta_i = 0.5y_i' + 0.5y_i''$	for all *i*	3.27
	$x_j'' \leq x_i' + M(1 - z_{ij}^x)$	for all *i* and *j*, $i \neq j$	3.28
	$y_j'' \leq y_i' + M(1 - z_{ij}^y)$	for all *i* and *j*, $i \neq j$	3.29
	$z_{ij}^x + z_{ji}^x + z_{ij}^y + z_{ji}^y \geq 1$	for all *i* and *j*, $i < j$	3.30
	$\alpha_i, \beta_i \geq 0$	for all *i*	3.31
	x_i', x_i'', y_i', y_i''	for all *i*	3.32
	z_{ij}^x, z_{ij}^y 0/1 integer	for all *i* and *j*, $i \neq j$	3.33

Equation 3.20 gives the distance-based objective function. The distance between two departments is rectilinear and is measured by calculating the difference between *x*-coordinates of department *i* and *j* and summing them with the difference between the *y*-coordinates. Constraints 3.21 and 3.22 are there to ensure that the length and width of a departments stays within their boundaries, while constraint 3.23 ensures that the department gets the proper area. In constraint 3.24 and 3.25 we make sure that all departments are placed within the building's coordinates. In 3.26 and 3.27 we determine the centroids of the departments.

Recall that we want the z_{ij}^x and z_{ij}^y to be active (z_{ij} = 1), when department *i* is strictly to the east or north, respectively, from department *j*. In other words, when z_{ij}^x=1, then M(1- z_{ij}^x) becomes zero and constraint $x_j'' \leq x_i'$ becomes active. On the other hand, when z_{ij}^x=0, department *i* would not be required to be strictly east of department *j* (thus constraint 3.28 and 3.29). However in that case department *i* does need to be either strictly to the west, north or south, i.e. either z_{ji}^x, z_{ij}^y or z_{ji}^y must be 1, hence constraint 3.30. Finally, constraint 3.31 and 3.32 makes sure the variables become non-negative and constraint 3.31 ensures that z_{ij}-variables become binary.

There are still some changes to be made to this model. The area is calculated by the non-linear constraint 3.7. In order to solve the MIP, the model needs to be linear. Besides, the objective function contains absolute values, which is not applicable in LP-modelling. Therefore, we create four new variables: α_{ij}^{+}, α_{ij}^{-}, β_{ij}^{+}, β_{ij}^{-}, which are the positive and negative part of for each term. We set

$\alpha_i - \alpha_j = \alpha_{ij}^{+} - \alpha_{ij}^{-}$ and $\beta_i - \beta_j = \beta_{ij}^{+} - \beta_{ij}^{-}$ then

$|\alpha_i - \alpha_j| = \alpha_{ij}^{+} - \alpha_{ij}^{-}$ and $|\beta_i - \beta_j| = \beta_{ij}^{+} - \beta_{ij}^{-}$

With these variables we can transform the non-linear MIP in a new linear MIP problem:

$$Min\ z = \sum_i \sum_j f_{ij} c_{ij} (\alpha_{ij}^{+} + \alpha_{ij}^{-} + \beta_{ij}^{+} + \beta_{ij}^{-}) \tag{3.34}$$

Subject to

$$L_i^l \le (x_i'' - x_i') \le L_i^u \quad \text{for all } i \tag{3.35}$$

$$W_i^l \le (y_i'' - y_i') \le W_i^u \quad \text{for all } i \tag{3.36}$$

$$P_i^L \le (x_i'' - x_i' + y_i'' - y_i') \le P_i^U \quad \text{for all } i \tag{3.37}$$

$$0 \le x_i' \le x_i'' \le B_x \quad \text{for all } i \tag{3.38}$$

$$0 \le y_i' \le y_i'' \le B_y \quad \text{for all } i \tag{3.39}$$

$$\alpha_i = 0.5x_i' + 0.5x_i'' \quad \text{for all } i \tag{3.40}$$

$$\beta_i = 0.5y_i' + 0.5y_i'' \quad \text{for all } i \tag{3.41}$$

$$\alpha_i - \alpha_j = \alpha_{ij}^{+} - \alpha_{ij}^{-} \quad \text{for all } i \text{ and } j,\ i \ne j \tag{3.42}$$

$$\beta_i - \beta_j = \beta_{ij}^{+} - \beta_{ij}^{-} \quad \text{for all } i \text{ and } j,\ i \ne j \tag{3.43}$$

$$x_j'' \le x_i' + M(1 - z_{ij}^x) \quad \text{for all } i \text{ and } j,\ i \ne j \tag{3.44}$$

$$y_j'' \le y_i' + M(1 - z_{ij}^y) \quad \text{for all } i \text{ and } j,\ i \ne j \tag{3.45}$$

$$z_{ij}^x + z_{ji}^x + z_{ij}^y + z_{ji}^y \ge 1 \quad \text{for all } i \text{ and } j,\ i < j \tag{3.46}$$

$$\alpha_i, \beta_i \ge 0 \quad \text{for all } i \tag{3.47}$$

$$x_i', x_i'', y_i', y_i'' \ge 0 \quad \text{for all } i \tag{3.48}$$

$$\alpha_{ij}^{+}, \alpha_{ij}^{-}, \beta_{ij}^{+}, \beta_{ij}^{-} \ge 0 \quad \text{for all } i,\ i \ne j \tag{3.49}$$

$$z_{ij}^x, z_{ij}^y \ \ 0/1 \ \text{integer} \quad \text{for all } i \text{ and } j,\ i \ne j \tag{3.50}$$

We modified the MIP by adding constraint 3.37, 3.42, 3.43 and 3.49 to ensure linearity.

LOGIC

Layout Optimization with Guillotine Induced Cuts (LOGIC) is a distance-based approach. LOGIC is construction algorithm, which means that, like the MIP, you won't need an initial layout. In LOGIC building will be divided into smaller and smaller portions by executing 'guillotine cuts' (Tompkins, 2010). Each cut can either be vertical or horizontal. If a cut is for example horizontal, departments will either be assigned to the northern side or southern side of the cut, in Figure 3.8 an example is given. In LOGIC multiple horizontal and vertical cuts are made. At each cut a subset of departments will be assigned to each side of the cut. LOGIC also provides a cut-tree in order to overview all decisions.

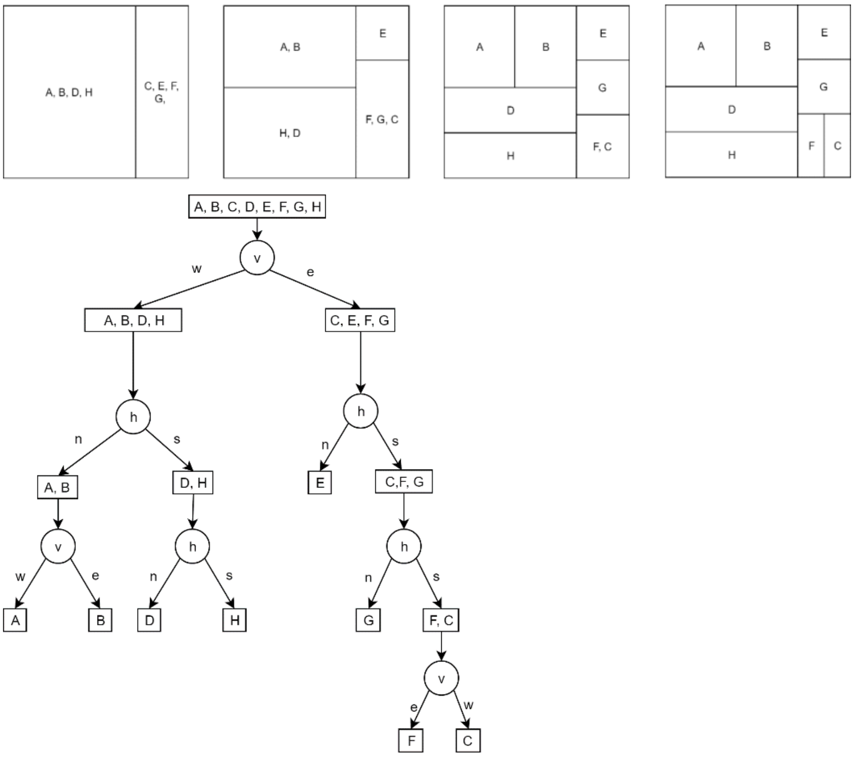


Figure 3.12: LOGIC example

MULTIPLE

Multi-floor Plant Layout Evaluation (MULTIPLE) was originally developed for multi-floor plant layout. MULTIPLE has a distance-based objective, where it measures the rectilinear distance. In MULTIPLE one would start with an initial layout. MULTIPLE is very similar to CRAFT with the exception of exchange procedure and layout information. Compared to CRAFT, MULTIPLE can exchange any department, whether they are adjacent or not. MULTIPLE achieves this by using space-filling curves.

Overview

In this sub section an overview is given in Table 3.13 to compare each algorithm.

Algorithm	Graph based	CRAFT	MIP	LOGIC	MULTIPLE
Continuous?	✔		✔	✔	
Non-rectangular area's	✔	✔		✔	✔
Distance based?		✔	✔	✔	✔
Rectilinear?		✔	✔		✔
Extensive swap options			✔		✔

Figure 3.13 - Overview of different algorithms

We tested each algorithm on five of our preferences we made clear in sub section 3.3.3. We found that MIP is the best option, since it gives an optimal solution and non-rectangular area's is not an important preference for Super B's facility. Second best option would be MULTIPLE. The only downside of MULTIPLE is that it is not continuous and only finds local optima.

3.3.5 Performance of a layout

In this section we go into further detail how to calculate the performance of a layout with the chosen distance-based approach. A layout's performance or efficiency is typically measured by material handling and transportation costs (Meller & Gau, 1996). Let *m* denote the number of departments, f_{ij} the flow from department *i* to department *j*, c_{ij} the costs of one-unit load transported form department *i* to department *j* and let d_{ij} denote the distance from department *i* to department *j*. In formula 3.51 the objective function is expressed mathematically.

$$\min z = \sum_{i=1}^{m} \sum_{j=1}^{m} (f_{ij} c_{ij}) d_{ij} \qquad (3.51)$$

Flow parameter

The flow f_{ij} is a constant parameter, that has to be quantified. Each flow can be calculated as the amount of material that is needed (in a certain time period) divided by the batch quantity. In order to map these flows a flow-to chart can be made. Here each department is showed with their flows from and to other departments.

Distance parameter

The distance d_{ij} is, in contrast to the flow, not fixed. The distance can be measured in two ways. The rectilinear distance see formula 3.52, and the Euclidian distance, see formula 3.53. The distances can either measured from a I/O point or from the centre of a department. When measuring the centre, it is important that all departments are rectangles, such that the centroid is not located in an empty space (i.e. with U shaped departments).

$$d_{ij}\ (Rectilinear) = [x_i - x_j] + [y_i - y_j] \tag{3.52}$$

$$d_{ij}\ (Euclidian) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{3.53}$$

Cost parameter

The cost c_{ij} is more extensive and difficult to determine. Each flow from department *i* to department *j* can differ. It mainly depends on with who, with what equipment the material and what additional time is required (in our case the time needed for picking, loading and unloading) to execute the flow. From Heragu (1997) we obtain formula 3.54.

$$C_{ij} = \frac{MHC_{ijk}}{f_{ij} * d_{ij}} \tag{3.54}$$

We calculate the total material handling costs to transport material from facility *i* to facility *j* (MHC_{ijk}) of material handling device (MHD) type *k* and divide this by the product of the distance and the flow matrix. The MHC_{ijk} consist of fixed and variable costs, see formula 3.55.

$$MHC_{ijk} = C_k * N_k * R_{ijk} + T_{ijk} * f_{ij} * OP \tag{3.55}$$

$$R_{ijk} = \frac{T_{ijk} * f_{ijk}}{\sum_{i=1}^{m} \sum_{j=1}^{n} T_{ijk} * f_{ijk}} \tag{3.56}$$

$$T_{ijk} = LAULT_{ijk} * Y_{ijk} + \frac{d_{ij} * Y_{ijk}}{S_k * TL_k} \tag{3.57}$$

The fixed costs are the investments costs of the required material handling device (C_k). This is multiplied with the number of devices that are in use (N_k) and the ratio of time spent on flow *i* to *j* and total time spent by MHD *k* (R_{ijk}). The variable costs are the product of the required time, the flow matrix and the operating costs per minute. The required time (T_{ijk}) is a sum of the loading, unloading and picking time ($LAULT_{ijk}$) and the travel time: the distance matrix divided by travel speed (S_k) in meters per minute and the percentage of non-empty transport (TL_k). Both the LAULT and travel time are multiplied with an auxiliary variable (Y_{ijk}), which is 1 if MHD *k* is used to transport material from department *i* to department *j* and 0 otherwise. Finally, the operating costs consists of all labour and non-labour (fuel, power and maintenance) operating costs per minute.

3.4 Conclusion

In this chapter we searched the literature for three main topics:

1. Section 3.1 *Forecasting*
2. Section 3.2 *Flow improvement*
3. Section 3.3 *Layout planning*

In the first section we found three models that we could use in forecasting: Time Series Analysis, Croston intermittent demand model and the Bass diffusion model. Each with their own characteristics and specific applications. Which model we choose, will be discussed in the Section 4.2, where we start with the forecasting.

In the second section we first found ways to identify which types of flow cause transportation waste, one of the eight forms of wastes in the lean philosophy. These were found to be backtracking and bypassing, which can be identified by constructing a flow chart. Each flow that goes back to a previous station or process is defined as the backtracking flow and each flow that surpasses a station or process is defined as the bypassing flow. The identification of these flows is done in Section 5.1. Next, we searched for methods to counter these flows. Using the lean philosophy, we found three planning and control methods: Kanban, POLCA and CONWIP. The selection of these methods is done in Section 5.2.

In the last section we researched layout planning. We divided this topic in five main subjects: definitions in layout planning; Muther's Systematic Layout Planning method; approaches within the change of layouts; the different metaheuristics; and finally, the calculation of the layout performance. We use these findings in Chapter 6.

4 Analysis of the current and forecasted situation

This chapter is divided in two parts. First in Section 4.1, we calculate *the performance of the current situation* in order to compare it in Chapter 6 with the alternative layouts. In Section 4.2 we select a forecast model and *forecast each battery type* in order to predict the demand. This chapter is part of the analysis phase of the SLP method (Figure 4.1), where we perform step 1 to 4. Forecasting is needed to in order to calculate the flow of materials (Step 2) and the space requirements (step 5), which is then calculated in chapter 6.

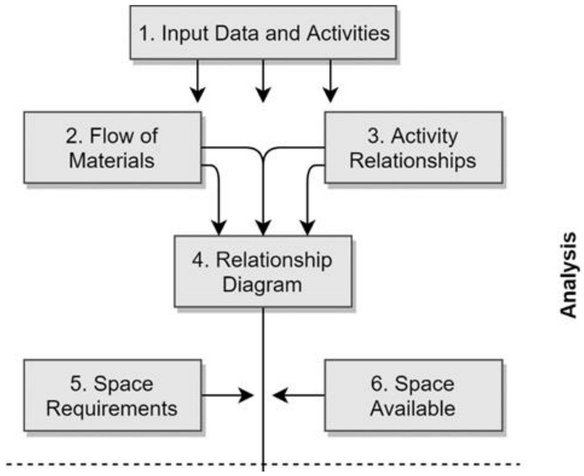


Figure 4.1 - Analysis phase of SLP

4.1 Current performance

In this section we calculated the distance-based objective for the current situation. Recall that the distance-based objective function is a summation, where each summand is a multiplication of distance, flows and the corresponding costs (function 4.1). We treat each subject separately in the next subsections. We start off with calculating the current flows between the department.

$$\min z = \sum_{i=1}^{m}\sum_{j=1}^{m}(f_{ij}c_{ij})d_{ij} \qquad (4.1)$$

4.1.1 Current flows

In order to obtain the flow of material we construct a from/to chart for all departments. We recognize 7 types of flows:

1. Material picking flows
2. Sub-assembly storage flows
3. Between production transport flows
4. Finished products flows
5. Cell transportation flows
6. Waste transportation flows
7. NCR transportation flows

During the whole process, from the start of the process (material picking) towards the end of the production process (finished products flows), the products are transported in batches. Therefore, we determine the first four types of flows by dividing the average quantity produced by the batch quantity. The time period we take is 1 week. We take the average of quarter 1 and 2 of 2019, to determine the average quantity produced. The batch quantity differs per SKU and is given in the production orders. The batch quantities are for all products a standard amount. This concludes all material flow.

The fifth flow type, the cell transportation flow, contains the delivery of lithium cells from warehouse towards production. In order to determine the cell transportation flows, we divide the total number of cells on a pallet by the demand of cells. The demand of the cells is equal to the amount of cells inside a battery times the demand of a battery.

The sixth flow type contains the waste transportation. This flow type contains of on the one hand the empty cell boxes on pallets and on the other hand residual waste. The first amount of flows is equal to the cell transportation flows, the second amount of flows we estimated through interviews with production operators.

The last type of flows, the NCR transportation flows, contains all flows after defects in components occur. When a component is damaged, the production operator takes the part to the department Warehouse Control. Here warehouse personnel picks a new item and delivers it to the operator, who is still waiting at Warehouse Control.

For each of the 7 types of flows, we have also determine the empty flows. Take for example the material picking flows for the Starter, see Figure 4.2. When warehouse personnel has to pick an order, it starts at the Warehouse Control to get the pick list. Next, it goes to material warehouse, this is an empty flow, indicated in *red*. Subsequently the person picks the material and transports it to the Starter

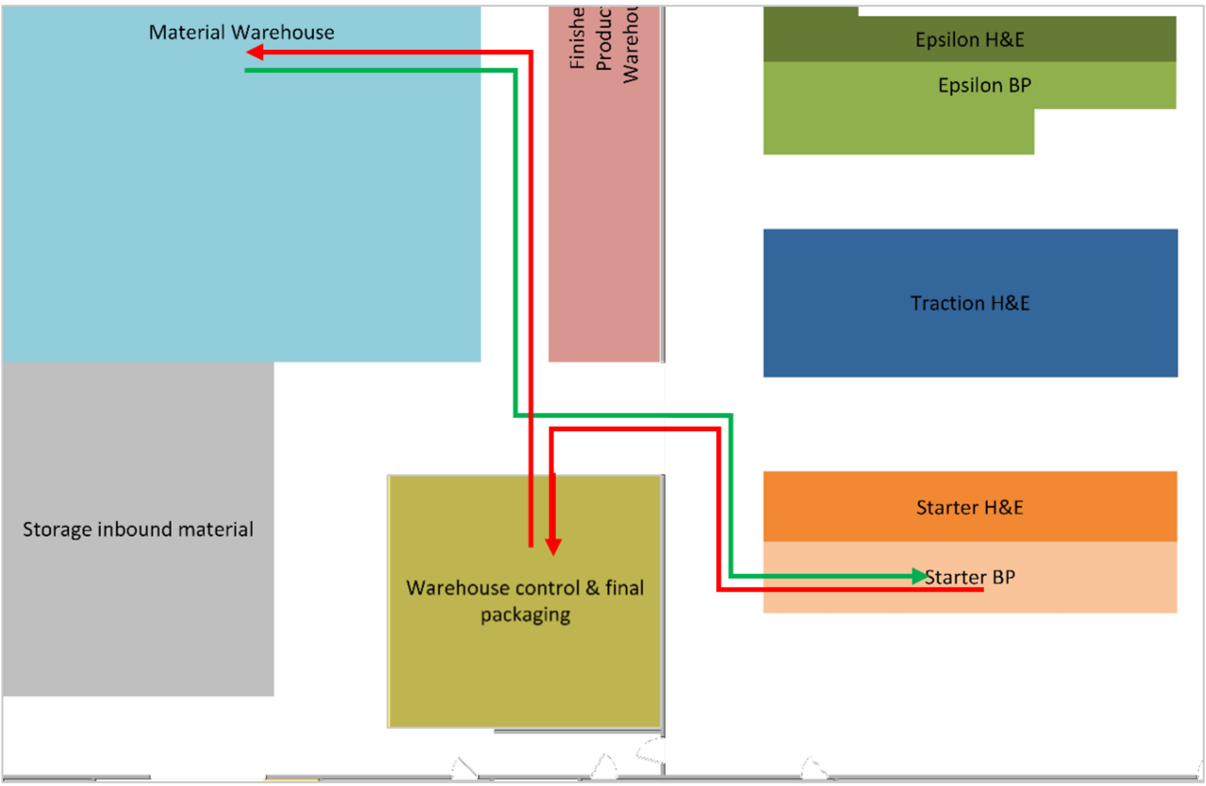


Figure 4.2 - Starter BP material picking flow

BP department and finally the person returns in an empty flow to Warehouse Control. The percentage of actual non-empty flow is then used in the cost calculations.

4.1.2 Distance

The calculation of distance depends on which model is chosen. Recall that distances can be measured from and to either the centre points or the I/O points. In the case of Super B, the storage of ingoing goods differ per type, for instance small material is placed somewhere else than the cells. So, we would have multiple I points and O points. Therefore, to simplify this, we choose the centre point. This also results no early loss of models, since all of them cope with central I/O points.

The distance can be calculated by using the Rectilinear or the Euclidean distance. Because of the multiple obstacles (walls, stations, storage racks, etc.) in the production facility, we think that the Rectilinear distance results the most realistic flows, since using the Euclidean distance results in people going through these obstacles. Therefore, we measure the centre points using the Rectilinear distance.

The next point of attention is the shape of each department. When choosing for example MIP problems, departments should all be rectangular in order to construct MIP model. This results in a shift of the department centroids, which also results in a slight change of distance.

Fortunately shifting the shapes of the departments is not a big issue in the case of Super B's production facility. All departments consist of (small) machines on workbenches, operator paths, material storage and waste storage, each of which can easily be relocated in order to get a rectangular department. Therefore, we only need to change the shape of the department, while keeping the area the same. For simplicity Take for example the Epsilon BP department, see Figure 4.3.

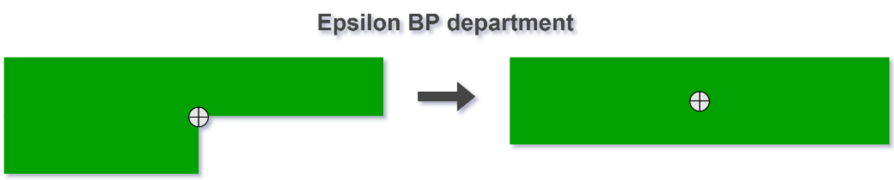


Figure 4.3 - Epsilon BP shifting department shape

We choose to shift the shapes of these departments, since the small benefits (the precision of the model) will not outweigh the large modelling problems that irregular shapes will cause.

Next, in order to calculate the distance, we set up a grid with *x* and *y* axis. We set the left wall of the warehouse as our *y* axis (where *x*=0) and the wall that separates production and warehouse with the testing area, office and breakroom as our *x*-axis (where *y*=0). From here we only need to measure the coordinates for each department's centroid. Finally, we use the rectilinear function 4.2 to calculate the distance from department *i* to *j*.

$$d_{ij}\ (Rectilinear) = [x_i - x_j] + [y_i - y_j] \qquad (4.2)$$

However, there is still one issue: these calculations don not take into account the entrances between production and warehouse. There are two main entrances between warehouse and production. The distance between warehouse departments and production departments are larger when both departments are located between the entrances. Since the warehouse departments are fixed, we only need to focus on the flows from and towards material and finished products warehouse. We measure this extra distance with a double IF statement for each:

$$\text{IF y.entrance1} < \text{y.dep(j)} < \text{y.entrance2 THEN}$$

$$\text{IF y.dep(j) - y.entrance1} < \text{y.entrance2 - y.dep(j) THEN}$$

$$\text{detour.dep(i)} = \text{y.dep(j) - y.entrance1} + \text{y.dep(i) - y.entrance1}$$

$$\text{ELSE detour.dep(i)} = \text{y.entrance2 - y.dep(j)} + \text{y.entrance2 - y.dep(i)}$$

$$\text{ENDIF}$$

$$\text{ENDIF}$$

For all flows from and towards the material or finished products warehouse (*department i*), we start comparing the y-coordinates of the entrances (*y.entrance*) with the y coordinate of a production department *j* (*y.dep(j)*). When the y-value of department *j* is in between the entrances then we calculate which entrance is closer to go through. This distance plus the distance from the same entrance towards warehouse (*department j*) is then added to the distance matrix, see Figure 4.3.

From\To	X	Y
M-WH	8.34	26.97
Cell-WH	8.34	45.32
Sub 1	31.12	47.96
Sub 2	36.98	47.50
BLA	43.19	46.58
PCB	39.01	45.89
BIB	39.54	49.29
Epsilon BP	33.07	23.96
Epsilon H&E	33.07	26.56
Traction H&E	33.07	15.81
Starter BP	33.07	5.67
Starter H&E	33.07	7.75
Waste area	10.20	0.00
WH-C	20.99	5.97
FP-WH	22.12	26.70

Rectilinear distance (m)

From\To	M-WH	Cell-WH	Sub 1	Sub 2	BLA	PCB	BIB	Epsilon BP	Epsilon H&E	Traction H&E	Starter BP	Starter H&E	Waste area	WH-C	FP-WH
M-WH	0	18	44	49	54	50	54	28	25	36	46	44	29	34	14
Cell-WH	18	0	25	31	36	31	35	46	43	54	64	62	47	52	32
Sub 1	44	25	0	6	13	10	10	26	23	34	44	42	69	52	30
Sub 2	49	31	6	0	7	4	4	27	25	36	46	44	74	58	36
BLA	54	36	13	7	0	5	6	33	30	41	51	49	80	63	41
PCB	50	31	10	4	5	0	4	28	25	36	46	44	75	58	36
BIB	54	35	10	4	6	4	0	32	29	40	50	48	79	62	40
Epsilon BP	28	46	26	27	33	28	32	0	3	8	18	16	47	30	14
Epsilon H&E	25	43	23	25	30	25	29	3	0	11	21	19	49	33	11
Traction H&E	36	54	34	36	41	36	40	8	11	0	10	8	39	22	22
Starter BP	46	64	44	46	51	46	50	18	21	10	0	2	29	12	32
Starter H&E	44	62	42	44	49	44	48	16	19	8	2	0	31	14	30
Waste area	29	47	69	74	80	75	79	47	49	39	29	31	0	17	39
WH-C	34	52	52	58	63	58	62	30	33	22	12	14	17	0	22
FP-WH	14	32	30	36	41	36	40	14	11	22	32	30	39	22	0

Figure 4.4 - Distance matrix (orange values account for extra entrance distances)

4.1.3 Costs

Recall that in order to calculate the costs per flow we need to calculate function 4.3.

$$C_{ij} = \frac{MHC_{ij}}{f_{ij} * d_{ij}} \qquad (4.3)$$

$$MHC_{ijk} = C_k * N_k * R_{ijk} + T_{ijk} * f_{ij} * OP \qquad (4.4)$$

The bottom part of the cost function is already determined in the previous sub sections. Therefore, we focus on the material handling costs between the department (*MHC_{ij}*), see formula 4.4. Recall that the material handling costs consists of fixed costs and variable costs. The fixed costs consist of investment costs. The fixed costs in Super B's case this would be the depreciation expenses of the material carts, pallet carts and the forklift. The material cart is used in flows where picked material, most of the sub-assemblies and finished starter batteries needs to be transported. The pallet cart is used in transporting Traction battery packs (sub 1s) and finished Traction batteries. The waste and lithium cells are transported with the forklift, these flows occur between production and warehouse. Recall that for each single material handling device the yearly depreciation costs (C_k) are calculated and multiplied with the number of devices and a factor R_{ijk}, which is the fraction of time spent on the pair of flows.

As mentioned in Section 3.7.3 the variable costs are a multiplication of time, flows and operating costs per minute. The time variable (T_{ij}) is calculated by summing the Loading and Unloading Time (*LAULT*) and time to travel the corresponding distance, see function 4.5.

$$T_{ijk} = (LAULT_{ijk} + \frac{d_{ij}}{S_k * TL_k}) * Y_{ijk} \qquad (4.5)$$

First we determine the *LAULT* between each pair of flows and per material handling device *k*. In the *LAULT* we include, of course, the loading and unloading time, but also the picking time. The time needed to pick an order was measured with the help of the warehousing personnel. Secondly the time it takes to cover the distance between two locations is a simple function of distance and speed (S_k). It is then divided by the empty flow factor, we discussed in Section 4.1.1. The summation of both the LAULT and the time to travel a certain distance is multiplied with a binary variable Y_{ijk}, which becomes *0* if the flow is not active.

With T_{ijk} we can multiply it with number of flows and the operator costs per minute to gain the variable costs. The fixed and variable costs are totalled and then divided by the flow times the distance. This results in cost-matrix.

4.1.4 Result

We present the outcome of the function per flow type: picked material, sub-assemblies, finished products, waste and cells. The results of calculating the current objective function are given in Table 4.1.

Flow type	Total costs
Picked material	€ 29,234.04
Sub-assemblies storage	€ 3,233.88
Between production transport	€ 4,597.81
Finished products	€ 6,517.78
Waste transport	€ 3,804.89
Cell transport	€ 2,319.39
NCR transport	€ 6,998.13
Annual material handling cost	€ 56,705.92

Table 4.1 - Material handling cost structure

Note that these results are only an estimation, where we, most likely, underestimated the costs. We assume that all personnel always take the shortest route, don't take detours and always walk at a constant speed. In reality the annual material handling costs are in all probability higher. It does, however, give us an overview of cost structure and of course an objective function to improve.

4.2 Forecasting

In order to construct a long term plan for Super B's production facility, we need to forecast each battery type. In Section 3.1 we searched for a couple of different forecasting methods, in that section an overview is given in Table 3.1. For our research we select the Bass diffusion model for all product types, because of four reasons: the Bass model is suitable for new product and product extensions; the Bass model is a long term forecasting which suits our time horizon and lastly the Bass diffusion model is the least dependent on the amount of data. Therefore, we will need to use data from similar products which is compatible with the Bass diffusion model. For each Bass diffusion model we will take 4 steps:

1. Determine the data set
2. Perform a quadratic regression and calculate parameters *p*, *q* and *m* of the data set
3. Calculate the expected sales and estimate the new parameter *m*
4. Analyse the results

4.2.1 Forecast Starter Battery

Let us start with the forecasting of the Starter battery. Super B really started producing batteries in mid-2015. This means we have a maximum of 4 years' worth of data. We choose, in order to comprise the lack of data, to use a short term forecast (of 3 quarters) created by the Sales department in our data set.

Next, we determine the quadratic regression of the dataset. Recall that the function from where we can extract the *a*, *b* and *c* parameters is a function of sales per order expressed in cumulative sales per order (Section 3.1.3, formula 3.11) . In appendix D the graph of this function is given, from a quadratic regression we gain the parameters *a, b* and *c*. Subsequently we can calculate the parameters *p*, *q* and *m*, using Section 3.1.3, formula 3.12 – 3.14. In Table the calculated parameters are given.

n(t)	447.47 + 0.1305*N(t) - 0.000005*N(t)^2
a	447.47
b	0.1305
c	-0.000005

Coefficient of innovation	p	0.0133562
Coefficient of imitation	q	0.1582562
Total market potential calculated	m*	31651.238
Total market potential Starter	m1	33000
Total market potential Smart Starter	m2	20000

Table 4.2 - Parameter calculations

There is a difference between the calculated market potential and the actual market potential. The calculated market potential is approximation based on the current data set. However recall that according to Bass (1969) it is possible to adjust this value. We decided to choose the market potential that fits Super B's expectations. We derive these numbers from their current position on the Product Life Cycle (discussed in Section 2.2.3), logical reasoning and experiences from within the company.

In consultation with Super B we set the market potential for the starter at 35,000 units. First, this is due to the life expectancy of the current capacity of Starter batteries. The lithium technology is constantly evolving. This means lithium cells will improve in energy density. As we already see in the Traction batteries where the 100A and 160A batteries will gradually be replaced with the 210A batteries from 2020. The smaller lithium cells for the Starter are not there yet, but an improve in efficiency should to be expected. Secondly we think that the Starter battery (without extensions) is currently in the mature phase of the product life cycle at the end of the peak period, so sales of the current products would slowly go downwards. Analysing the historic sales we think that the current product mix of the Starter would have a total market potential of 35,000 units.

However Super B plans to launch a new version of the Starter battery at Q1 of 2020: the Smart Starter. The Smart Starter is an extension to the existing Starter and would therefore, have the same p and q values of its predecessor (Bass and Norton, 1987). Only the market potential has to be chosen again. This time, it is somewhat harder to estimate since we don't have any previous sales. The Smart software is only introduced in 5 of the 9 Starter battery types. These types currently cover about 44% of the total number of starter batteries. If it would reach the same amount of sales of what we expect of the current types, it would mean a market potential of 15,400. We know that customers of Super B starter batteries are not price sensitive and often want the best product on the market. The Smart Starter is an innovative product that fits well in that market. The new product is, in contrast with the current products, not comparable with any competing products, so the expectations are that it (despite the higher price) performs better than the current types. With consultation with the experts of the Sales department we estimate the market potential at 26,950 units, see Table 4.3.

Aspect	Starter	Smart Starter	Multiplication factor
Previous sales	9 types: 100%	5 types: 44%	*0.44
Technology	Existing technology	New technology	*1.75
Market potential	35,000	26,950	*0.77

Table 4.3 - Market potential estimation

In conclusion this would result in Figure 4.6, where our peak period would be at the moment of introduction of the Smart Starter, Q1 of 2020. At this moment we expect a peak sales around the 1750 units.

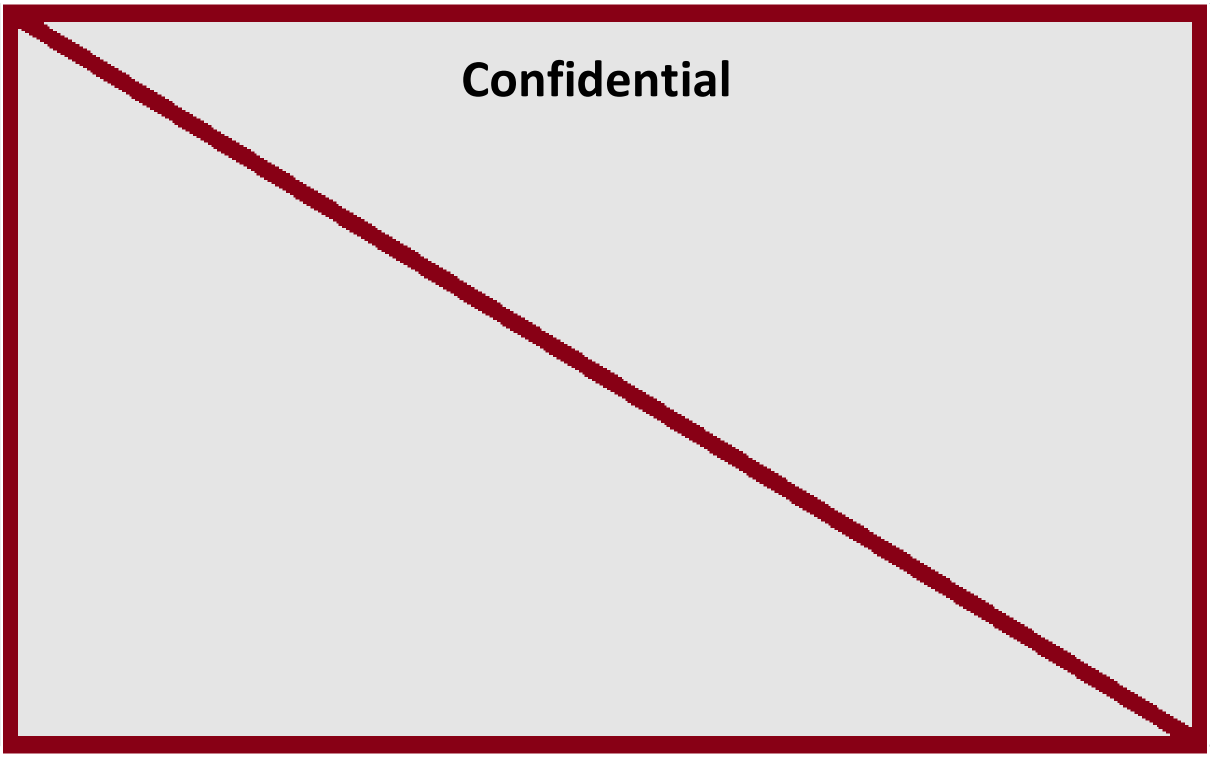


Figure 4.5 - Forecast of the Starter batteries

4.2.2 Forecast Traction Battery

The data set size of the Traction battery is about the same as the Starter, which is 4 years of usable data. The same principle goes for the Traction as the Starter batter, here we also use some short term forecasting to get better results of the long term forecasting. We perform the same method for the Traction as for the Starter, which means we start with the quadratic regression. In Table 4.4 the *a*, *b* and *c* values and subsequently the *p*, *q* and *m*.

n(t)	292.76+ 0.1616*N(t-1) - 0.000007*N(t-1)^2
a	292.76
b	0.1616
c	-0.000007

Coefficient of innovation	p	0.0083646
Coefficient of imitation	q	0.1699646
Total market potential calculated	m*	24773.897
Total market potential 100A & 160A	m1	35000
Total market potential 210A	m2	35000

Table 4.4 - Parameter values traction

We decided to set the market potential of the current Traction batteries (100A & 160A) at 35,000 units. This is again based on their current position in the product life cycle and the historic sales. The market potential of the 210A should be at least the same as the 100A and 160A together, since the global energy demand and thus the demand for higher capacity products is rising. However, with the introduction of the 105A, some of the customers will choose that product over the traction which results in lower sales of the Traction. Therefore, in consultation with the experts of Super B, we set the market potential of the 210A extension of the Traction the same as the 100A and 160A: 35,000 units. In Figure 4.7 the forecast of the Traction is given. The moment of peak sales would be at the end of our project time horizon: Q2 2023, where around 1850 units should be ordered.

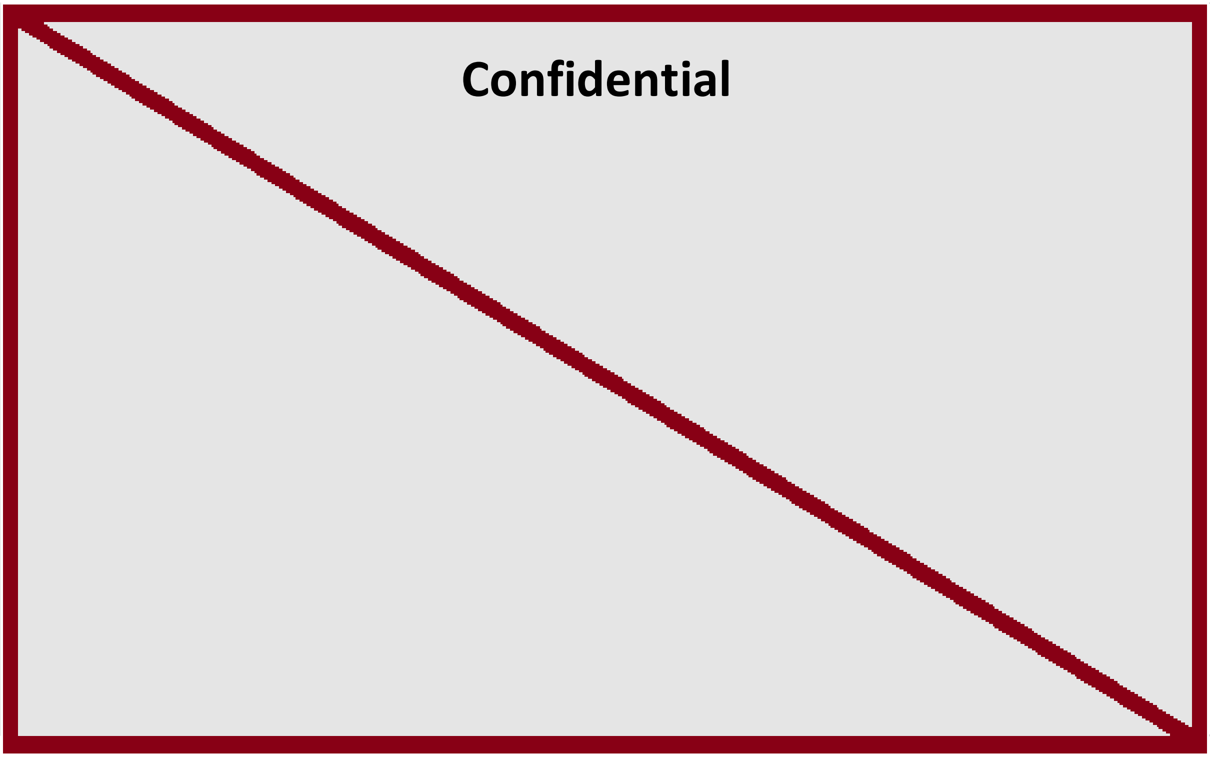


Figure 4.6 - Forecast of Traction batteries

4.2.3 Forecast Epsilon Battery

The Epsilon has even less data available than the Starter and Traction. The Epsilon started its production in 2017, so we only have 2,5 years' worth of data, with the short term forecast this would be 3 years and a quarter, which is still mediocre. However according to Bass it is still possible to use the data for a Bass model. Another possibility is using the data of a different analogous product. This would be the other energy battery, the Traction. In order to make a choice we use the Bass model on both the data sets, where we choose an equal market potential that suits the Epsilon battery and choose in consultation with Super B. We choose a market capacity potential of 30.0000. This is determined on the basis of the current position in the product life cycle and in consultation with Super B's sales experts. In Figure 4.8 we see the demand curve with the Epsilon data set. In Figure 4.9 we see the demand curve if we use the data set of the traction. If we compare both demand curves, we can conclude that the model using the Epsilon data has, besides the much better fit, also a less progressive curve. Super B believes the Epsilon won't grow as hard as the Traction did. Therefore, we choose the Epsilon dataset despite the lack of data.

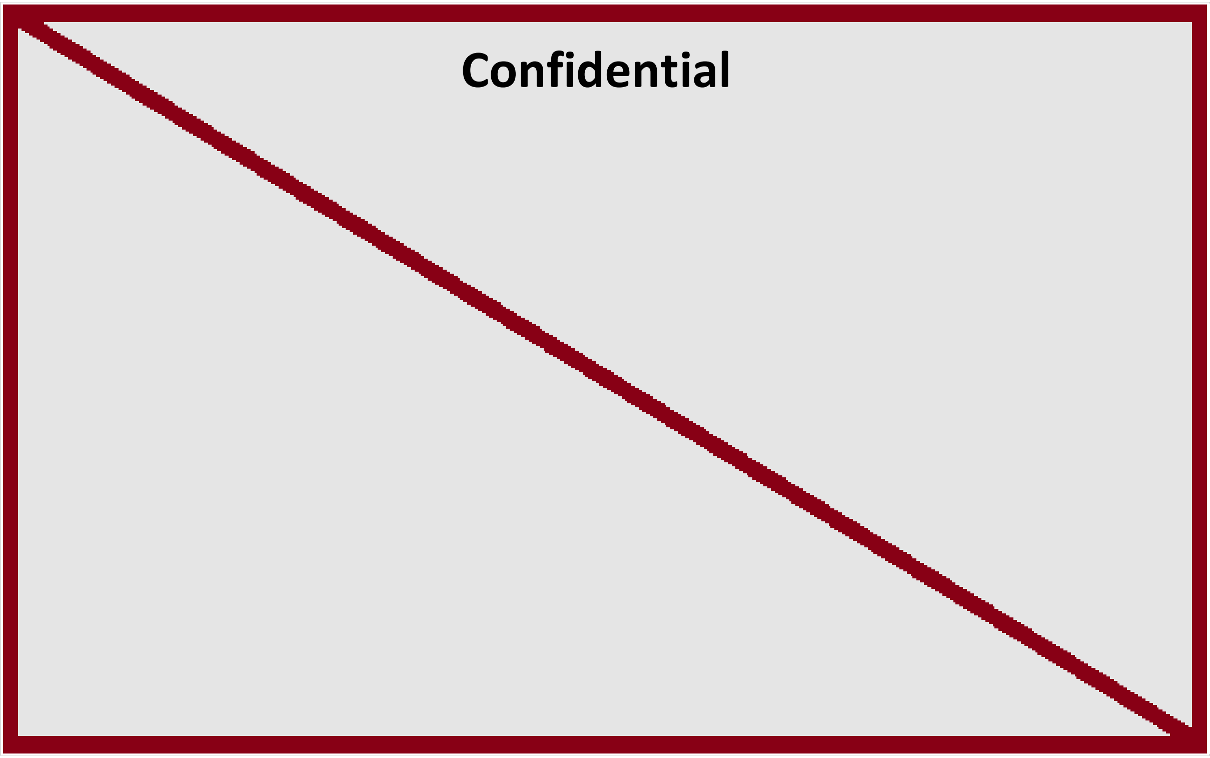


Figure 4.7 - Bass Diffusion model Epsilon (Epsilon Data)

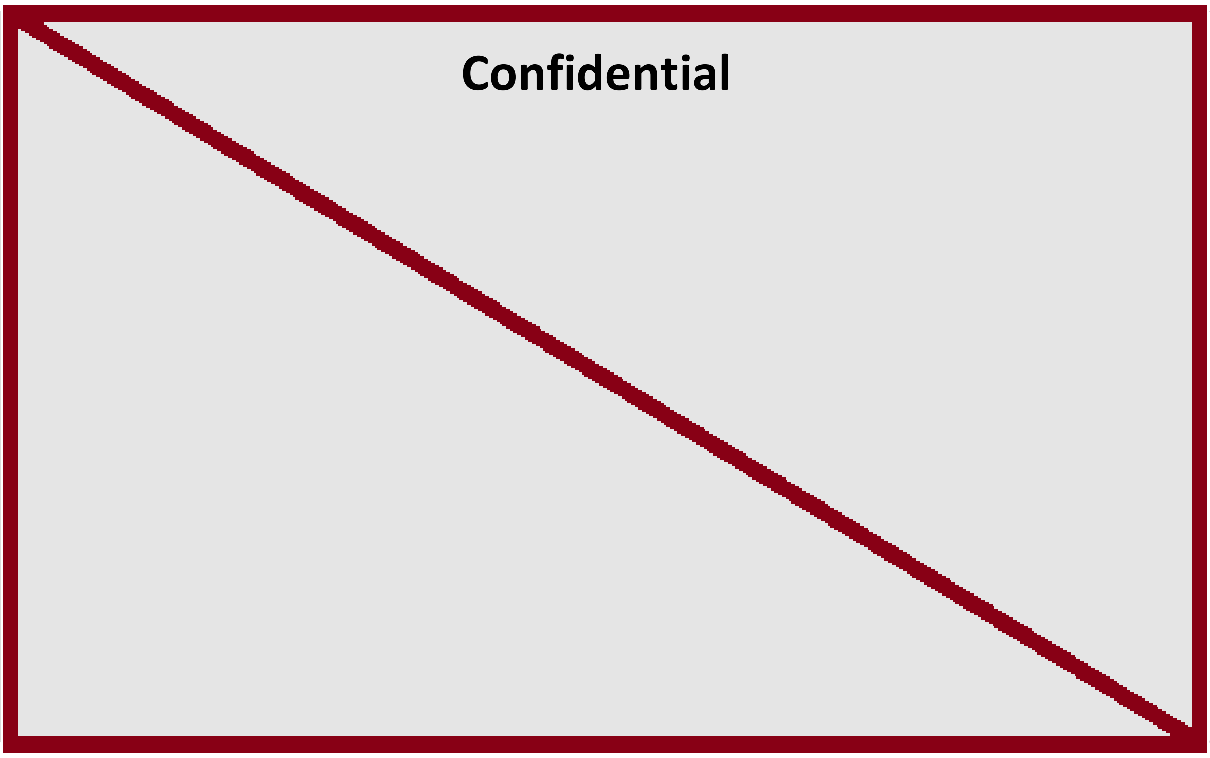


Figure 4.8 - Bass Diffusion model Epsilon (Traction data)

The peak of the Epsilon battery using this model is during Q2 and Q3 in 2021, with a peak sales of 935 units per quarter.

4.2.4 Forecast 105E Battery

The 105 Energy Battery is a completely new product where production starts in Q1 2020. Therefore, we have no data at all of this product. We choose to use the parameters of the traction for the forecast of the 105E. The 105E is related the most to the Traction. Both batteries can be connected into an integrated system and uses the same type of lithium cells. Besides, the traction has the most data available. We only have to estimate the potential market value. We do this by comparing the 105E with the Traction. Compared to the Traction, the 105E has a better IP rating (waterproof), a more compact form (flexibility) and a higher energy density. In addition it is expected due to these characteristics customers would choose the 105E over the Traction. When this is the case the customers have to buy two 105E in order to get the same capacity as one Traction battery. In consultation with the Experts of the Sales department we set the market potential at 60,000 units. In Figure 4.10 the forecast of the 105E is given.

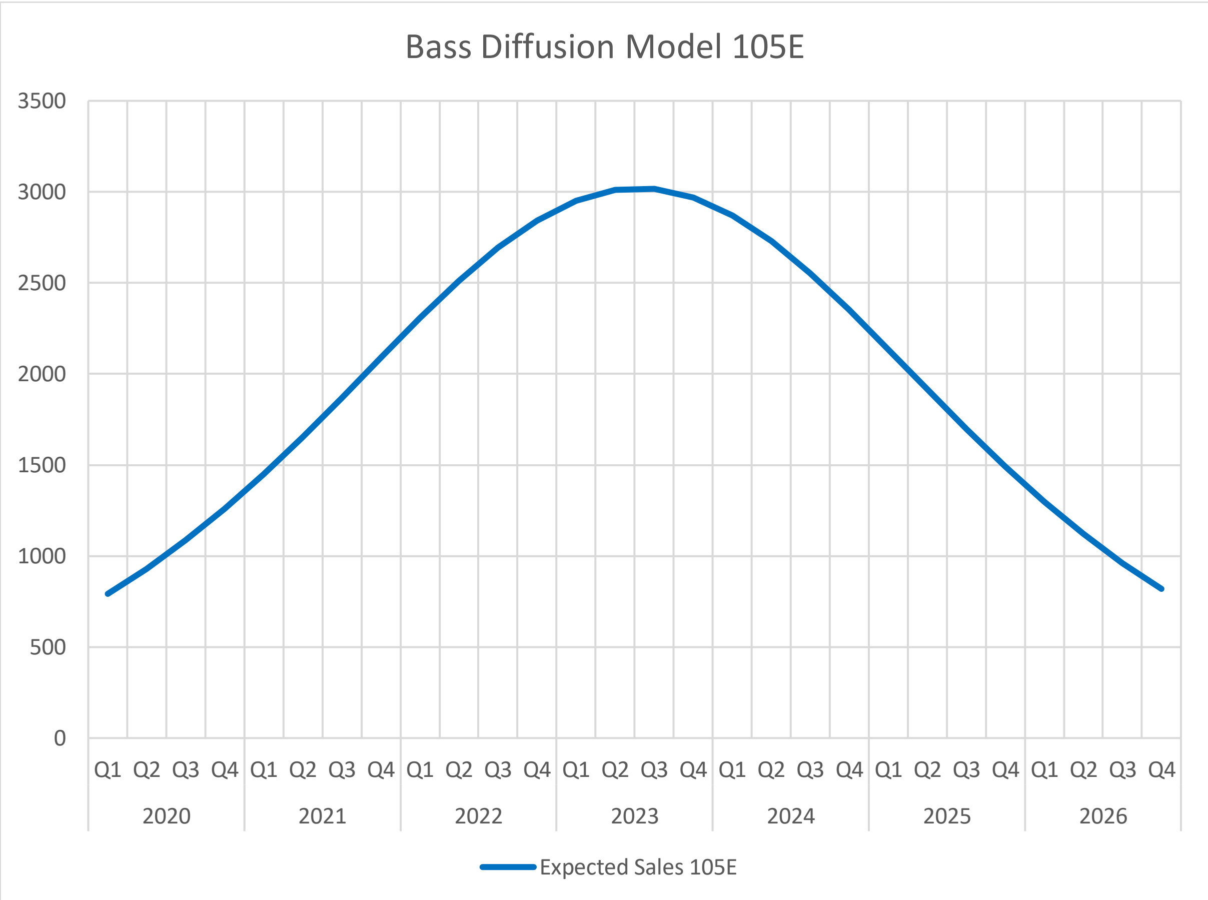


Figure 4.9 - 105E Battery Forecast

The peak of the 105E is 2023 Q2 and Q3, which is within our time horizon, so this results in a peak value around the 3000 units in 2023 Q2.

4.3 Conclusion

In Chapter 4 we covered two main topics:

- The current performance
- Growth in total quantities

We estimated the costs of the material handling from and towards the production area to be €56,700. While, this is a rash estimation, since not all flows and costs can be measured, but it gives us a good indication on the cost distribution per flow.

Secondly we forecasted each battery type in order to estimate future flows and required space. We forecasted the future sales numbers using the Bass model, since the Bass model copes with long term

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Table 4.5 - Moment and size of peak sales

Table 4.2 shows comparison between the current and the peak amount of the sales for each battery. This means that, in the coming 4 years, Super B needs to produce 22,5% more batteries each year on average. In total most batteries are sold in Q2 2023. In the next chapter we introduce new logistical improvements.

5 Developing logistical improvements

In this chapter we search for methods to implement lean manufacturing, in order to make our first improvements to our objective function. In Section 5.1 we first search for the flows that cause backtracking and congestion. In order to counter these flows and further optimize logistical processes. We select the best planning and control methods in Section 5.2. We examine Section 5.2 by separating production planning and material supply planning. In Section 5.3 we configure an inventory policy for all material. In Section 5.4 we estimate the effect of this Solution and in Section 5.5 we investigate the storage requirements in order to implement our solution. Finally, in Section 5.6 we do a cost-benefit analysis of our solution.

5.1 Transportation waste

In this section we find the flows that cause waste in the current situation at Super B's production site. We search for the backtracking and bypassing flows through a production place diagram. We analyse the relationship diagram, where the material flow is given. We start with the Traction, see Figure 5.1.

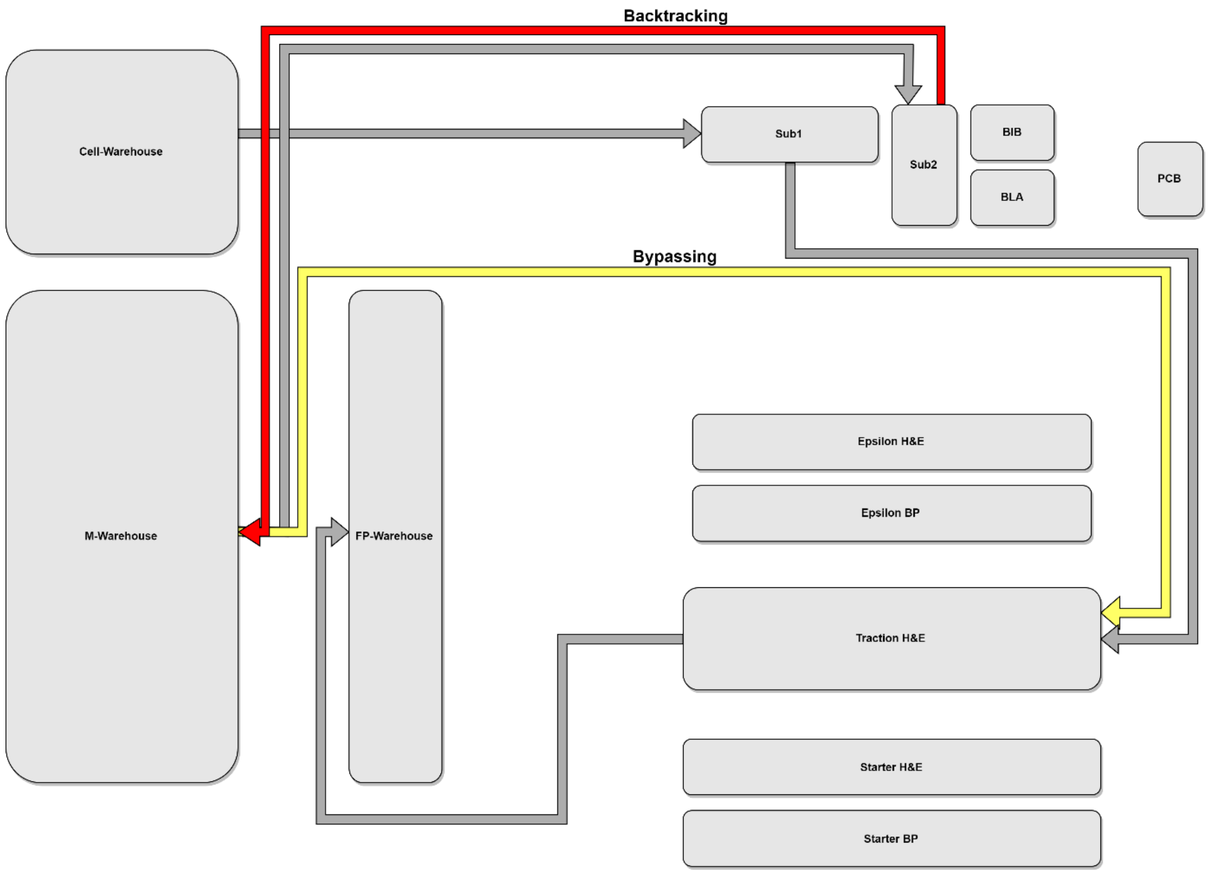


Figure 5.1 - Traction Relationship Chart

Process starts with the material picking and cells transportation for the production of the sub-assemblies. Recall that in Section 2.1.4 we discussed that the Sub 2, after production, first gets stored at the Material Warehouse. This is a backtracking flow: the WIP goes to a preceding department. Next, the items get picked and go directly to the Traction H&E, while at the same time the Sub 1 gets transported to the Traction H&E, the Sub 2 surpassed the Sub 1 station, which indicates a bypassing flow.

Next, we look at the Epsilon relationship diagram, see Figure 5.2.

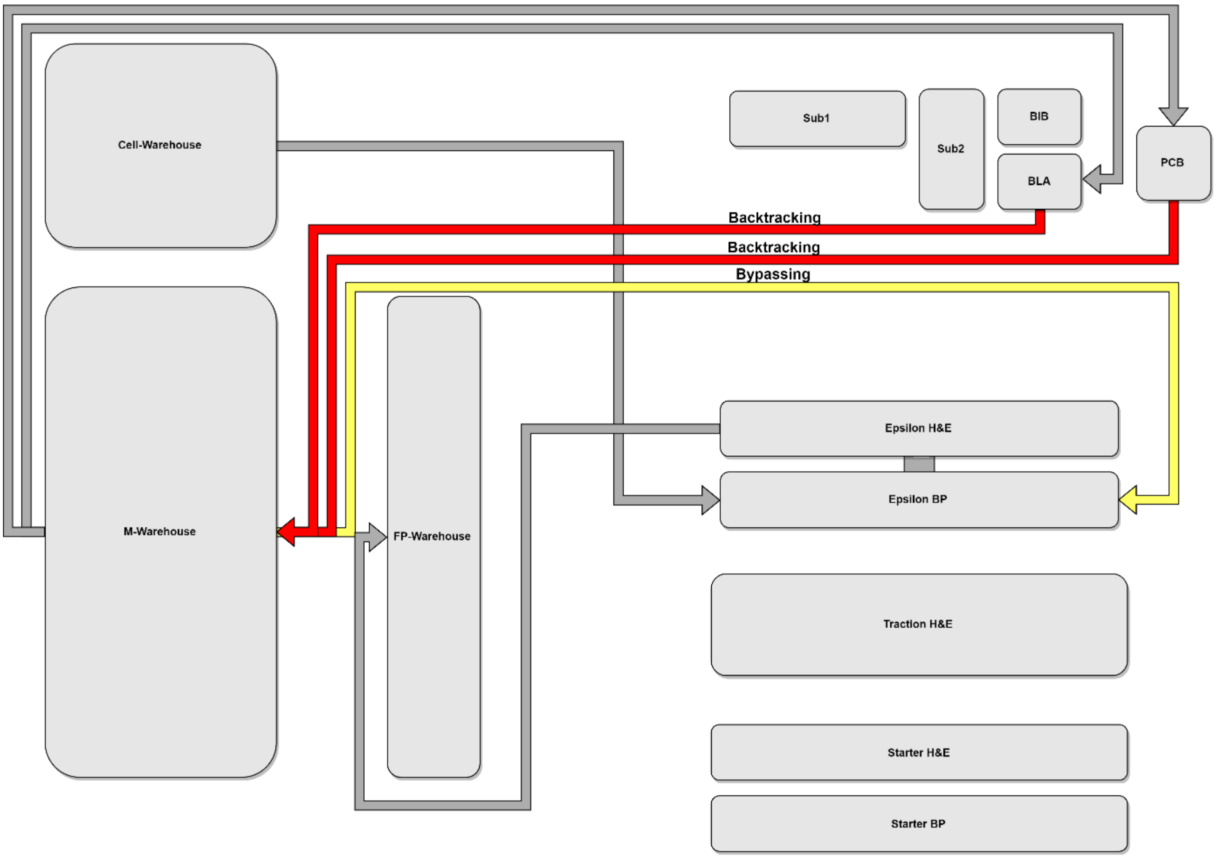


Figure 5.2 - Epsilon relationship diagram

The material movement of the Epsilon is related to the material movement of the Traction. The storage of sub-assemblies of the Epsilon, the BLA and PCB, are backtracking movements and, again, the retrieval from these products to the Epsilon is a bypassing flow.

The relationship diagram for the starter can be found in Appendix B, Figure … For the starter there were no backtracking or bypassing flows, however this could still happen with the introduction of the Smart Starter, if Super B uses the same approach as for the other sub-assemblies.

Thus, we found 3 backtracking flows and 2 bypassing flows, see Table 5.1.

#	Flow	Flow type	Product group
1.	Sub 2 Station → Material Warehouse	Backtracking	Traction
2.	Material Warehouse → Traction H&E	Bypassing	Traction
3.	BLA → Material Warehouse	Backtracking	Epsilon
4.	PCB → Material Warehouse	Backtracking	Epsilon
5.	Material Warehouse → Epsilon BP	Bypassing	Epsilon

Table 5.1 - Current backtracking and bypassing flows at Super B

These flows are responsible for the annual costs of sub-assembly storage we found in Section 4.1.4, which is €8,384.51 just for transportation and picking, not including the storage capacity and costs, quality risks and possibility of obsolete stock.

5.2 Selection of planning and control methods

In chapter 3 we found the three common planning and control methods in order to improve flow movement: Kanban, POLCA and CONWIP. Each of them with their own (dis)advantages. We are going to introduce these planning and control methods to the product groups in order to counter backtracking and bypassing and additionally get a smooth flow line and limited WIP. We assign these planning and control methods in production processes as well as a new material planning and control method.

5.2.1 Production planning and control

We start with exploring new planning and control methods for the production processes. Let us first recap each method we explored in Section 3.3. In this section we found that Kanban is a simple card-based system that copes with high quantity and low variety parts. POLCA is a more extensive card-based system that comes out best with route specific products. It copes with high variation but reduces the flexibility of the line. Changes in the product mix and/or the processes are difficult to manage. CONWIP was the third method we investigated. A CONWIP-card is not associated to a certain part type, but only with a certain quantity on an as-needed basis. CONWIP results in a push-pull system. CONWIP is well suited for made-to-order parts with a lot of varying parts.

In order to make a selection between the methods, we each method on five characteristics: product variety, demand variability, change flexibility, continues flow and simplicity of implementation. We score each method in Table 5.2, based on the gathered information of the literature research in Chapter 3.

*Note that the MRP is currently in use and thus does not have to be implemented.

Requirements	MRP (Current)	Kanban	POLCA	CONWIP
Product variety	+	-	+	+
Demand variability	+	+/-	+	+/-
Change flexibility	-	+	-	+
Continuous flow	-	+	+	-
Simplicity of implementation	+*	+	-	+/-

Table 5.2 - Selection of the best planning method based on our findings in Chapter 3

From this Table we can conclude that Kanban is the best option for Super B to use as the new production planning and control method.

5.2.2 Material planning and control

In the previous section we chose a Kanban system as a production planning and control system, these where all flows in between production processes and finished goods. In this section we explore how and if Kanban could also reduce time spent on the supply of material from warehouse towards production. We still have the option between a push or pull system for the supply of material, despite the fact that we selected a pull system within production. This would result in either a pull or a push-pull system for the whole process within Super B's facility.

A downside of Kanban for material supply is the amount of storage that is needed for each individual stock keeping unit (SKU). Therefore, we start with looking at the required number of SKUs at each station. In Table 5.2 we listed the variety of all SKU which are required at each station. We listed how many types each station has and determined how many SKUs are required at each station.

Station	Number of types	Required SKUs for each station	
Starter BP	11	2 SKUs the same for all models:	2 SKUs
		1 SKU different for 5 types:	5 SKUs
		3 SKUs different for 11 types:	33 SKUs
		Total:	**40 SKUs**
Starter H&E	11	9 SKUs the same for all models:	9 SKUs
		4 SKUs different for 8 types:	32 SKUs
		5 SKUs different for 11 types:	55 SKUs
		Total:	**96 SKUs**
Smart Starter (sub)	2	6 SKUs the same for all models	6 SKUs
		5 SKUs different for 2 types	10 SKUs
		Total:	**16 SKUs**
Epsilon BP	1	**Total:**	**28 SKUs**

Epsilon H&E	1	**Total:**	**19 SKUs**
BLA (sub)	1	**Total:**	**8 SKUs**
PCB support (sub)	1	**Total:**	**4 SKUs**
Traction H&E	3	16 SKU the same for all models:	16 SKUs
		2 SKUs different for 3 types:	6 SKUs
		3 SKUs different for 2 types:	6 SKUs
		Total:	**28 SKUs**
Sub 1	2	**Total:**	**6 SKUs**
Sub 2	2	9 SKUs the same for all models	9 SKUs
		3 SKUs different for 2 types	6 SKUs
		Total:	**15 SKUs**
105E	1	**Total:**	**32 SKUs**

Table 5.3 - Number of stock keeping units (SKU) for each product and sub-assembly

From this table we can't tell the difference between the SKUs, a SKU could for example vary from a screw to a battery case. So, the table does not tell us whether all SKUs could fit as Kanban at the line. What we can tell from this table is whether there are too many SKUs to keep stock at the production line, regardless of the size. A large number of different SKUs at a single line makes it difficult to for warehouse to handle and complex for production employees. This makes it error-prone for both warehouse and production processes.

From the table we can conclude that most stations have a reasonable number of SKUs (± 40) to place at each department. This makes the implementation of Kanban possible for the 105E, Epsilon and Traction, see Figure 5.3. However, the Starter Housing & Electronics station has a significantly larger number of SKUs. The Starter H&E has a high variety and a high number of SKUs, too high to keep on stock at the production line. There will simply not be enough space at the line and picking material becomes error prone. Therefore, we construct a material planning and control system that can cope with the high variety of these material. We construct a push-pull system. Whenever Starter batteries are required, a high priority signal, in the form of a Kanban card, is sent to Material Warehouse. Material warehouse pushes the order with picked material towards Starter H&E, while Starter H&E pulls sub-assemblies from Smart Starter station and Battery Pack station. This results in a hybrid push-pull system, see the Starter flowchart in Figure 5.3.

There can still be some SKUs stored at the Starter H&E for Kanban usage. We set the Y SKUs as the **push** material and X SKUs as the **pull** material stored at the production line. The Y SKUs should be the larger non-universal items and the X SKUs should be the smaller universal items. Smaller items logically uses less space at the production line, so more SKUs can be stored. Besides, the size of the SKUs, the universality of the material is important. SKUs that need to be applied on more than one product type, can be stored in one place at larger quantities and don't need to be individually picked for each separate order. In the next section we take a profounder look at the placement and Kanban quantities of each SKU.

Another problem that arises, which is not given in this table, is the multiple stations that the Traction H&E has. Each station needs the same SKUs. The storage of new SKUs at the Traction H&E should be easily accessible for all stations. This could either be done with a central item rack or with decentral item racks located at each station. However, both methods have their disadvantages. A central rack decreases the accessibility and decentral racks results in four different racks, all with an individual need to be refilled. We will discuss in detail in Section 5.5.

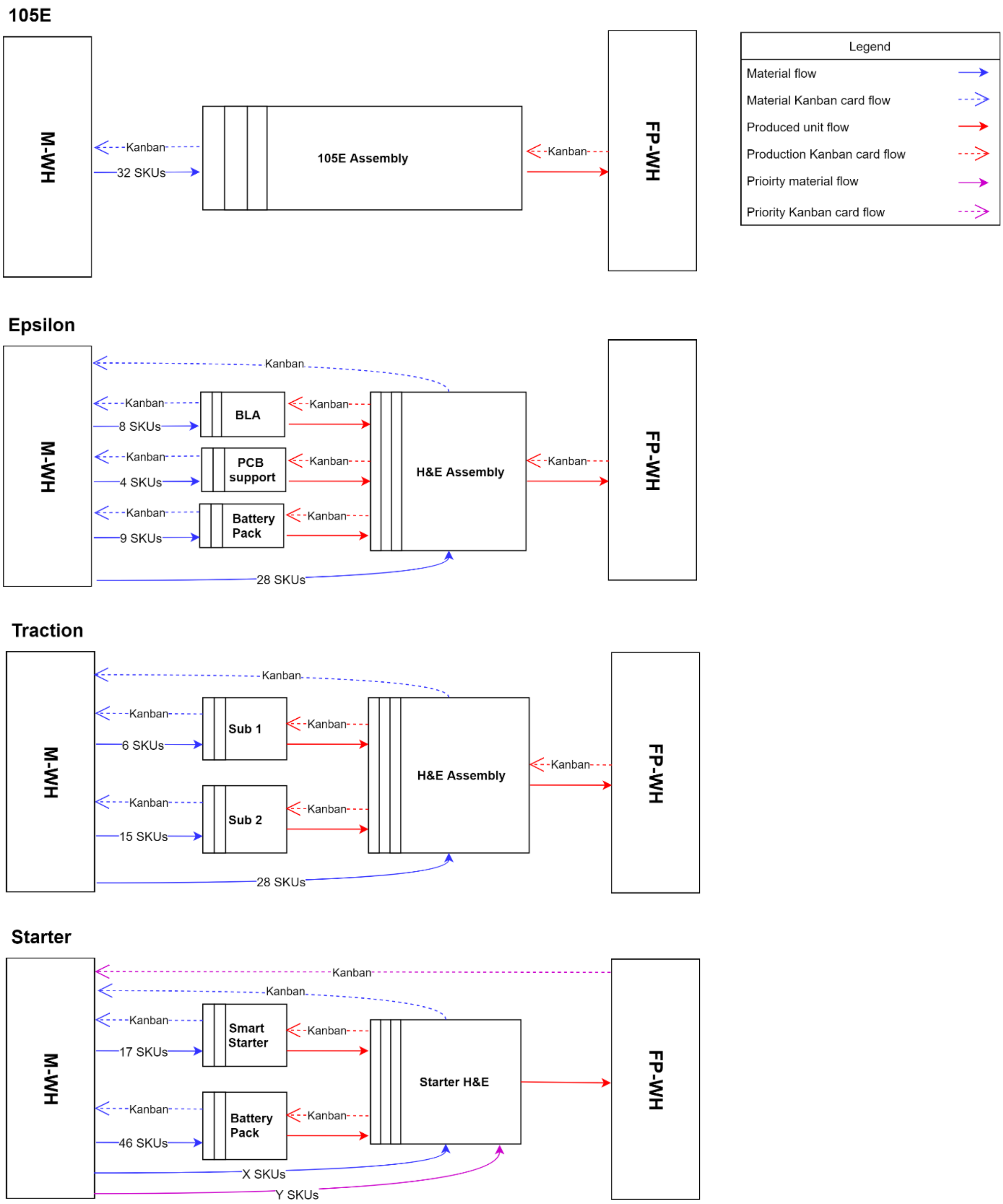


Figure 5.3 – Schematic overview of the new material & information flow

5.3 Configuration

In this Section we configure every SKU and sub-assembly. We search for appropriate policies for the material and we take a further look at which SKUs at the Starter line should be in the pull system and which should be in the push system. Furthermore, we take into account the implementation of these policies.

5.3.1 Line material inventory

Setting up new planning and control methods for material requires us to do three main steps:

- Calculate demand for each component
- Classify each component
- Determine a strategy for the distribution of the different categories of material

Demand

In order to calculate the amount needed at the production line, we first need to decide how many parts are needed on a daily basis. The demand of each SKU and Sub-assembly depends of the amount that goes in one finished product, the amount of product types it serves and the demand for the corresponding product at a certain point in time. In the BOM of each product we can find the amount that goes in one product type and how many product types the item serves. We multiply these with the expected growth rate of the corresponding product in that period, which we found in Section 4.2. This results in a list of the expected demand for each SKU.

Material classification

In order to classify the material, we distinguish them via *volume* and *generality*. We determine the volume by measuring the amount of each component fits in a standard container used by Super B. We need to perform a (time-consuming) measurement for all components (260 SKUs) used by production. This information is also required for the calculation of Kanban quantities. Secondly, we want to know how general each component is, or in other words how much of each component is used in multiple types of products.

Let us first consider *volume.* Super B uses standard container sizes, see Table 5.4. Super B prefers to fill these standard containers with packages that are predetermined by the supplier. This ensures a faster and easier way of picking. However, whether it is practical differs per SKU. Sometimes, the SKUs are too large or too fragile to transport in the standard containers, then we look at alternatives. We check per SKU if it could be picked in a standard container, such that we have an insight in the volume. If so, we measure the amount that fits in the *small* container C_i, while taking into account the predetermined packaging amount. For example, a bin that can be filled to its max with 1100 units, while it is packaged per 500 units by the supplier, will instead contain 1000 units.

Container	Dimensions L*W (mm)	Number fit on warehouse cart	Size ratio
Small bin	200*150	48	1
Medium bin	400*300	12	4
Large bin	600*400	6	8
Europallet	1200*800	0	-

Table 5.4 - Super B's standard container sizes

Now, let us consider the *generality* of each component. The generality was also dealt with in the previous paragraph (Table 5.3), where we calculated the number of SKUs per department. Now, we look the other way around. We take a look at how general each component is, see formula 5.1.

$$G_i = \frac{N_i}{T} \qquad (5.1)$$

In this formula, G_i stands for the generality of component *i*, N_i indicates the number of product types the component is used in and T the total number of product types. General components tend to have a relatively larger demand, since the component can be used in multiple products (Limère, 2012).

Considering both the number of items that fit in a small container and the generality of each component we classify each component in 5 different types, see Table 5.5.

Type	Number of items in container C_i	Generality G_i
A	200+	0 - 1
B	10 - 200	0.2 - 1
C	10 - 200	0 - 0.2
D	0 - 10	0.2 - 1
E	0 - 10	0 - 0.2

Table 5.5 - Material classification

Distribution strategy for material categories

Next, we want to determine which policy we implement for each material type. Each policy requires the calculation of two variables: *the reorder point* and *the reorder quantity.* Table 5.6 gives an overview of each type and their inventory policy.

Type	Main inventory policy	Exceptions	Inventory policy exceptions
A	Two-Bin	-	-
B	Kanban	-	-
C	Push control	Starter BP components	Kanban
D	Kanban	Large volume containers	On request
E	Push control	-	-

Table 5.6 - Component policies

For type A material we consider the simple *Two-Bin* system. In a Two-Bin system, two bins (or containers) are filled with the corresponding material. When the bin is empty, it is moved to the material warehouse, where it is refilled, next it is brought back to the production line. In the meantime, the second bin is used, and becomes the first bin. This process goes on and on. Thus, the reorder point and reorder quantity are both 1 bin.

For the type B and D, we use the standard *Kanban* strategy. Therefore, first take a look at the Kanban formula, formula 5.2. With this formula one calculates how many cards (or containers) need to be at stock the moment of reordering, thus the reorder point. We set the lead time as the review period + average picking time of all items set to pick that day. In order to control all material flow movement, we let warehouse personnel collect all the Kanban cards once a day at the beginning of each day. Thus, the review period is set at 1 day. In order to approximate the picking time, we take the current average picking time per day, which is 0.36 days (2.9 hours). Thus, the lead time is set at 1.36 days. The safety factor is set at 30%, as time progress and employees get to know the system the safety factor can be adjusted downwards. The result of this formula shows the number of containers that need to present during the picking of new containers, or in other words the reorder point.

$$Number\ of\ Kanban\ cards = \frac{Lead\ time * Demand * (1 + Safety\ factor)}{Container\ capacity} \tag{5.2}$$

Subsequently, we determine the order quantity. The order quantity is a trade-off between the number of flows and the amount of floor stock. We set a maximum number of containers, based on the available space, for both product groups so that we have a fixed reorder-amount. For some of the specific type D components we use standard supplier containers, such as pallets. A new pallet would be acquired on request by the operator.

For the last two types, C and E, we use a *push control* system. This goes in a similar manner as the current picking process. The reorder point and reorder quantity are decided by a pull from FP-Warehouse, as we discussed in the previous section.

For the Type C material there is also an exception. The components that are used at the Starter BP station are also controlled with Kanban, since the Starter BP station has a limited number of SKUs present at the line.

5.3.2 Sub-assembly policy

For the sub-assembly we already stated in Section 5.2 to use the planning and control method Kanban. This means we use the same policy as for Type D components only now items move from sub-assembly stations to housing and assembly stations. We use formula 5.2 again for the calculation of the Kanban cards.

5.3.3 Kanban cards

Each SKU gets their own dedicated place. Each SKU will receive a Kanban card. This card contains 10 types of information:

- Part No.
- Part description
- Pick Location
- Bin size
- Quantity per bin
- Number of bins
- Station name
- Shelf Location
- Reorder point
- Barcode (part nr)

We created a tool that generates Kanban cards that take into account these types of information. In Figure 5.4 an example of a generated Kanban card is given. The program generates the card after the part number has been entered by the operator.

Kanban Card		
Part No. :	**Bin Type:**	**Station Name:**
610000000050	Small Bin - 200*150 mm	Epsilon - BP
Part Description:	**Item Quantity per Bin:**	**Shelf Location:**
LN 5 tab D 60P	150	E-BP-2.1
Pick Location:	**Reorder-amount Bins:**	**Reorderpoint:**
E.3.2	1	1
Barcode:		

Figure 5.4 - Generated Kanban card

5.3.4 Picking

In this subsection we take a look at the new method of picking. The new picking process can be subdivided in three types:

- Kanban picking
- Pallet placement
- Push control picking

Kanban picking

As stated before, Kanban picking takes place at the beginning of each day. It starts with warehouse personnel collecting all the cards. Each barcode of each card is scanned and registered in the ERP system at the warehouse control centre, such that warehousing can keep track of the inventory at the assembly line and the material warehouse. Next, the picking starts. It is unknown beforehand how many parts are being picked and if it all fits on one cart, since it is often a somewhat random job. Therefore, we introduce a new delivery method that transform the resupply process into a standardized and cyclic work: *the milk-run concept*. Basically, in a milk-run, instead of visiting multiple stations separate times with one cart, one would visit multiple stations in one run by combining multiple carts. With a milk-run one would have the option of a variable picking capacity while picking all cards in one run.

This does, however, requires minor adjustments to the current carts, such that they can be (dis)connected easily. In the next section we go into further detail what effects method has on the picking times and the amount flows.

Pallet placement

Pallet placement will happen the same way it happens in the current situation: just before a pallet runs out of (for example lithium cells) a replenishment signal is given towards warehouse personnel, who then transport the pallet with a forklift to production.

Push control picking

The type C and E components are also picked in mainly the same manner as in the current situation. The process starts with a Kanban card from FP-warehouse. This Kanban card is a high priority, since the start of the production at the Starter H&E station highly depends on this. This means that a separate cart goes through picking as soon as the card arrives, the material is picked in exact amounts and transported directly to the Starter H&E station.

5.4 Effects on the parameters

In this section we consider the effects of our logistical improvements in terms of the objective function. Recall, form Section 4.1, that the distance-based objective function is a summation, where each summand is a multiplication of distance, flows and the corresponding costs. Our new planning and control method have influence on the flows and costs of the current situation.

5.4.1 Flow parameter

Let us first identify which flows are affected by the logistical improvements. In Table 5.7 a from-to chart is given. We identified three types of change in flow intensity: more flows per week in *yellow*, less flows given in *green* and no flows in *blue*. The blue flows **A** are the flows from sub-assembly storage and NCR waste. Due to Kanban sub-assemblies are no longer stored at the material warehouse but at sub-assembly and H&E stations, hence the yellow flows **B**. The yellow flows, however, result in shorter distances and can later, in Chapter 6, be minimised by relocating the stations.

The other blue flows **C** are the NCR waste flows. These are the flows from production towards WH-C, due to defective material. With the use of Kanban, production is no longer dependent on exact amounts of material. When a defect of a component occurs, a new component can simply be grabbed from the on-hand stock. There is an exception with the Starter H&E station, since there are still some components driven by a push system. To calculate this, we re-examine the NCR data for which components still use push control and are likely to fail.

The yellow flows **D**, are the new flows from material that is delivered in pallets. All pallets are stored near the Cell-WH department. Instead of creating a whole new department between M-WH and Cell-WH, we assume pallets are delivered from the Cell-WH.

Finally, the blue flows **E** disappear, due to Kanban. Recall that with the introduction of the Milk-run concept, the 'Kanban flows' standardizes with cyclic work. However, it does create a modelling problem for our next SLP solution approach. In our layout model we need fixed flows to perform changes in the block layout. With the milk-run concept, however, the flows are dependent on the distance: the operator walks from department to department dependent on which one is closer. This creates a new problem to our model, known as the Traveling Salesman Problem (TSP). This creates a loop in finding the optimal solution, since the optimal flow depends on distance and the optimal distance depends on the flow. We address this problem in Chapter 6, for now we assume that the warehouse personnel walks along the departments with the nearest neighbour principle. The person should first walk the route to collect all the cards, which we consider as an empty flow, and secondly to deliver the material, a non-empty flow. This results in the yellow flows **F**: starting from material warehouse toward Starter BP and ending at the Sub 1 station back to the material warehouse.

From: To:	M-WH	Cell-WH	Sub 1	Sub 2	BLA	PCB	BIB	Epsilon BP	Epsilon H&E	Traction H&E	Starter BP	Starter H&E	Waste area	WH-C	FP-WH
M-WH			E	E	E	E		E	E	E	F				
Cell-WH			D	D					D	D					
Sub 1	F													C	
Sub 2	A		F							B				C	
BLA	A			F					B					C	
PCB	A				F				B					C	
BIB														C	
Epsilon BP						F								C	
Epsilon H&E								F						C	
Traction H&E									F					C	
Starter BP												F		C	
Starter H&E										F				C	
Waste area															
WH-C															
FP-WH															

Table 5.7 – Logistical flow improvements

With the policies and amount of storage for each SKU calculated in the previous paragraph we can now estimate the value of the green and yellow flows. From the previous paragraph we determine for each SKU:

- the reorder point;
- the reorder quantity of each SKU expressed in terms of small bins (or pallets);
- the expected demand per day (changeable for each period according to our forecast).

From these numbers we estimate the number of small bins and pallets that need to be refilled on average for each day in Table 5.8, which is determined at 48.52 bins per day on average in Q3 2019. From Table 5.4 of the previous paragraph we determined that each cart can hold up to 48 small bins. Warehouse personnel can hold up to 3 carts per run, so in total 3*48=144 small bins per run. This means that the required number of small bins can easily be fulfilled in one flow. Even when we select the period with the highest demand (Q2 2023), we have only use 2 carts, thus 1 flow per day.

Station	Number of containers refilled per day (expressed in small sized bins)	Number of additional pallets per day
Starter BP	2.52	0
Epsilon BP	7.53	0
Sub 1 station	0.80	0.18
Smart Starter	2.47	0
Battery lid Assembly	0.43	0
PCB Suppport	3.65	0
Sub 2 station	12.11	0.08
Starter HE	1.57	0
Epsilon HE	5.43	0.36
Traction HE	12.01	0.17
105E	-	-
Total	**48.52 small bins per day**	**0.79 pallets per day**

Table 5.8 – Average number of refills per day in Q3 2019

5.4.2 Costs parameter

The cost factor will also change with our new logistical improvements. Recall that costs consist of fixed and variable costs. We assume the fixed cost won't change. The variable costs will get influenced. Recall from Section 4.1.3 that the variable costs is calculated by multiplying the loading and unloading time (T_{ijk}), the flows (f_{ij}) and the operating costs per minute (OP), see formula 5.3.

$$Variable\ MHC_{ijk} = T_{ijk} * f_{ij} * OP \qquad (5.3)$$

Besides, of course the flows, the loading and unloading time will also change. Now that we use the pull production in combination with milk-run, we now can calculate how long it on average takes to pick the Kanban SKUs. Basically, there are two options to obtain these new values: either by measuring or by estimating. Since, in this research we don't have the time to measure all SKUs separately, we estimate the new picking time. We look per battery type the average time it took for each bin in the current situation, divide it by the number of SKUs that where picked and then multiply it by our predicted number of bins per day. By using the current picking time, we most probably overestimate the picking time. Recall with our new bin quantities, we accounted for predetermined packaging, which results in faster picking. However, the actual results of these changes can only be found by measuring a high number of SKUs. Due to the time limits of this research, we therefore choose to overestimate this picking time, by using the current situation.

5.5 New storage requirements

In this section we calculate the effects the logistical improvements have on the storage requirements. In the current situation Super B uses carts as method of transportation as well as a method of storing item at the production line. A warehouse worker simply puts the cart next to the station for the production operator to grab the needed components one by one. However, in our new situation a cart as storage method is far from ideal. Kanban requires fixed storage locations for each component, such that bins can be easily identified and reducing the error sensitivity. Each SKU requires its own dedicated space at the corresponding station. The best way to clearly storage this is with Kanban shelves. The in/outbound policy of the Kanban cards is always First In - First Out (FIFO), therefore roller shelves are preferred. We suggest two options to store the Kanban bins: in Kanban shelves (Figure 5.5), or directly at a lean workbench (Figure 5.6). A Kanban shelf can generally hold more items, while a lean workbench is more convenient for the operator, since all material is within reach.

Figure 5.5 – Example of a Kanban shelf (ESE Direct, 2019)

Figure 5.6 - Lean workbench (Disset Odiseo, 2019)

The dimensions of the shelf given in Figure 5.5 can easily be varied. For now, let us consider a large shelf with the dimensions 1500*1800*800 mm (H*W*D). This shelf can hold a maximum of 75 different SKUs and up to 375 small bins, 60 medium bins or 30 large bins and adds 2 m^2 of required space to the corresponding department area. A lean workbench of 1800*1500*820 mm (H*W*D), as in Figure 5.6, could hold op to 22 different SKUs and up to 30 small bins, 8 medium bins or 4 large bins, but does not add additional space since it would replace existing workbenches.

Next, let us consider the area required for pallet placement. Super B uses standard euro pallets (800*1200), which uses about 1 m^2. However, the pallets also need to be placed and retrieved by the forklifts. According to Tompkins (2010), forklifts need at least a 2.7 metres wide aisle, so an additional area of 2.7*2.7 = 7.3 m^2, plus the area of the pallet makes it 8.3 m^2.

Station	Material Kanban shelves (2 m^2)	Lean workbenches	Additional pallets (8.25 m^2)	Sub-assemlby Kanban shelves (2 m^2)	Additional space (m^2)
Starter BP	0	2	0	0	0
Epsilon BP	1	0	0	0	2
Sub 1 station	0	1	2	0	16.5
Smart Starter	0	1	0	0	0
BLA	0	1	0	0	0
PCB	0	1	0	0	0
Sub 2	0	2	1	0	8.25
Starter H&E	1	0	0	1	4
Epsilon H&E	0	2	2	2	20.5
Traction H&E	0	4	1	1	10.25
105E	0	1	3	0	24.75
Total	**2**	**15**	**9**	**4**	**86.25**

Table 5.9 - Additional space required as a result of the new logistical improvements

In Appendix F.1 we listed all bins and pallets that are required in storage and in Table 5.9, we summed the results of our solution in terms of additional storage for each department at the production site.

For the Traction H&E department, we took a more extensive look. Super B has four stations placed at the Traction H&E, each requiring the same material. One could place one large shelf for all four stations, which improves the picking process, since warehouse personnel only need to check one bin for each SKU. However, this comes at the expense of efficiency at production: each time an operator requires new material, the operator needs to separately pick the material at the shelf, located central to all four stations. An alternative is placing four lean workbenches, which results in more bins at production, but no constant movement of production operators to collect material. Thus, this is a consideration between having 4 times as much material bins at the Traction H&E department or the constant movement of production operators to collect material. The effects of a central shelf (higher lead times) are considerably more negative for Super B than the effects of decentral shelves (the placement of more bins at productions). Note that the average amount of bins that need to be picked each day are the same, since the demand of each bin is also divided by 4. Therefore, we choose to place 4 lean workbenches.

The sub-assemblies are stored at the Housing and Electronics stations. After assembling the sub-assembly bins are directly transported to the subsequent process, where the sub-assemblies are stored in large Kanban shelves. The placement of the shelves and workbenches are considered in the next chapter.

5.6 Costs and benefits of solution II

In this section we discuss the costs and benefits of implementing our new planning and control method. We first discuss approximations of the costs and secondly the benefits of this solution.

5.6.1 Investment costs

The costs of implementing this solution is divided in two categories: material costs and additional area. The material costs consist of new shelves and lean workbenches that are required. This can easily be calculated. From Section 5.5 we know that Super B requires 2 Kanban shelves, 3 sub-assembly racks and 15 new lean workbenches in order to implement the solution. According to Esedirect.co.uk (2019) a Kanban shelf, with rollers, should costs about €750. The sub-assembly racks are somewhat larger shelves and should costs about €1000. The 15 new workbenches should costs about €1000 each (lean-with-lista.com, 2019). All in total this would add up to **€19,500 of investment costs**. Secondly, we need additional space at the production site. The cost of 1 m^2 of additional space is not known, but with the available space of the facility this should not result in problems. In section 6.1 we go into further detail how much space is available and how much additional space is required.

5.6.2 Annual benefits

The new planning and control method have a positive influence on three subjects: number of flows (transport), picking time and the continuation of production. First, the number of flows will be significantly less. Currently, on average, warehouse personnel have to supply production with a very fluctuating 35 flows a week in the current situation, this can be reduced to a more constant 16 flows a week. Secondly the picking time is reduced, from on average 990 minutes spent on picking per week, we estimate this to be 570 minutes per week. This is mainly due to the more convenient picking quantities: instead of picking all material in batches of 10 or 20, we looked for each SKU at the pre-packaged supplier quantity. Finally, the continuation of production is improved. In the current situation, in case of defect material, operators must go to the warehouse themselves, to request new material. Subsequently warehouse personnel have to put their current activities on hold, to help the operator. With our solution, the operator can put the defect component aside and grab himself a new one with the on-hand inventory, so that the production process continues and warehouse personnel does not get interrupted. This leads to shorter product lead times and lower material handling costs. Unfortunately, we do not have the data to add this in our benefit analysis.

This all results in a new costs calculation, see Table 5.10.

Flow type	Current material handling costs	Material handling costs after Solution II
Picked material	€ 29,234.04	€ 13,020.96
Sub-assemblies storage	€ 3,233.88	€ 0.00
Between production transport	€ 4,597.81	€ 10,250.62
Finished products	€ 6,517.78	€ 6,435.20
Waste transport	€ 3,804.89	€ 4,027.32
Cell transport	€ 2,319.39	€ 3,077.08
NCR transport	€ 6,998.13	€ 56.26
Annual costs	**€ 56,705.92**	**€ 36,867.44**

Table 5.10 - Costs breakdown after Solution 2 (Q1 & Q2 2019)

As explained in Section 5.4, we see much smaller costs dedicated to material picking and almost no costs in the sub-assembly storage and NCR transport flows. However, some costs also rise: the between production transport cost is significantly higher, because of the milk-run concept and sub-assembly transport; secondly the waste and cell transport is higher since more pallets are stored at the production line. This all results in an annual benefit of (€56,705.92 - €36,867.44) = €19,838.48 (using the current demand).

5.6.3 Cost versus benefits

In order to properly compare the current investment cost with the future annual benefits, we calculate the present value (*P*) of the benefits (*F*) time horizon of 4 years (*N*), see Table . In order to calculate the Present Value we use formula 5.4 (Sullivan, 2003).

$$P = \sum_{N=1}^{4} \frac{F_N}{(1+i)^N} \tag{5.4}$$

In this formula the Weighted Average Cost of Capital (*WACC*) is used as the interest rate (*i*). Basically, the *WACC* is a calculation of a firm's cost of capital. The WACC is used to decide whether an investment is worth investing in, rather than investing the same money in something more profitable. The extended formulation of *WACC* can be found in Appendix F.2. Super B currently has a *WACC* of 12% and thus we set the *i* at 0.12.

The annual benefits differ per year. Therefore we calculate each annual benefits separately. For our calculation, the first year starts at Q3 2019 and ends at Q2 2020, second year starts at Q3 2020 till Q2

2021, etc. We use the forecast models of Section 4.2 to predict the average demand for each period. In Table 5.11 we listed both annual costs of the current situation as from the new situation. Note that we have to assume the locations and planning and control methods of the Smart Starter and 105E in the current situation. In consultation with Super B, we place both departments at the most logical locations in the current situation. We place the Smart Starter next to the other sub-assemblies. The 105E is placed at the large empty space between the Epsilon and the sub-assemblies, see appendix F.3. It is also save to assume that, in the current situation, both 105E as the Smart Starter departments are push-controlled. The flows are estimated using our forecast divided by the batch size of 20 units (for both departments). The costs (picking time, investment costs, etc.) for each department are estimated using costs of the similar departments (Traction and Epsilon for the 105E and BLA and Sub 2 for the Smart Starter). Estimating the costs of both the current situation and the situation after solution II gives us the results given in Table 5.12.

Period *N*	Annual costs current situation	Annual costs after Solution II	Future benefits F_N
2019-2020	€ 58,493.28	€ 41,444.12	€ 17,049.16
2020-2021	€ 65,352.25	€ 44,035.90	€ 21,316.35
2021-2022	€ 69,090.82	€ 45,279.46	€ 23,811.36
2022-2023	€ 76,368.72	€ 46,912.25	€ 29,456.47

Table 5.11 – Annual cost differences after solution II (without new departments)

Next, we can calculate the present value, see calculation 5.5.

$$P = \sum_{N=1}^{4} \frac{F_N}{(1.12)^N} = € \, 67{,}884.30 \qquad (5.5)$$

The Net Present Value (*NPV*), which is the present value minus the investment costs, of Solution II is (€67,884.30 - €19,500.-=) **€48,384.30**. Therefore, we recommend Solution II to be introduced in the production facility of Super B.

5.7 Conclusion

In this chapter we focused on flow reduction. We did this, by first identifying which flows at the Super B facility causes backtracking and bypassing, i.e. the wastes in transportation. Secondly, in Section 5.2 we selected production and control methods, previously found in the literature. We distinguished two types planning and control methods, one for the planning of material supply and one for the planning of end product and sub-assembly production. For both material supply as for the sub-assemblies we selected a pull approach. This is with the exception of the Start H&E material, which gets a hybrid push/pull approach, due to the large number of components. In Section 5.3 we configured every component. We did this by categorising each component based on its size and generality. We created for each category an inventory policy (reorder point, reorder amount, reorder bin size, etc.). Besides, we constructed a program that generates Kanban cards when entering the component number. The card shows all necessary information regarding the components inventory policy.

In Section 5.4 we considered the effects of our proposed solution. We introduced a new way of picking the Kanban cards, using the milk-run concept. With this method we ensure a stable and standardized amount of picking moments. We substantiated this by calculating the average amount of bins needed to resupply production each day for the next 4 years. This amount can easily be refilled in one run. So the new planning and control methods have a direct impact on the number flows in our objective function. Besides, the flows, the related costs are also positively affected by our solution. Mainly the picking times are significantly smaller, due to no limitations by batch sizes and thence recognising predetermined packaging of the supplier.

However, these changes does come with a big downside: higher space requirements. In Section 5.5 we calculated the amount of new storage requirements needed in order to fulfil our at-line storage plans. In Section 5.6 we made the trade-off between the investment costs of this project and the annual benefits. In order to compare the annual benefits with the investment costs, we calculated the Present We first calculated the investments costs (€19,500) and future benefits. The future benefits resulted in a present value of €67,884.30 and thus a Net Present Value of €48,384.30. Hence, we advise Super B to implement Solution II.

6 Developing alternative layouts

Now that we have finished Solution 2, we go back to Solution 1 and use the data of the improvements of Solution 2. Recall that we use Muther's Systematic Layout Planning as our solution approach. Currently we have completed steps 1 – 4 in the previous chapters, see Figure 6.1. We now focus on steps 5 – 10. We do this by dividing this chapter in 6 sections: in Section 6.1 we perform the steps regarding *the space of the facility*; in Section 6.2 *model setup*; Section 6.3 we discuss the scenarios and configurations; Section 6.4 we select the layouts and detail them; Section 6.5 we do the cost-benefit analysis of the selected and finally, in Section 6.4 we give our conclusion.

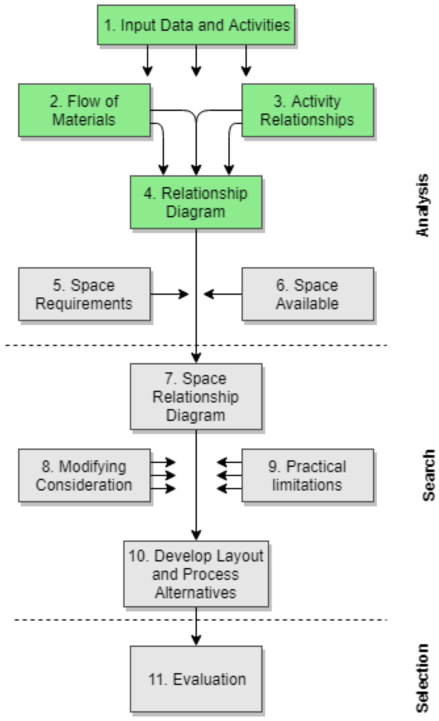


Figure 6.1 - Current Progress in SLP

6.1 Facility space

In this section we perform steps 5-7 of the SLP: *space requirements*, *space available* and the *space relationship diagram*.

Recall that in Section 3.3.2 we discussed how the space requirements need to be measured and calculated. Calculating the required space is a bottom-up approach.

First, we need to calculate workstation space requirements, secondly departmental space requirements and finally the main aisle space requirements. However, in the case of Super B's production line, there is a somewhat thin line between departments and stations. The Sub 1 station for example is in fact a department, since there only exists one station. Therefore, when calculating the space requirements, we directly look at the all space requirements for all station per department, instead of each station separately. Recall that workstation space requirements depend on:

- **Equipment**

  The equipment consists of workbenches and machinery. The surface of equipment can easily be measured.

- **Material**

  The material space consists of inbound material, in-process material and waste storage. Waste storage can also be easily measured. For the inbound and in-process material storage we have to include the new storage racks. The exact placement of these racks does not matter since changes will be made in the redesign of the layout. For now, we only need to calculate the space it requires at each department, this is done in

- **Personnel**

  The exact required personnel area has to meet the minimum requirements. According to Tompkins (2010) a minimum aisle width of 75 centimetres is needed for an operator to travel past stationary objects. When an operator walks between a stationary object and a machine an aisle width of 90 centimetres is required. A path is drawn from station to station. In addition to the operator, the forklift must also be taken into account. The minimal aisle width of the forklift is 2.7 meters.

We constructed a floorplan for the all departments, with the equipment area highlighted in *green*, the material area in *yellow* and the personnel area in *red*, in Figure 6.2 the floorplan of the Epsilon BP and H&E department are given as an example. In Appendix G the rest of the departments with their floorplans are given. We can now calculate the total area a department should need. In Table 6.1 we calculated the initial area for each department and added additional space needed as a result from solution 2.

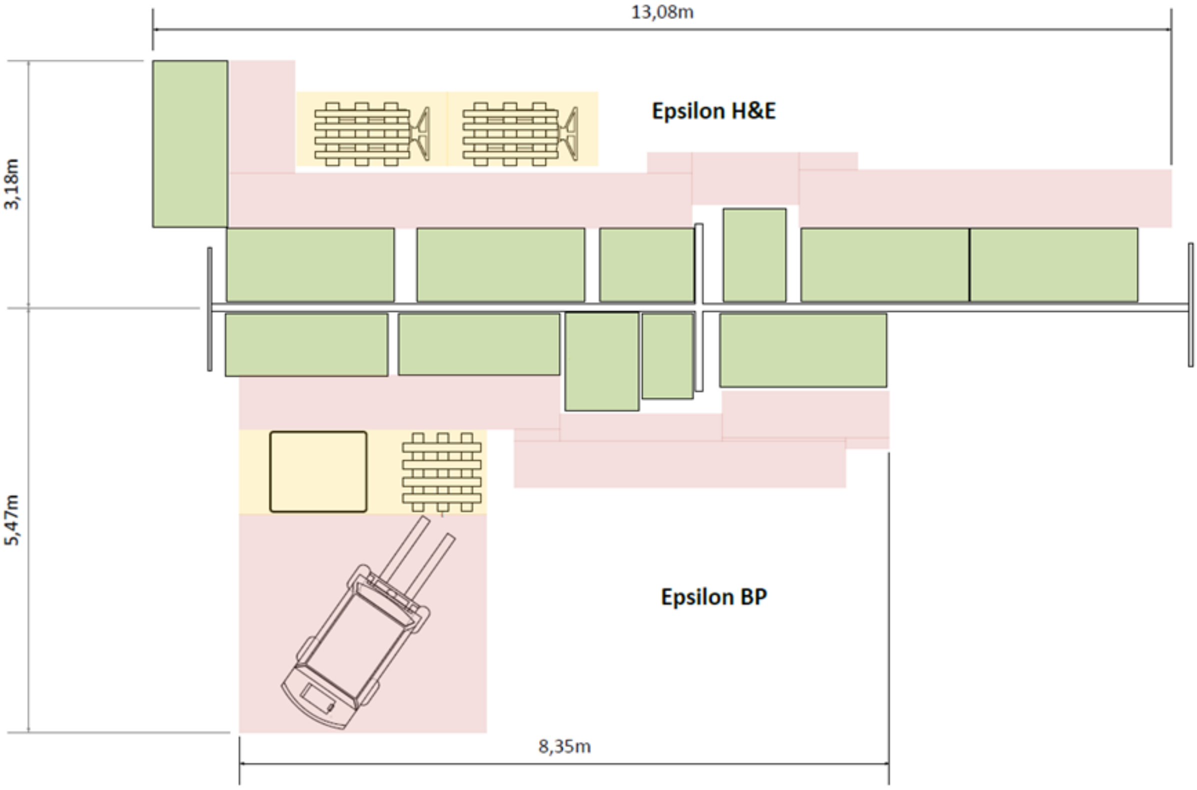


Figure 6.2 - Epsilon BP and H&E current floorplan

Departments	Initial area (m^2)	Additional storage space (m^2)	Total area (m^2)
M-WH	400	0	400
Cell-WH	165	0	165
Waste area	20	0	20
WH-Control	90	0	90
FP-WH	95	0	95
Sub 1	23	16.5	39.5
Sub 2	12	8.25	20.25
Traction H&E	75	10.25	85.25
BLA	6	0	6
PCB	6	0	6
BIB	9	0	9
Epsilon BP	32	2	34
Epsilon H&E	23	20.5	43.5
Smart Starter	10	0	10
Starter BP	38	0	38
Starter H&E	30	4	34
105E	30	24.75	54.75
Total	**1064**	**86.25**	**1150.25**

Table 6.1 - Space requirements per department

Next, we must ensure that there are aisles to reach each department, thus not just an operator path between stations. These are called main aisles and must be wider. Super B currently uses main isles with a width of 2 metres. In Table 6.2 we see that only 33% of the area is in use in our new situation. This means that, after relaxing our end model, we can easily add the aisles between departments. Also, future expansions in production department areas should not form major challenges.

Departments	Area (m^2)	Percentage in use
Total warehouse area	1248	
Warehouse department area	770	62%
Total production area	1040	
Production department area	380.25	33%

Table 6.2 - Area occupancy

6.2 Layout redesign model

In this section we start with our model design. We start with the method selection, subsequently we recap the input of our model that we have collected over the past chapters. Next we construct a concept of the program, such that the model gives a good representation of Super B's facility. Finally, we program the model.

6.2.1 Model selection

We first select a model. Recall from Section 3.3.4 that the most precise and best option would be a MIP model. Therefore, we did first programmed the *MIP model*. However, the model tends to be way too large for free solver programmes to handle, coping with only 3 departments (instead of the necessary 12). This model is given in Appendix H.1. Secondly, we considered *MULTIPLE*. Recall that MULTIPLE uses a space-filling curves to swap departments. MULTIPLE may not be the most precise method, since the method only produces local optima: the model only continues with swaps that improve the objective function, while a better solution sometimes first requires a 'bad swap', i.e. a swap that deteriorates the objective function.

However, in combination with *Simulated Annealing* one could get better results. In Simulated Annealing we use a probability function that is controlled by a cooling parameter. This probability function determines whether a 'bad swap' gets accepted. If a bad swap occurs, one would draw a random number, if this number is below the cooling parameter, the bad swap gets accepted. The cooling parameter gets smaller and smaller after every iteration: fewer bad swaps get accepted. Further explanation of simulated annealing and the exact calculation of the cooling parameter can be found in Appendix H.2.

We select Microsoft Excel's VBA as our program to model the situations, as it allows us to easily use previously constructed dynamic spreadsheets: the objective calculations and forecasts. Besides, we want a model that can easily be adapted by Super B, when changes are required, VBA and Excel offer us these options.

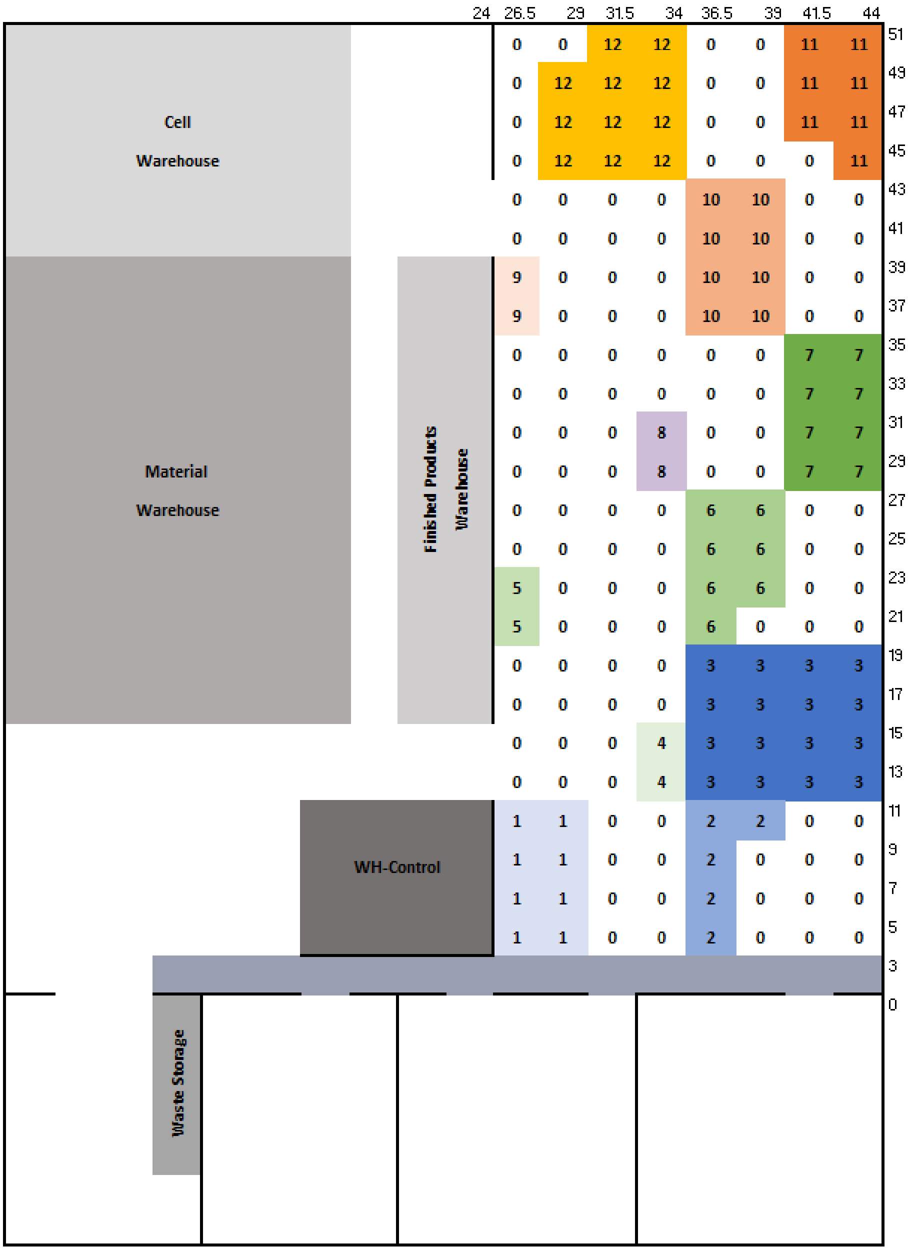
6.2.2 New model redesign

In order to design our model, we start with constructing a layout in Microsoft Excel. We draw a *x*-axis (width of the building) and *y*-axis (length of the building) to mark the production facility, it becomes an 8x24 grid. This grid represents only the production facility, since only there changes are made. However, we have the warehouse on the east side of the production facility. Therefore, we start our x-axis of the grid at 24 meters (the width of the warehouse) and ends at 44 metres (the width of the production hall). We also include a main aisle of 3 metres at the southside of the building, which means the y-axis starts at 3 meters and ends at 51 meters (length of the building). This means the 8x24 grid covers an area of (20*48=) 960 m^2 and one block covers an area of (960/(8*24)=) 5 m^2. Since there is a possibility Super B may move to a different location in the next 4 years, we made the model modifiable for new buildings. The grid size and ratio stay the same, but the width and length of the building are fully customizable. However, since there is no information about a new location, we continue to assume Super B is staying at their current facility.

In MULTIPLE we use space-filling curves. Therefore, we need to draw a curve through the 8x24 grid. The space-filling curve is drawn to fit in an 8x24 grid. The first block, where the curve starts, gets value 1, the second 2 and so on till (8*24=) 192. We appoint these 192 blocks to the integer-variable *n*. The blocks 1 till 192 can be 'stretched out' and be seen as a simple line. We divide the line in segments of 16 blocks. In each segment only one department is placed. The empty space between the departments is valued *0*. Each segment is a range of values of *n* that consist of either a department (*i*) or empty space (*0*). The number of blocks per department is calculated using Table 6.1 of the previous section. Now, we have 12 departments divided over 12 segments, such that all departments can swap with each other. With the departments, placed in order (from 1 to 12) in the grid, we construct an initial layout, see Figure 6.3. Note that this is not the current layout of Super Bs production facility.

Secondly, we want to calculate the *x* and *y* coordinates each block *n*, such that we can calculate the centre point of each department, by taking the average of all x and y values of n-blocks that are in use by the corresponding department.

The *x* and *y* coordinates correspond with the real-life location, such that we can fill them in our distance matrix of Section 4.1, which automatically calculates the distances between departments and subsequently the corresponding objective function.



Nr	Department
1	Sub 1
2	Sub 2
3	Traction H&E
4	BLA
5	PCB
6	Epsilon BP
7	Epsilon H&E
8	BIB
9	Smart Starter
10	Starter BP
11	Starter H&E
12	105E

Figure 6.3 – Visualization of the model

Conceptual model

Now that we have completed the foundation of our model, we can start with the conceptual design of the model, see Figure 6.4.

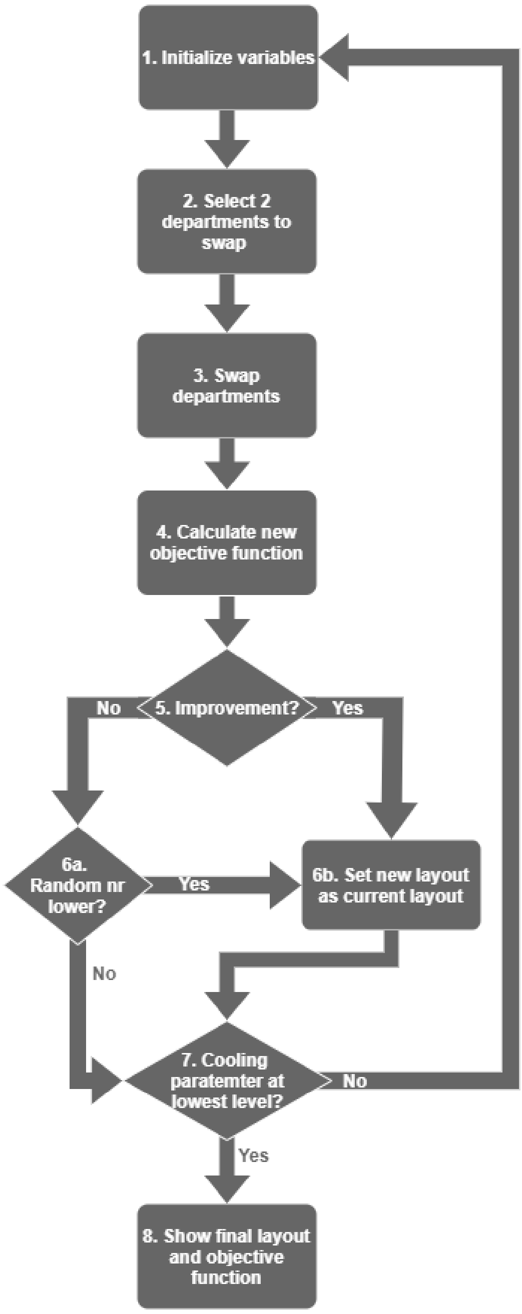


Figure 6.4 - Conceptual model

We start with **step 1**: initializing the variables. Here we calculate the cooling parameter (*c*), reset our looping parameters, save the current layout and calculate for each department, the *x* and *y* coordinates according to the current layout.

In **step 2** we select two departments. These are the department that are going to swap. We call them department *i* and *j*. The selection is random, where both departments must be different.

In **step 3** we swap the departments. This step can be performed in multiple ways, as we show in the next subsection. For now, we explain a simple two-way swap, called *2-opt*, with a segment size of 16. We start with the search for the *n*-value, where both departments begin, we call them *starti* and *startj*. We then search in which segment they are located, by dividing these n-values by 16 and rounding them down. Now that we acquired the position of both segments, we first save for department *i* and *j* both segments to arrays and then paste the array from one department on the segment of the other department.

In **step 4** we calculate the new objective function, by first recalculating the new centre points of the swapped departments and secondly by recalculating our distance matrix. Secondly, recall that with the introduction of the milk-run concept, a different walking route occurs when departments switch. This means we need to switch our set of flows as well, before calculating the new objective function. We use the space-filling curve of MULTIPLE to indicate the walking route. We first specify the sequence of departments in the space-filling curve and secondly link this route with the flow matrix. Finally, we calculate the new objective function.

In **step 5** we check for improvement. In this IF statement we check whether the swap results in a worse objective function (next: step 6a) or a better solution (next: step 6b).

If the objective function did not improve, we perform another check in **step 6a**. Here we draw a random number between 0-1, we call it *rnd*. If *rnd* is lower than the simulated annealing probability function, called χ(*c*), we accept the change, despite it being worse, and treat it like an improved solution (next:

step 6b). If the *rnd* is not lower than the $\chi(c)$, we skip step 6b and we go to the next check (next: step 7).

In **step 6b** we either get an improved result or worse result (with $rnd < \chi(c)$), either way the layout becomes the new current layout. This means we replace the previous range of *n*-values with the new range of *n*-values.

In **step 7** we perform a final check on whether we can finish running our algorithm. This depends on the current value of *c* and the predetermined stop value of *c*: c_{stop}. If $c \leq c_{stop}$ then finish the algorithm and show the result. Else if $c > c_{stop}$ we go back to step 1, where we initialize the variables and thus also lower the *c*-value.

Finally, in **step 8** the program shows the best objective function and corresponding layout found in the algorithm.

6.2.3 Improvement options to our algorithm

As stated before, we have multiple alterations to the algorithm that differ from simple but fast, to more precisely but also more time consuming. Besides, some improvement options could oblige us to certain restrictions or assumptions. Let us first go into more detail with our current basic swap option: two departments swap in segments of 16 blocks. So, we split our range of *n*-values in segments of 16 blocks, such that we have exactly (192 / 16 =) 12 segments in the range of n-values. All departments can participate in swapping. All departments are located at the start of each segment. This means we always have empty space between departments that do not cover the full segment, see Figure 6.4 for an example.

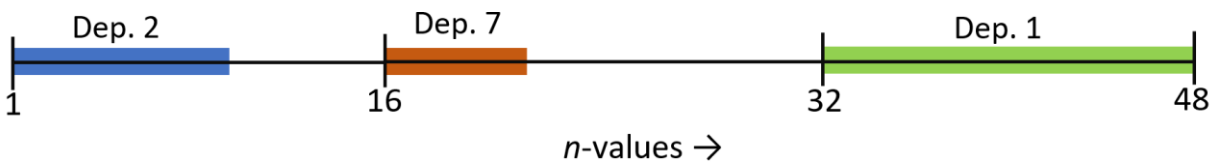


Figure 6.5 - Example of department distribution

From here on we start making changes in swapping, such that the results are either better or more representative towards reality. In Table 6.3, we listed opportunities to improve our algorithm. One option does not exclude the other, i.e. we could combine these options.

Nr.	Option description	Positive effects	Negative effects
1.	Segments of 8 blocks	More precise	Larger departments (>8) can't swap
2.	3 department swaps at once	Larger search space	No guarantee of better results, more time-consuming
3.	Combining departments within product groups	Less time consuming & successive departments are placed next to each other	Larger space between department groups

4.	Move departments within each segment	Better results	More time-consuming
5.	Different space-filling curves	Broader range of solutions	-

Table 6.3 - Improvement options

In the first option we will double the number of segments, such that each segment has a size of 8 blocks. We will introduce dummy departments (departments that have no effect on the objective function) for the empty segments, such that swapping with empty space is possible. This results in a significantly larger search space and more precise results. The downside of option 1 is that larger departments won't be switched, these departments will stick to their current position. We found two ways to resolve this. First, we apply some relaxation to the area constraint. Departments with an area of 9, for example, are reduced to 8, such that swaps can be made. Since, there exists a lot of empty space between departments, areas can easily be restored afterwards. Secondly, option 1 can be combined with the 16-segment approach. Such that when larger departments (*area* > 8) are selected, the algorithm switches to a 16 segment swap and swaps two 8 segment departments with one 16 segment department.

In the second option we exchange 3 departments at once, also called *3-opt*. In 3-opt we look at the best possible configurations with changing the three selected departments. Each time three new departments are selected. This department can be arranged in different configurations. Next to the current configuration, there are (3! – 1 =) 5 other ways to configure them. Within the algorithm we create an inner loop, where we search for the best configuration. The best configuration is then compared to the current one. If it is better, it gets accepted, if not we check the random number and the calculated probability (simulated annealing). The big downside of this option is the significantly larger computation time compared to 2-opt (≈15 times longer).

The third option we take to improve our model, is to group the departments. This is done by combining all product group departments (sub-assemblies, battery packs and housing & electronics stations). This action will cause a positive impact on the calculation time and it is a rational choice, since it only logical to put successive departments together. However, this action could also lead to less precise results and larger spaces between non-successive departments. For this sub problem, it would also mean we do not need to use a heuristic anymore, but can simply find the global optimum, since we reduced the problem to 6 department groups (including 1 dummy department), which results in only (6! =) 720 iterations. After swapping all group departments, we also swap the departments within the group departments. In each segment we swap the departments and the empty space for, again, all possible combinations. This algorithm results in an extra (4! + 5! + 2! + 4! + 2! =) 172 iterations.

With the fourth option we want to optimize within each segment. Now, as stated before, the departments always begin at the start of each segment. For large departments with an area of 16 or 8 (considering option 1) this won't matter, but all smaller departments have space to move within the segment. With this option we take this into consideration. However, optimizing this after every swap will cost a lot of computation time, therefore we only consider placing the departments to either the beginning, the middle or the end of the segment.

Finally, the fifth option to consider, is using different space-filling curves. The space-filling curves have a great influence on shape and placement of departments. Unlike the other options, it is hard to tell what the outcome of different space-filling curves will be and which one suits better. Therefore, we consider this as an extra dimension in modelling our scenarios in Section 6.3.

In the next section we discuss which improvement options we are going to implement for our experiments.

6.3 Scenarios & configurations

In this section we think of which scenarios & configurations we use in our experimentations. We create three dimensions: time period , algorithm options and space-filling curves.

6.3.1 Time period

In Section 4.2 we created a forecast for all product groups using the BASS model. In Figure 6.6 we summarized the results our forecast in four periods. The biggest differences in periods can be seen in the increase in demand of the 105E. The 105E is expected to become the bestselling product of Super B. However, because it is a completely new product, disappointing results must also be taken into account. Therefore, Super B is mainly interested in 2 periods: the 2019-2020 period and 2022-2023 period, scenario 1 & 2 respectively.

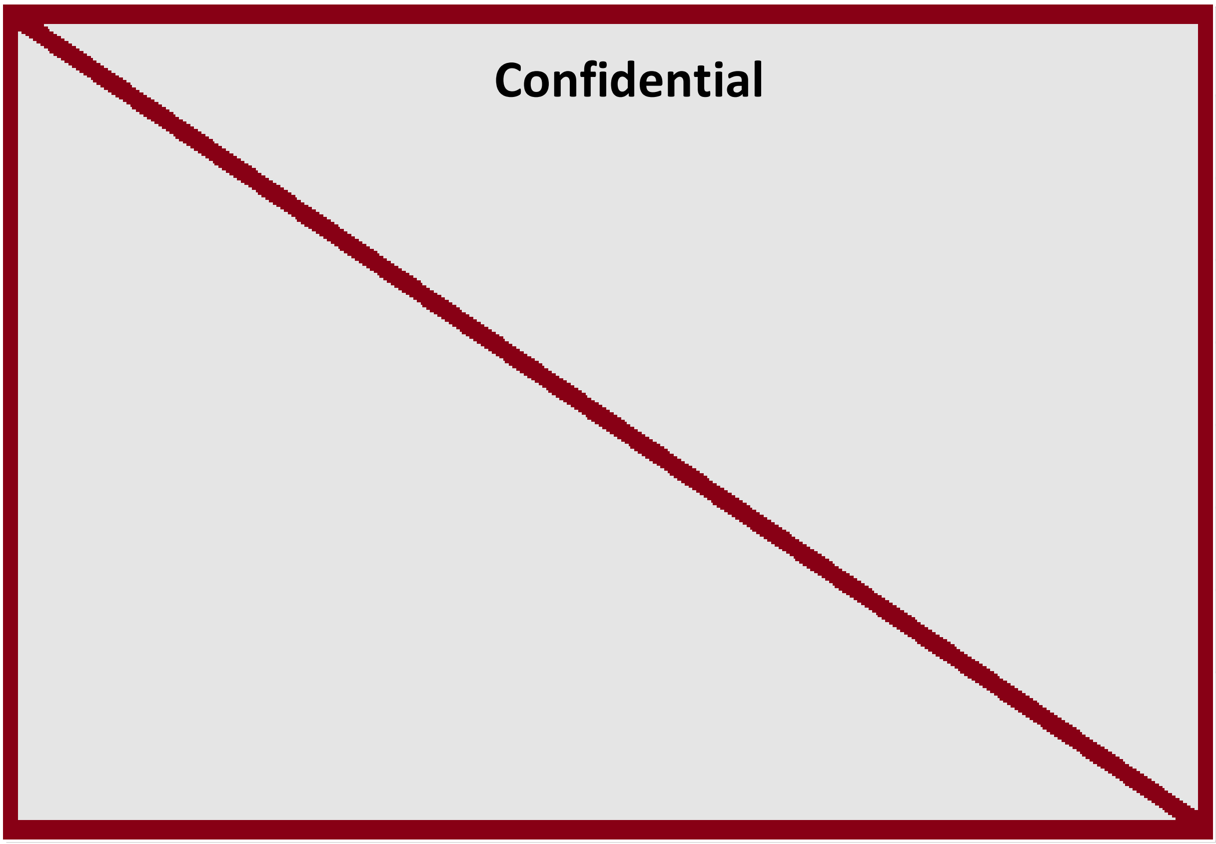


Figure 6.6 - Demand variations in 4 years based on the forecast of Chapter 4

6.3.2 Algorithm options

After successfully implemented all improvement options in the model, we have to combine and test the improvements. We create 3 algorithms based on the options given in Table 6.3:

- First, for **Algorithm 1**, option 3 (the group swap) is used. Here we divide the space-filling curve in segments of 32 blocks and go through all possibilities.
- Secondly, we discussed that with option 1 (8 segment swap) and option 4 (within segment improvement) is best to combined with our standard algorithm (16 segment). Let us call this combination **Algorithm 2**.
- Lastly, in **Algorithm 3**, we use the option 2 (3-opt) and option 4 (within segment improvement) as a swap-algorithm.

6.3.3 Space-filling curves

We constructed 4 space-filling curves, given in Appendix H.3. In *MULTIPLE*, a space-filling curve should naturally be an uninterrupted curve. However, since we use segments of 8, 16 and 32, we can interrupt the curve, as long as the segments are not interrupted. This is our third dimension with the experiments in our model

6.4 The selecting and detailing layouts

In this section we take a look at the which layouts is the most promising. We do not simply want to only select the layout with the lowest objective function. It must also have feasible department shapes and a clear structure. This part of our research asks a more creative approach. We construct a 4-step approach for the selection of the best layout:

Step 1: Creating 24 Layouts: Create 12 layouts for scenario 1 & 12 layouts for scenario 2.

Step 2: Selecting 4 layouts for both periods

Step 3: Detail the 4 layouts

Step 4: Recommend 1 layout

6.4.1 Step 1: Creating 24 layouts

We first generate 24 new layouts out of the 3 algorithm options and 4 space-filling curves and 2 time periods. This is our first step in the selection process. We perform 10.000 iterations for algorithm 1 & 2 and 897 iterations for algorithm 3. We start the cooling parameter for algorithm 1 & 2 at 3000 degrees and let it ‘cool down’ to 10 degrees, such that, in the beginning we accept almost all changes and at the end only improvements. The results of the 24 layouts can be found in Appendix H.4. We observe that the objective function of all layouts don’t vary widely from each other within each time period. There is, however, a small difference in scores between the algorithms used. We observe that algorithm 1 and space-filling curve 3, score the best on average.

The small differences can be explained by the use of the milk-run concept of Solution II. With this concept we reduced and standardised material flows, such that exact positions of each department where less important than we thought beforehand.

6.4.2 Step 2: Selecting the 4 layouts

Of these 24 layouts we select 4 layouts to further detail. Beforehand we wanted choose these layouts according to a selection process, where we tested each layout on objective function and flexibility in expansion. However, flexibility in expansion is not a good criteria in this situation.

Expansion in the production capacity could be done by expanding the labour force or by expanding the amount of equipment. In the case of expanding Super B's labour force, naturally no additional area in departments is needed. When it is down to the amount of equipment, additional area is required. In Section 6.1 we calculated that, after introducing Solution II, Super B uses only 33% of the total production area. This means expansion could easily be done in terms of required area, as can be seen later in our resulting layouts. So it would be no point of use by adding flexibility in expansion as a criteria in the selection process.

Therefore we created a different selection procedure to select 4 layouts to further detail. On the hand we select 2 layouts based on just the lowest objective function, one for each scenario. On the other hand, we let Super B choose 2 layouts out of the 24 generated layouts, again, one for each scenario. Super B takes a look at which layouts are the most interesting to them and which they want me to further detail.

Nr	Department
1	Sub 1
2	Sub 2
3	Traction H&E
4	BLA
5	PCB
6	Epsilon BP
7	Epsilon H&E
8	BIB
9	Smart Starter
10	Starter BP
11	Starter H&E
12	105E

Figure 6.7 - Department legend

We first discuss and compare the two layouts of the same scenario, after which we compare differences between the two scenarios. In Figure 6.7 the legend for the layouts is given.

In the first scenario, experiment 3 has the lowest objective function. This layout is given in Figure 6.8. Experiment 3 is the result of algorithm 1 and space-filling curve 3 and gives an objective function of €28,690.54. Super B choses experiment 12 as their favourite, see Figure 6.9. In this experiment space-filling curve 4 and the 3-opt is used and generates an objective function of €29,012.81. When comparing both layouts we notice that our algorithms places both the Traction H&E departments, as well as the Starter H&E department, near the entrances. Only, in the best layout the Traction departments are placed at the northern entrance of the building, while in the slightly worse layout the Starter departments are placed there. The differences in objective function are, however, relatively small. This is due to the fact that both the Traction and the Starter have similar demand levels and the distances towards the material warehouse and the finished products warehouse are the same for both entrances. We also see a clear distinction between the space-filling curves. The department-shapes of space-filling curve 3 (in the best layout) are more squared, while space-filling 4 is more stretched out.

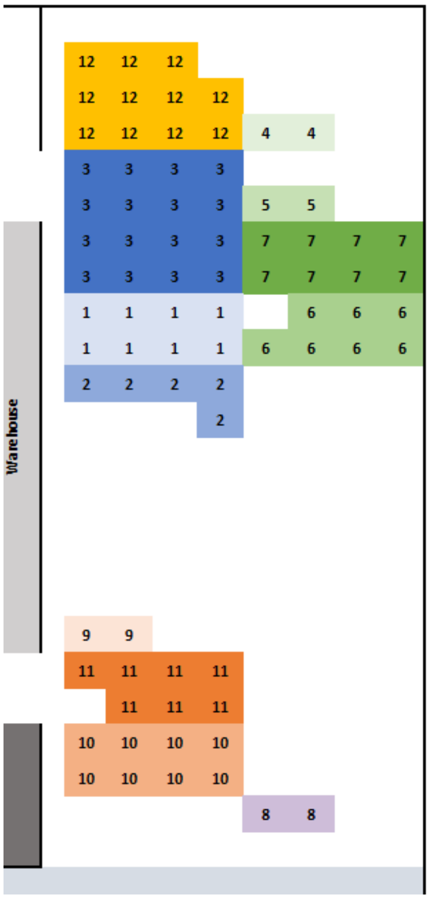


Figure 6.9 - Scenario 2: layout with the lowest objective function

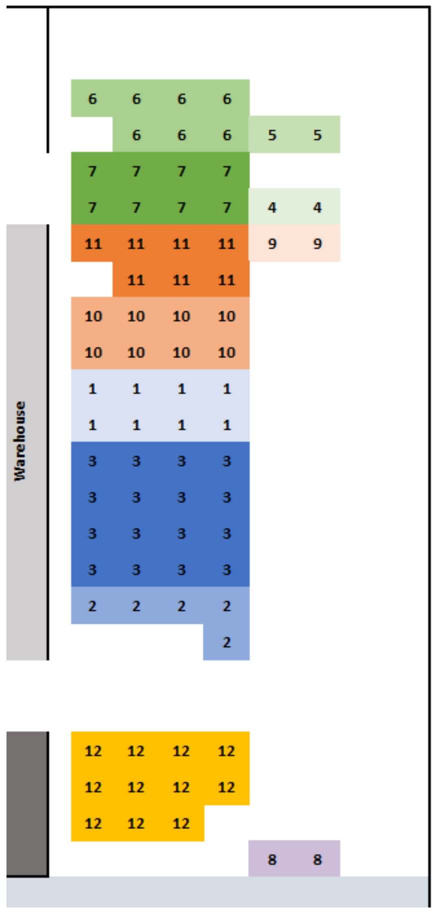


Figure 6.8 - Scenario 2: layout chosen by Super B

Next, we look at scenario 2. Here the layout with the lowest objective function is experiment 19. Experiment 19 is given in Figure 6.10. This layout is the result of space-filling curve 3 and algorithm 2 (8 & 16 segments swap), which gives an objective function of €33,462.99. The layout chosen by Super B is given in Figure 6.11. This is the result after using space-filling curve 3 and algorithm 3. This layout has an objective function of €33,949.57. In scenario 2 we see that the 105E gets, in both layouts, placed closer to the entrances compared to scenario 1. This is, of course, due to the fact that the 105E is the product with the highest demand level in scenario 2. However, we still see that (also in other 10 layouts) the Starter departments are on average slightly closer to the best positions (the entrances) than the 105E. This seems illogical and can be the result of only finding a local optima. However, the other layouts also show similar results. It can be explained by the push controlled flows. Recall from Section 5.2.2 that the Starter H&E department has to many SKUs to store in-line, so we would use a hybrid push-pull system. This requires an additional material flow from and towards material warehouse, that would explain the algorithms preference of placing the Starter departments at best position: near the entrance.

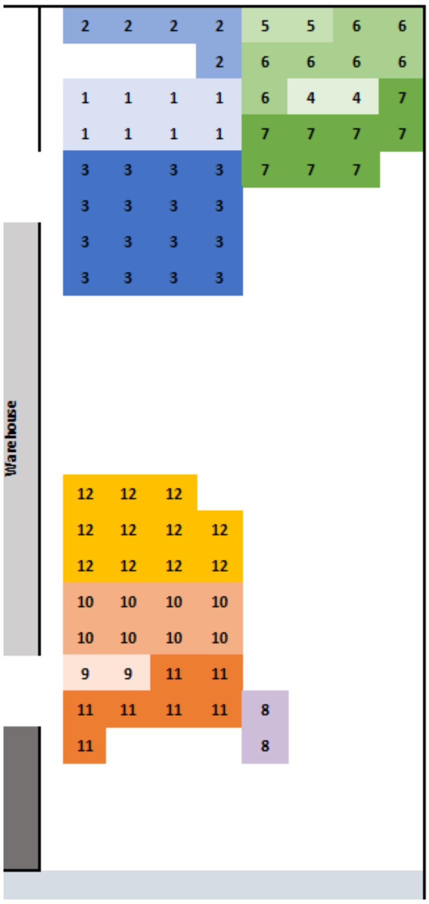


Figure 6.10 - Scenario 1: layout with the lowest objective function

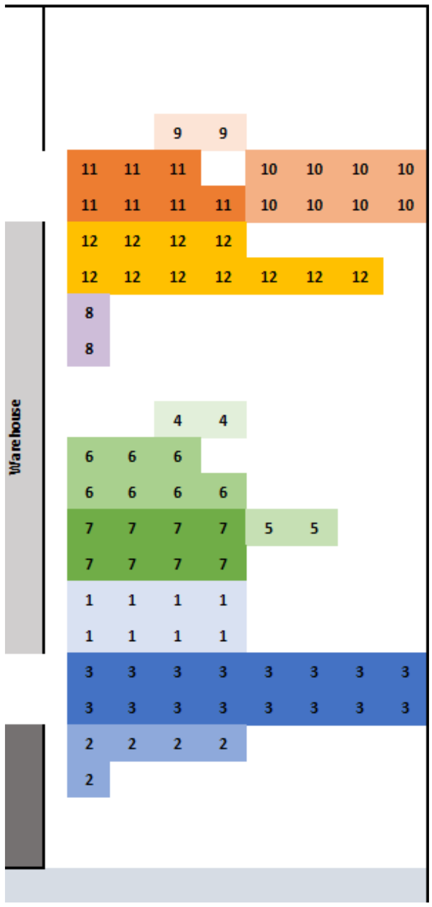


Figure 6.11 - Scenario 1: layout chosen by Super B

6.4.3 Step 3: Detailing the layouts

Before selecting one final layout, we first detail all the four favourites, since this is the more creative part of this solution, there may not be one best solution. So, we do recommend one layout to get a final result, but we leave the other 3 options open for Super B, by detailing those as well.

We use Microsoft Visio to draw the detailed layout. We start off with drawing the block-departments in the production facility in more logical shapes, this is done by ‘relaxing’ our block-departments. By relaxing we mainly reduce the odd department shapes and create paths for forklifts near the entrances. This is done while keeping the changes in objective function to a minimum. Our relaxed layouts of are given in Appendix H.5.

Next, we draw the final detailed layouts. Recall that in Section 5.5 we replaced some of the workbenches with new lean workbenches and added some material and sub-assembly shelves. Besides these changes, we keep the same equipment and machines for detailing our layout. Detailing the layout also means reorganizing the flows within the departments. One of the most ideal flow shape within a department is the U-shaped flow, see Figure 6.12. According to Tompkins (2010) the benefits of a U-shaped flow include enhanced visibility, improved communication, improved teamwork, reduced travel distance, reduced space, reduced handling and improved control over input/output to the department. We implement a U-shaped flow at the departments where this is possible, without comprising our predetermined block layout.

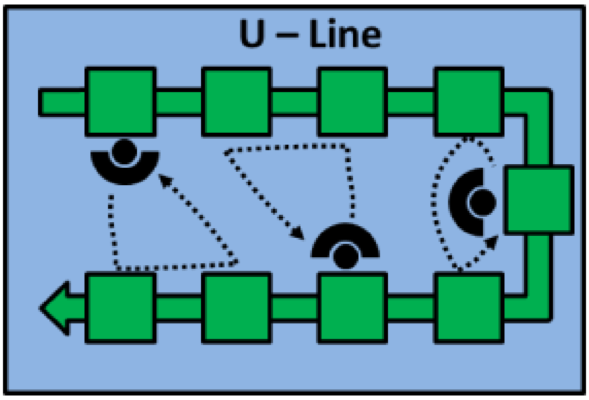


Figure 6.12 – U-shaped flow (AllAboutLean.com, 2019)

The four detailed layouts can be found in Appendix I.2, I.3, I.4 & I.5 respectively. The legend for these floorplans is given in Appendix I.1.

6.4.4 Step 4: Recommend one layout

In our last step we recommend one of the four layouts that we think Super B should implement. We make this choice on the basis of the lowest total costs over the 4 year period. This means we first have to recalculate the x- and y-coordinates, since we slightly relocated each department by relaxing the layouts. In Table 6.4 we listed each layout against each period

Period	Scenario 1: Lowest obj.	Scenario 1: Super B's choice	Scenario 2: Lowest obj.	Scenario 2: Super B's choice
2019-2020	€ 28,995.84	€ 29,440.80	€ 30,188.99	€ 30,666.22
2020-2021	€ 31,788.16	€ 31,555.05	€ 31,542.48	€ 32,834.09
2021-2022	€ 33,497.13	€ 33,112.50	€ 32,311.53	€ 32,678.47
2022-2023	€ 34,907.33	€ 34,695.35	€ 33,772.13	€ 34,110.64

Table 6.4 - Total annual material handling costs for each layout

Same as in Section 5.6.2 we calculate the present value in order to compare the annual costs, so we again use formula 6.1. only now we calculate the present value over the costs instead of the benefits, so we want the present value to be as low as possible. In Table 6.5 we give the present value for each layout.

$$P = \sum_{N=1}^{4} \frac{F_N}{(1.12)^N} \qquad (6.1)$$

	Scenario 1: Lowest obj.	Scenario 1: Super B's choice	Scenario 2: Lowest obj.	Scenario 2: Super B's choice
Present value of costs	€ 97,257.30	€ 97,060.27	€ 96,561.43	€ 98,493.50

Table 6.5 – Present value of the annual material handling costs for each layout

Here we can conclude that the layout from scenario 2 where we obtained the lowest objective function scores the best when considering the present value. Therefore, we now continue to compare this layout with the current layout in the next section.

6.5 Costs and benefits of Solution I

In this section we discuss the costs and benefits of implementing our new selected layout. We first discuss approximations of the costs and secondly the benefits of this solution.

6.5.1 Costs

We estimate the costs of our layout redesign by dividing the costs in two categories:

- Downtime & moving costs
- Installation costs

Downtime & moving costs

In the weeks prior to the moving, we recommend Super B to temporary increase the inventory, in order to cope with the demand during the moving process, so that Super B has no loss in sales. We estimate the moving process to take approximately three days. In these three days some warehouse and production personnel could do the moving. We assume it would take 8 men to move all departments in three days. So, let us assume it costs 3 days * 8 hours * 8 men * €35/hour = €6720. We disregard the short-term inventory costs.

Installation costs

Replacing departments to new location could mean that we need to take some rearrangement in compressed air piping, electricity supply, ethernet cabling and air extraction systems. We contacted an installation company to do a quotation of these costs. They assume that in the current production facility it would costs about €2000 on material cost (mainly due to the air extraction systems) and €1600 on labour costs (2 days of labour), thus €3600 of installation costs plus the downtime & moving costs would make it €10,320 in total.

6.5.2 Benefits

In order to properly compare the effects of only changing the layout of our solution with the current layout, we compare our new Solution I, new layout and new production and planning methods, with the configuration of Solution II, so with the current layout and the new production and planning methods. In Table 6.6 we calculate the annual material handling costs with the current layout and the annual material handling costs after implementing the layout found in Solution I.

Period *N*	Annual costs with the current layout	Annual costs after Solution I	Future benefits F_N
2019-2020	€ 41,444.12	€ 30,188.99	€ 11,255.13
2020-2021	€ 44,035.90	€ 31,542.48	€ 12,493.42
2021-2022	€ 45,279.46	€ 32,311.53	€ 12,967.93
2022-2023	€ 46,912.25	€ 33,772.13	€ 13,140.12

Table 6.6 - Annual benefits after Solution I

6.5.3 Cost versus benefits

Recall from Section 5.6.3 that, in order to properly compare the annual benefits with the investment costs, we calculate the present value of the benefits. This is done in calculation 6.2.

$$P = \sum_{N=1}^{4} \frac{F_N}{(1.12)^N} = \text{€ } 35{,}657.93 \qquad (6.2)$$

The present value of the benefits (€35,657.93) is higher than the investment costs (€10,320.-). This results in a Net Present Value of **€ 25,337.93**. Therefore, we recommend Solution I to be introduced in the production facility of Super B.

6.6 Conclusion

After the findings in Chapter 5, where we recommended Solution II, in this chapter we improved the layout. We did so by focusing on the reduction of the distances within our objective function. We started this chapter with estimating how much extra area was needed after the implementation of Solution II in Section 6.1. Next, in Section 6.2 we started with the design of our model. We concluded that current LP-programs could not handle the amount of variables and constraints of this problems. Therefore, we chose the heuristic *MULTIPLE*, which we found in the literature research in Chapter 3. We designed a model that is not only applicable for Super B's current facility, but also new for facilities (in-model facility sizes are variable), in the event that Super B decides to leave to a new premises. While normally MULTIPLE only results in local optima, we introduced Simulated Annealing such that we enlarge our search space and gain better results. We first configured a simple swapping algorithm we then improved using different modifications. Not all modifications could be used at once, so we introduced our first dimension, *algorithms*, in scenarios in Section 6.3. With our second dimension, *space-filling curves*, we introduced a change in the curve used in MULTIPLE. With this dimension we differ positions and shapes of departments. Our last scenario dimension was the time period. Due to similar demand levels at multiple periods we only chose two periods: 2019-2020 and 2022-2023. Next, in Section 6.4, we created 24 layouts. We found that differences in the objective function between the layouts where a lot lower than we expected beforehand. This was mainly due to our findings in Solution II: the milk-run concept. With this concept we reduced and standardised material flows, such that less flows can be optimised. This means that exact positions of each department where less important than we thought beforehand.

From the 24 layouts, we selected one layout from each period that had the lowest objective function and secondly we let Super B chose one layout from each period, since a layout selection is also subjective. We detailed these four layouts, which can be found in Appendix I.2 -I.5. From these four layouts we recommended one layout that had the lowest objective function over all periods. We estimated the costs and compared them to the present value of the recommended layout. We can conclude that Solution I has a net present value of € 25,337.93, so we recommend Super B to implement this layout.

7 Conclusion and recommendation

In this chapter, we first give a final answer to our main research question and the sub research questions in Section 7.1. In Section 7.2 we discuss our limitations in this research. Finally, in Section 7.3 we give a recommendation and advise Super B on future research topics.

7.1 Conclusion

In this section we answer our research question:

How can Super B redesign its production layout and logistical processes in order to minimize its transport related material handling costs while keeping future expansion into account?

We do this by first answering our sub research questions.

7.1.1 Which activities does Super B perform and how are they organized?

In Chapter 1 we explained the general process an order takes that results in of the three main battery types. Although different, the three battery types have similar process steps. Super B uses a MRP (push controlled) planning system, where batteries are pushed in batches towards next process steps.

We also investigated the future projects Super Bs is working on. We concluded that studies about performance calculations for layouts and forecasting were needed. We conclude that difficulties consist mainly of the forecasting the quantities of current and new products and components.

7.1.2 Which literature can be found to further analyse and improve the current situation and which of the literature found is applicable to our problem?

In chapter 3 we searched the literature for three main topics:

1. *Forecasting*
2. *Flow improvement*
3. *Layout planning*

In the our topic about forecasting we found three models that we could use: Time Series Analysis, Croston's intermittent demand model and the Bass diffusion model. The Time Series Analysis is a commonly used method for forecasting short to medium term demand. Our second model we found was Croston's demand model. This model is used for intermittent demand patterns: high peaks at irregular moments. We slightly modified this model, such that, after a peak, the demand level stays at the peak level. This idea was convenient for forecasting OEM demand. Our third model we investigated, was the BASS diffusion model. This model is specially made for long term forecasting products with small amount of historic data. The model is based on the product life cycle principle.

For our second topic, Flow improvement, we found ways to identify which types of flow cause transportation waste, one of the eight forms of wastes in the lean philosophy. These were found to be backtracking and bypassing, which can be identified by constructing a flow chart. Each flow that goes back to a previous station or process is defined as the backtracking flow and each flow that surpasses a station or process is defined as the bypassing flow. Subsequently, we searched for methods to counter these flows. Using the lean philosophy, we found three planning and control methods: Kanban, POLCA and CONWIP. Each methods has its own characteristics, but all ensure a pull system.

In the last section we researched layout planning. We divided this topic in five main subjects: definitions in layout planning; Muther's Systematic Layout Planning method; approaches within the change of layouts; the different metaheuristics; and finally, the calculation of the layout performance.

7.1.3 What is the current performance of the layout and how does it get affected in the future?

The costs of a layout is measured by the distance based objective function. the distance-based objective function is a summation, where each summand is a multiplication of distance, flows and the corresponding costs.

We estimated the current material handling costs from and towards the production area to be €56,700. While, this is a rash estimation, since not all flows and costs can be measured, but it gives us a good indication on the cost distribution per flow.

Secondly we forecasted each battery type in order to estimate future flows and required space. We forecasted the future sales numbers using the Bass model, since the Bass model copes with long term forecasting and introduction of new products and extensions.

Super B needs to produce 22,5% more batteries each year on average. In total most batteries are sold in Q2 2023, see Figure 7.1.

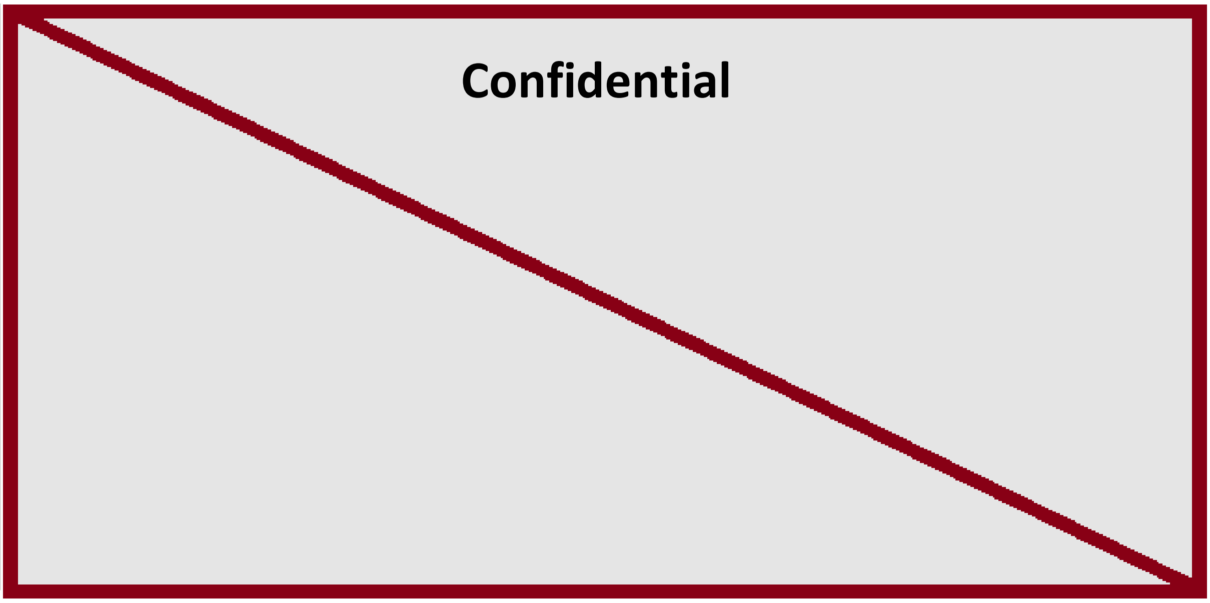


Figure 7.1 - Demand variations

7.1.4 What options can realise the reduction of transportation waste?

To answer this question we first identified which flows at the Super B facility causes backtracking and bypassing, i.e. the wastes in transportation. Next, we selected production and control methods, previously found in the literature. We distinguished two types planning and control methods, one for the planning of material supply and one for the planning of end product and sub-assembly production. For both material supply as for the sub-assemblies we selected a pull approach This is with the exception of the Start H&E material, which gets a hybrid push/pull approach, due to the large number of components. Next, we configured every component. We did this by categorising each component based on its size and generality. We created for each category an inventory policy (reorder point, reorder amount, reorder bin size, etc.). Besides, we constructed a program that generates Kanban cards when entering the component number. The card shows all necessary information regarding the components inventory policy.

Subsequently, we considered the effects of our proposed solution. We introduced a new way of picking the Kanban cards, using the milk-run concept. With this method we ensure a stable and standardized amount of picking moments. We substantiated this by calculating the average amount of bins needed to resupply production each day for the next four years. This amount can easily be refilled in one run. So the new planning and control methods have a direct impact on the number flows in our objective function. Besides, the flows, the related costs are also positively affected by our solution. Mainly the picking times are significantly smaller, due to no limitations by batch sizes and thence recognising predetermined packaging of the supplier.

However, these changes does come with a big downside: higher space requirements. We calculated the amount of new storage requirements needed in order to fulfil our at-line storage plans. Finally, we made the trade-off between the investment costs of this project and the annual benefits. In order to compare the annual benefits with the investment costs, we calculated the Present We first calculated the investments costs (€19,500) and future benefits. The future benefits resulted in a present value of €67,884.30 and thus a Net Present Value of €48,384.30.

7.1.5 Which new layouts can we construct to minimize total travel distance, while keeping new logistical flows in mind?

In order to answer this question, we started with estimating how much extra area was needed after the implementation of Solution II. Next, we started with the design of our model. We concluded that current LP-programs could not handle the amount of variables and constraints of this problems. Therefore, we chose the heuristic MULTIPLE. We designed a model that is not only applicable for Super B's current facility, but also new for other, in the event that Super B decides to leave to a new premises. While normally MULTIPLE only results in local optima, we combined it with Simulated Annealing such that we enlarge our search space and gain better results. We first configured a simple swapping algorithm we then improved using different modifications. Not all modifications could be used at once, so we introduced our first dimension in scenarios: algorithms. With our second dimension, space-filling curves, we introduced a change in the curve used in MULTIPLE. With this dimension we differ positions and shapes of departments. Our last scenario dimension was the time period. Due to similar demand levels at multiple periods we only chose two periods: 2019-2020 and 2022-2023. Next, in we created 24 layouts. We found that differences in the objective function between the layouts where a lot lower than we expected beforehand. This was mainly due to our findings in Solution II: the milk-run concept. With this concept we reduced and standardised material flows, such that less flows can be optimised. This means that exact positions of each department where less important than we thought beforehand.

From the 24 layouts, we selected one layout from each period that had the lowest objective function and secondly we let Super B chose one layout from each period, since a layout selection is also subjective. We detailed these four layouts, which can be found in Appendix I.2 -I.5. From these four layouts we recommended one layout that had the lowest objective function over all periods. We estimated the costs and compared them to the present value of the recommended layout. We can conclude that Solution I has a net present value of € 25,337.93, so we recommend Super B to implement this layout.

7.1.6 Answering our main research question

How can Super B redesign its production layout and logistical processes in order to minimize its transport related material handling costs while keeping future expansion into account?

We advise Super B to invest in equipment and time needed to implement the planning and control methods, elaborated in Chapter 5, in order to significantly reduce material handling costs. Besides, we advise Super B to relocate departments according to the layout plan given in Appendix I.4.

Implementing these two solutions should make Super B more efficient and future ready, while directly saving **€ 73,772.23** in material handling costs over the next four years.

7.2 Research limitations

In this section we discuss our research limitations. Our main concern during our research was the lack of data. Super B currently uses a ERP system called *Exact.* Before switching to *Exact* in October 2018, Super B used the ERP system called *Mamut*, that was used from May 2015. We had to rearrange old data dumps, that may or may not have been incomplete, in order to compare it with the latest data of Exact. Secondly during our research things in Super B's production process changed, such that 'our' current situation didn't fully match the actual current situation. Fortunately we did most of our measurements in the beginning of our research, however some measurements (mainly in picking times), we had to estimate. These limitations made this research more challenging and educational.

7.3 Recommendations and further research

We recommend Super B to follow the instructions

	Action	Week (2019-2020)	Executer(s)
Solution II - Sub-assembly Planning & Control	Install sub-assembly shelves at each department and mark shelf locations	49	Production personnel
	Make Kanban cards for each sub-assembly with the corresponding shelf location	49	Warehouse personnel
	Start storing sub-assemblies (in Kanban-quantities) directly at the corresponding Housing & Electronics department	50	Production personnel
Solution II - Material Planning & Control	Install material shelves at each department and mark shelf locations (wait with the new workbenches)	51 – 1 (during holiday period)	Production personnel

	Make Kanban cards for each component with the corresponding shelf locations	51 – 1 (during holiday period)	Warehouse personnel
	Start storing material (in Kanban quantities) at the corresponding departments	2 – 3	Warehouse personnel
Solution I – Layout Redesign	Start building a temporary inventory as a preparation for the move	4-7	Production personnel
	Start with the moving process: - Move shelves - Replace workbenches - Move machines	8-9	Warehouse & Production personnel
	Rearrangement of electricity supply, compressed air piping and computer cabling	8-9	Installation company

7.4 Further research

We recommend Super B to do further analysis on two topics:

- Capacity analysis
- Pull system through the whole process
- Ease of material handling

7.4.1 Capacity analysis

We recommend Super B to research the production capacity needed to fulfil future demand. This can be done with a bottleneck analysis. Super B should start with extensive measurements of cycle times, set up times, etc. of each station. Subsequently one could set up a queuing system and find the bottlenecks. Either by increasing the corresponding capacity or using line-balancing one could improve the efficiency of the production process.

7.4.2 Pull system through the whole process

We only focussed on improving the planning and control method for the production facility. However, pull production can be applied through the whole process. Now that we use Kanban for in-line production inventory, it must also be aligned with the purchasing process of material. Such that, the inventory policy in the warehouse also gets optimised.

7.4.3 Ease of material handling

I produced some batteries myself at the beginning of my research. From my own experience, the heavy traction batteries are hard to handle. Moving, lifting and turning them takes a lot effort, we advise Super B to investigate possibilities of conveyor belts and some sort of devices to easily turn batteries or by modifying the product design, such that it becomes easier to produce.

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APPENDICES

A. Product Structures

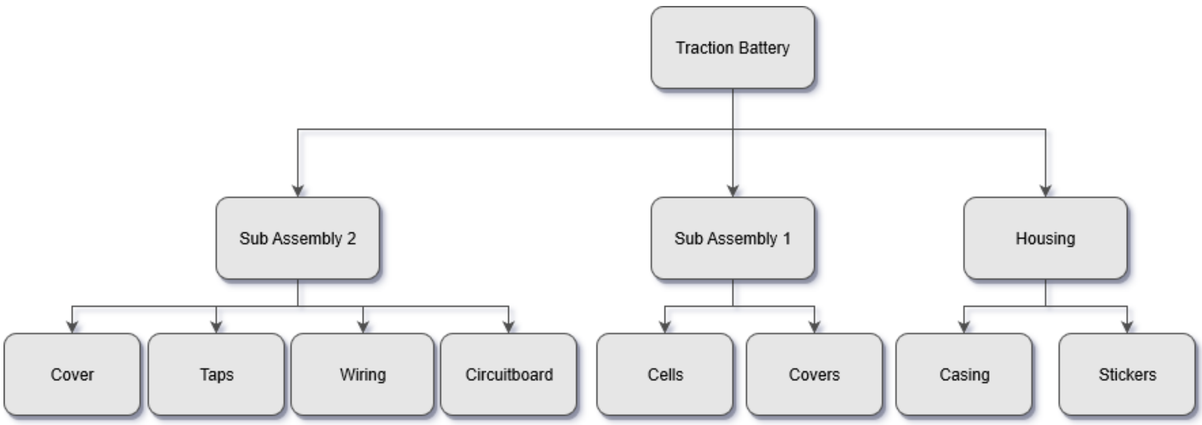


Figure 7.2 - Traction battery product structure

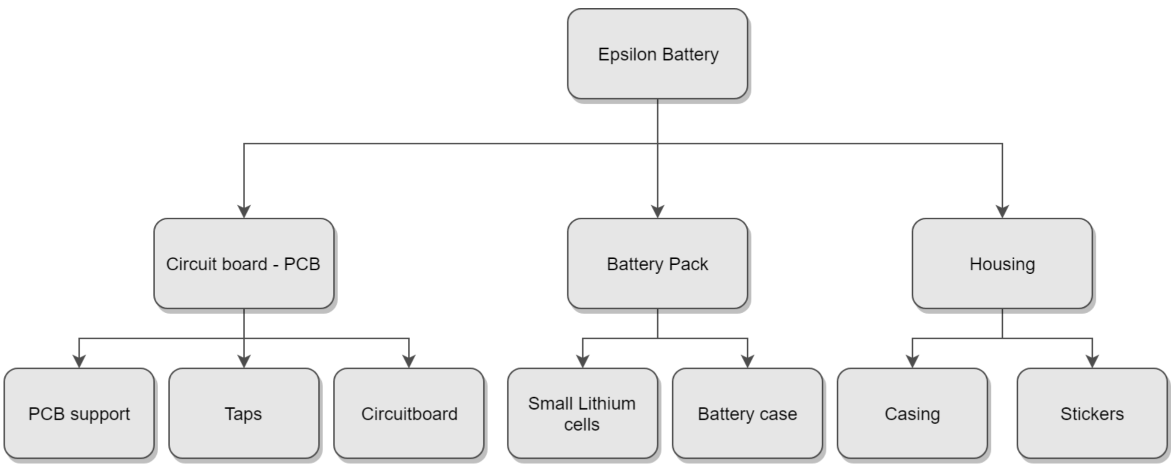


Figure 7.3 - Epsilon battery product structure

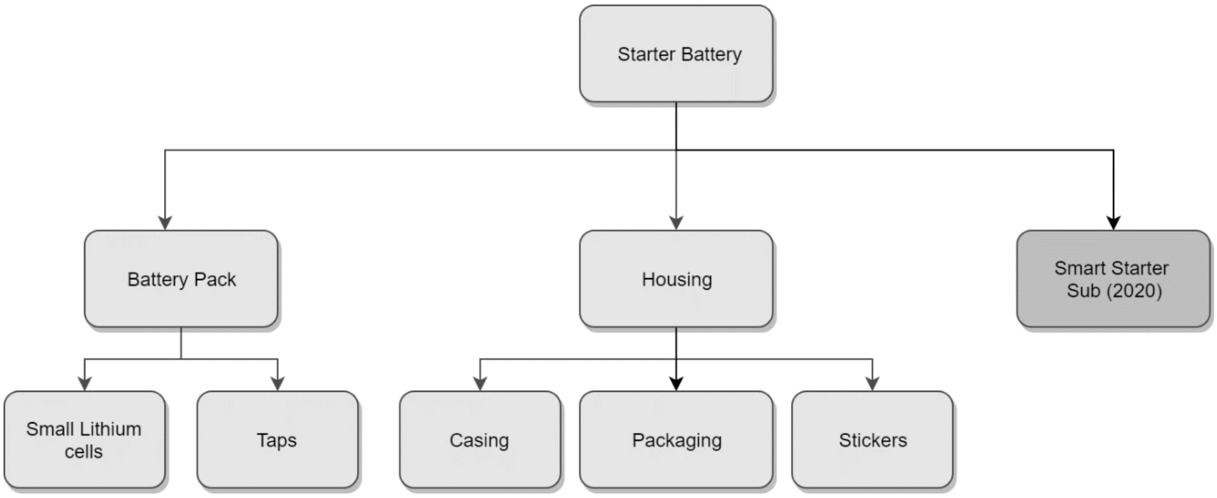
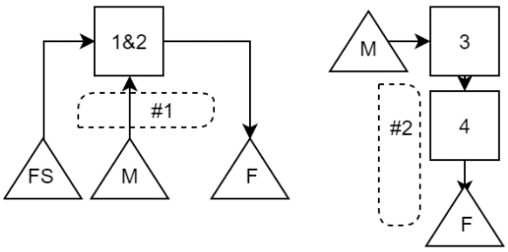


Figure 7.4 - Starter battery product structure

B. Flows

B.1 Flow Diagrams

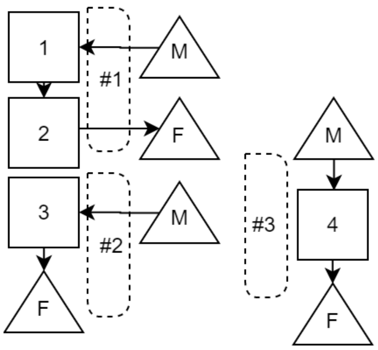


Sub 1:
1: Cell assembly
2: Internal housing assembly

Sub2:
3: Electronics assembly
4: Sub 2 testing

FS: Floor stock
M: Material temporary storage
F: Finished goods temporary storage

Figure 7.5 - Sub1, sub 2 in-process flows



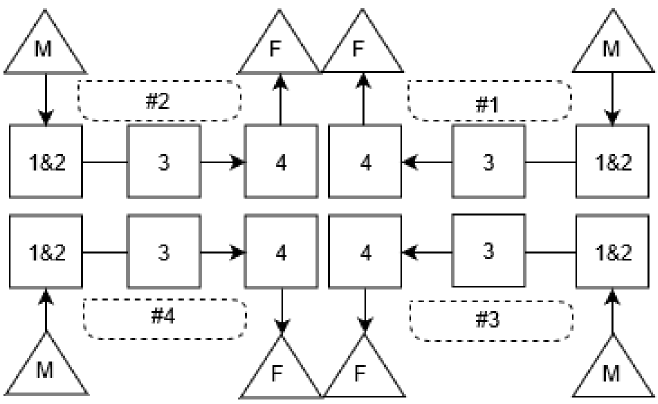
BIB:
1: BIB assembly
2: BIB testing

PCB:
3: PCB assembly

BLA:
4: Battery Lid assembly

FS: Floor stock
M: Material temporary storage
F: Finished goods temporary storage

Figure 7.6 - BIB, PCB and BLA in-process flows



1: Battery and electronics assembly
2: Battery housing assemlby
3: Extra charging (optional)
4: Balancing, Testing and Charging

M: Material temporary storage
F: Finished goods storage

Figure 7.7 - Traction in-process flow

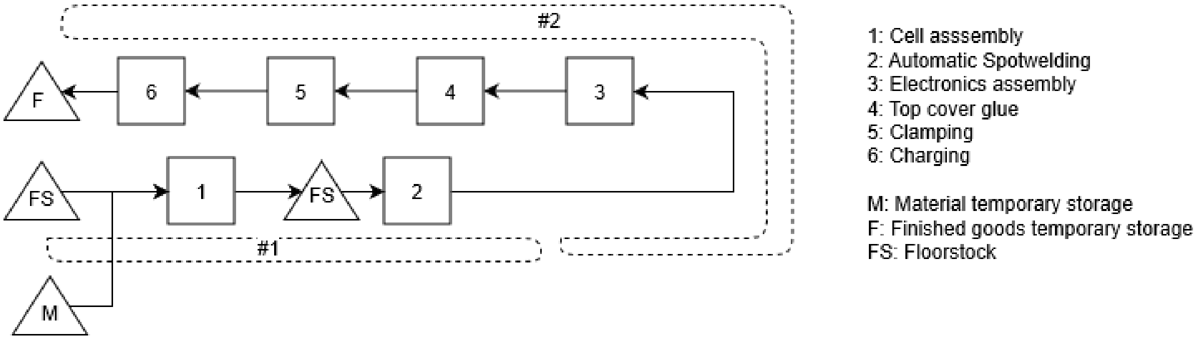


Figure 7.9 - Epsilon in-process flow

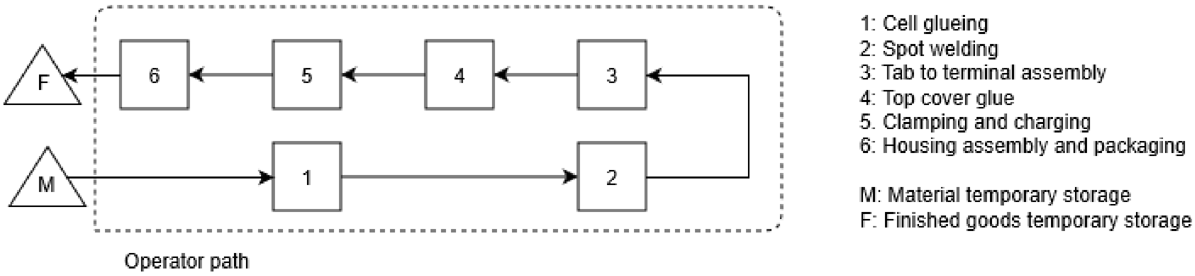


Figure 7.8 - Starter in-process flow

B.2 Flow-to-chart

From: / To:	M-WH	Cell-WH	Sub 1	Sub 2	BLA	PCB	BIB	Epsilon BP	Epsilon H&E	Traction H&E	Starter BP	Starter H&E	Waste area	WH-C	FP-WH
M-WH	-	-	4	4	1	2	1	3	3	8	10	-	-	-	-
Cell-WH	-	-	3	-	-	-	-	1	-	-	0	-	-	-	-
Sub 1	-	-	-	-	-	-	-	-	-	8	-	-	3	-	-
Sub 2	4	-	-	-	-	-	-	-	-	-	-	-	-	1	-
BLA	1	-	-	-	-	-	-	-	-	-	-	-	-	1	-
PCB	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BIB	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Epsilon BP	-	-	-	-	-	-	-	-	3	-	-	-	1	-	-
Epsilon H&E	-	-	-	-	-	-	-	-	-	-	-	-	-	7	3
Traction H&E	-	-	-	-	-	-	-	-	-	-	-	-	-	2	8
Starter BP	-	-	-	-	-	-	-	-	-	-	-	10	0	-	-
Starter H&E	-	-	-	-	-	-	-	-	-	-	-	-	-	4	10
Waste area	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WH-C	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FP-WH	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 7.1 - Flow-To-Chart: flows per week (rounded)

B.3 Space relationship chart starter

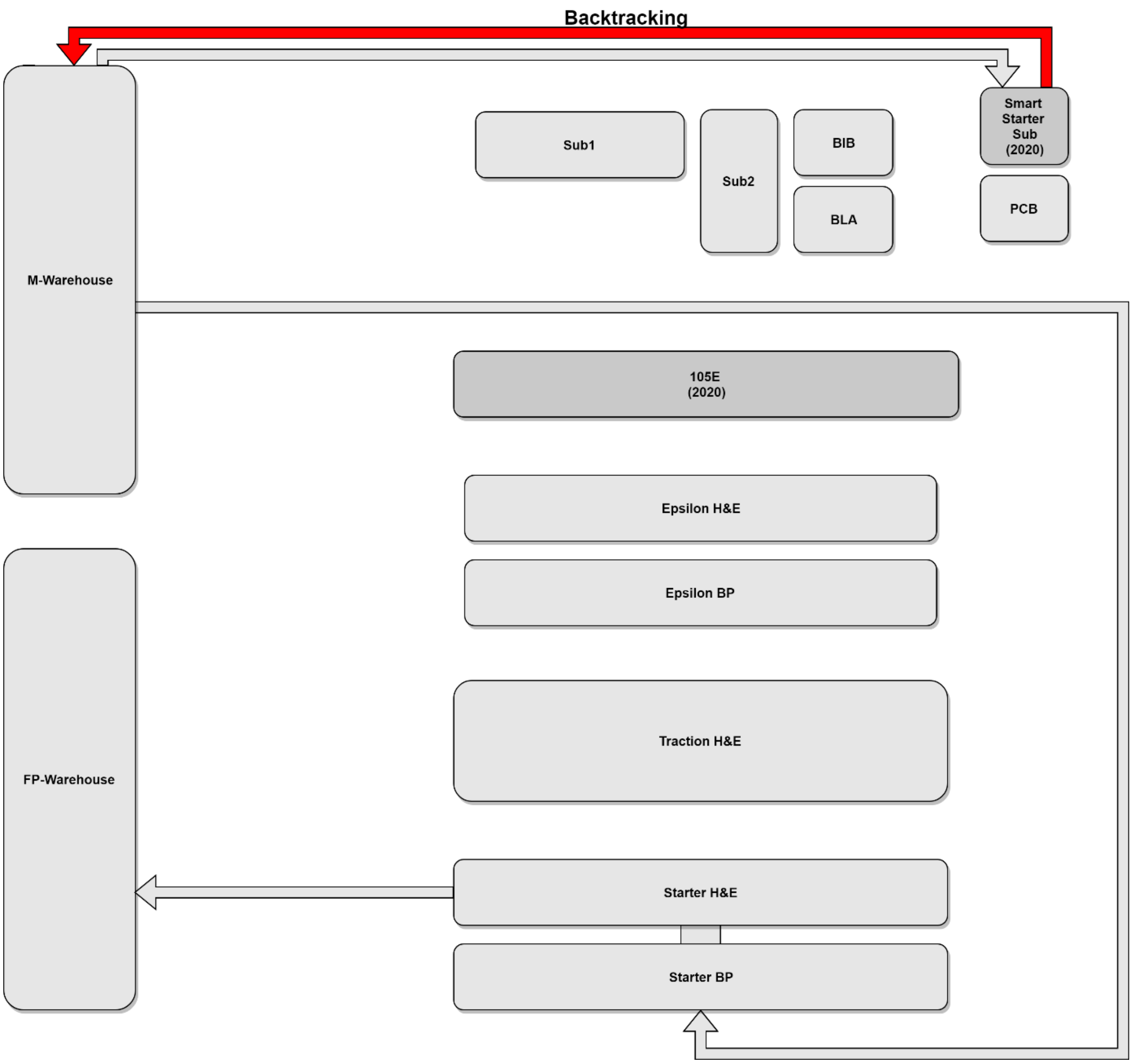


Figure 7.10 - Backtracking Starter

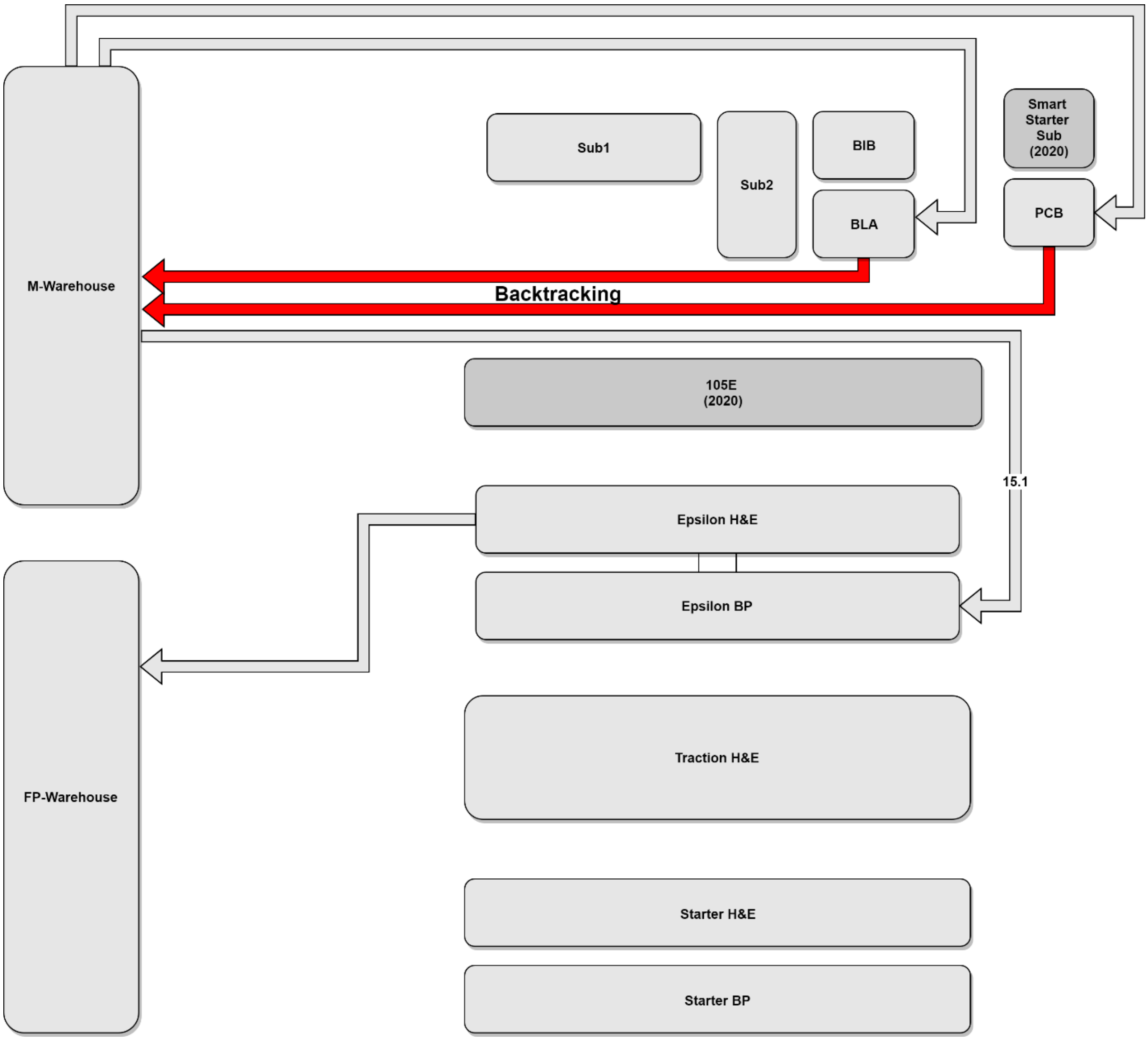


Figure 7.11 - Backtracking Epsilon

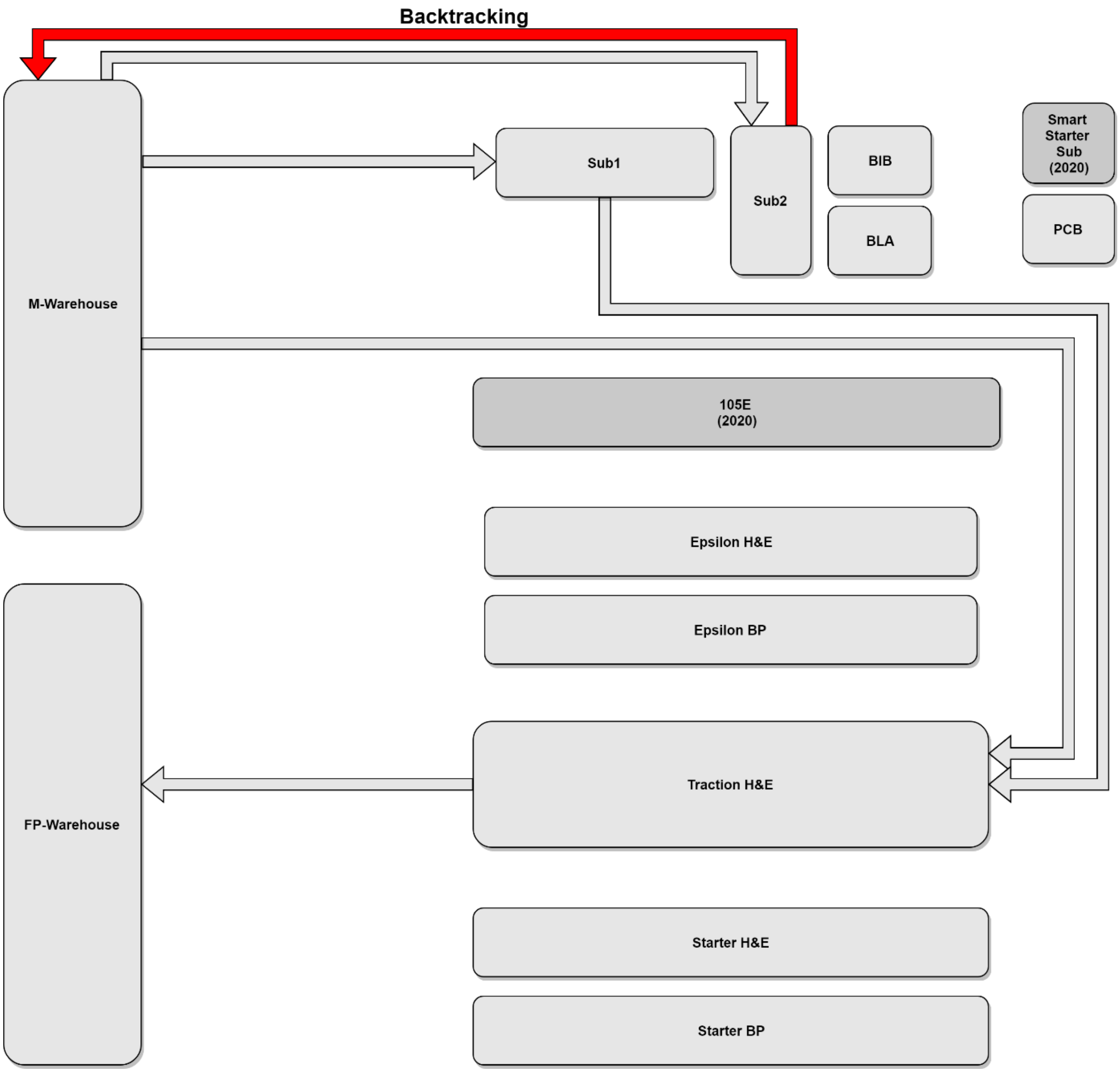


Figure 7.12 - Backtracking Traction

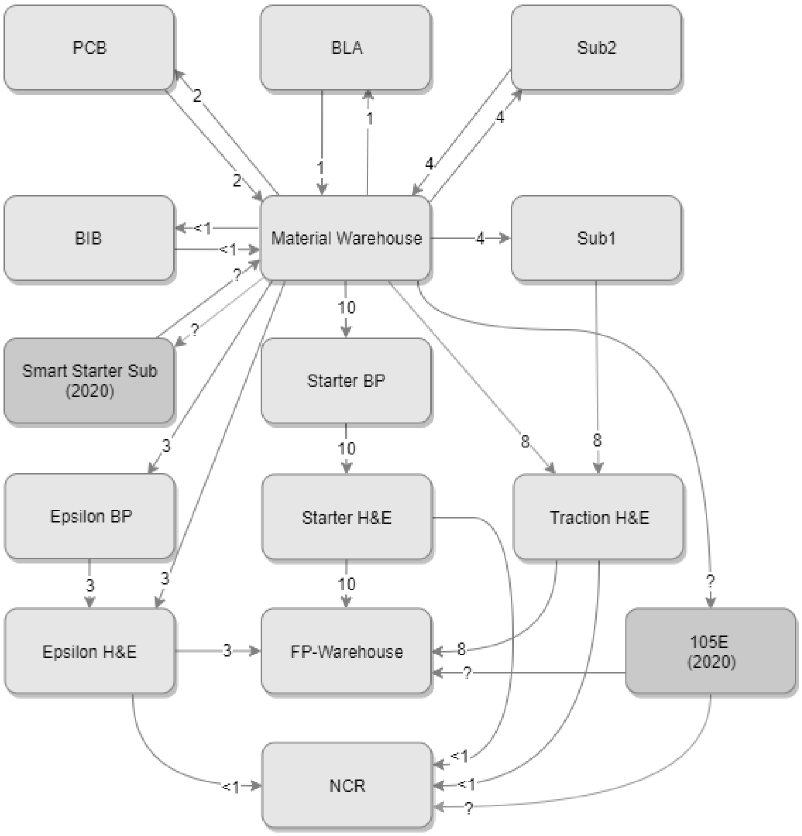


Figure 7.13 -Current number of flows per week between departments

C. Quantities sold and produced

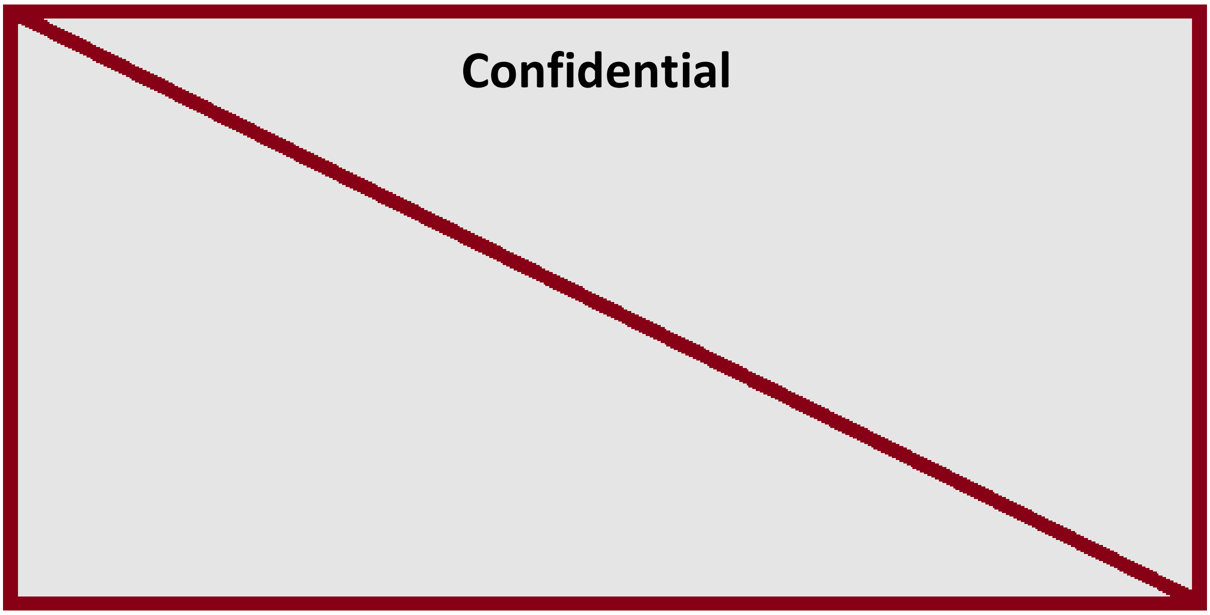


Figure 7.14 - Total Sales volume and trend of all main batteries per week of the last 6 months

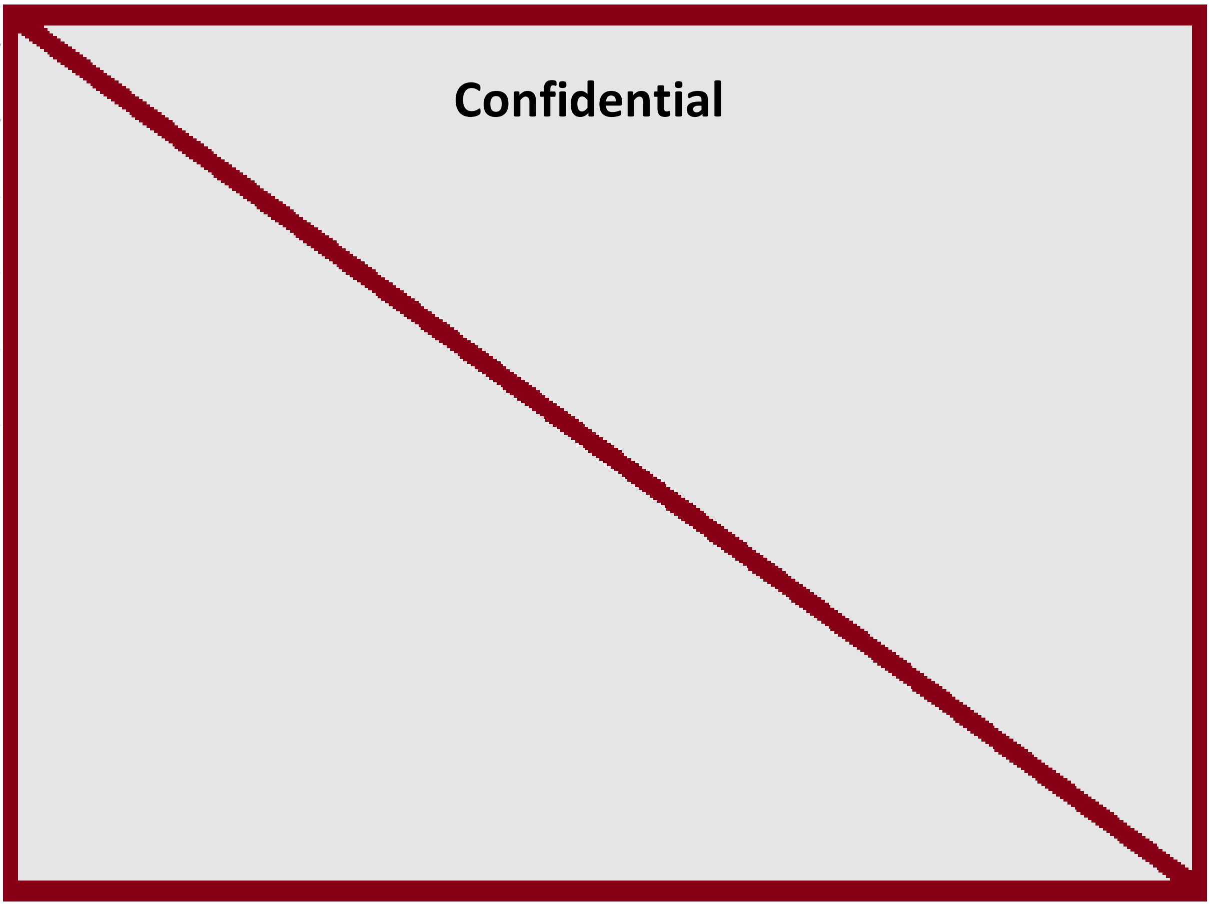


Figure 7.15 - Battery Sales and prognosis per week of the last 2 years

D. Forecasts

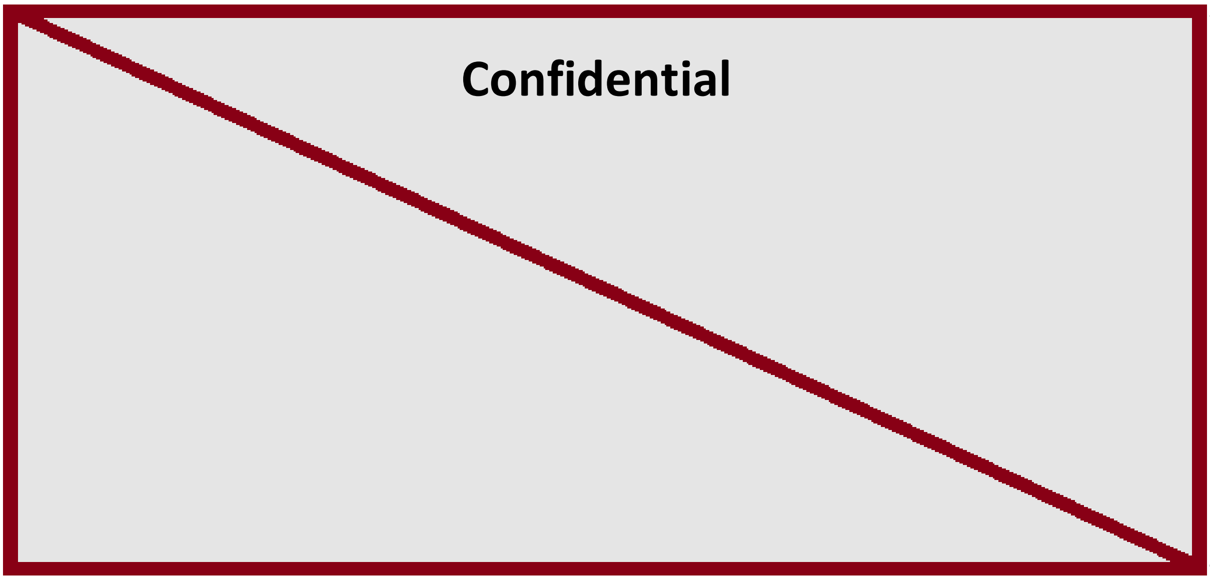


Figure 7.16 -Sales per quarter expressed in cumulative sales Starter (forecasted values in yellow)

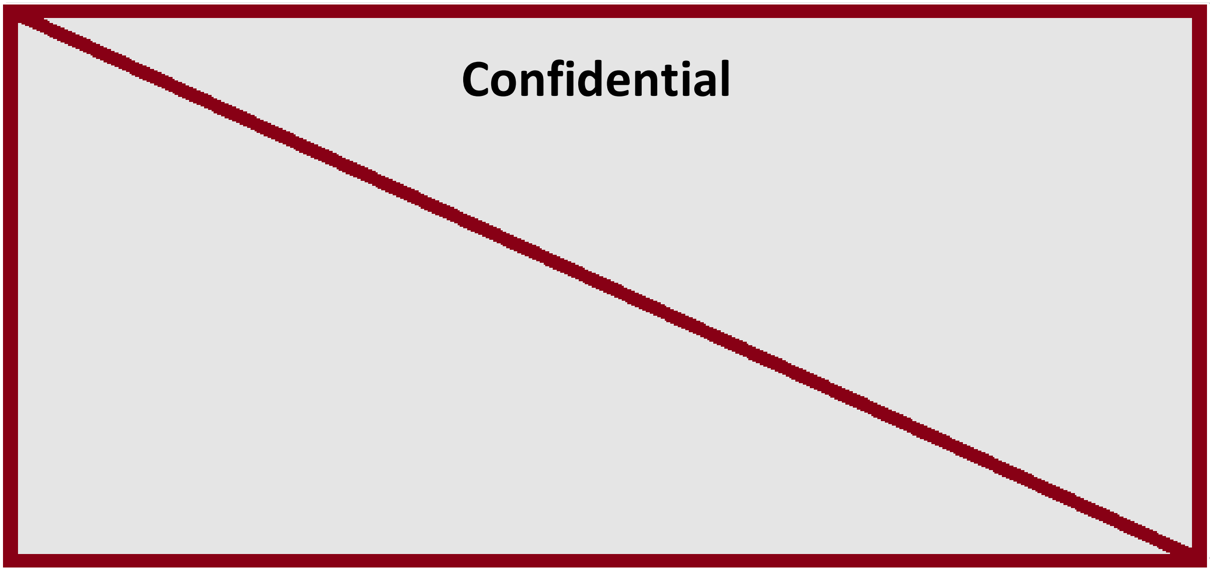


Figure 7.17 - Sales per quarter expressed in cumulative sales Traction (forecasted values in yellow)

E. Literature research search terms

We mainly used Scopus to search for reliable sources. Besides, we found literature and presentation slides from the courses of the bachelor and master study Industrial Engineering & Management. In the following Table the main search terms per section are given.

Table 7.2 - Literature search terms in Scopus

Section	Search terms
Section 3.1 – Forecasting	• "Forecast methods" AND "Manufacturing" • "Time series" AND "level" AND "trend" • "Forecasting" AND "Intermittent demand" • "Long term forecasting" AND "BASS" • "BASS" AND "Extensions"
Section 3.2 – Reduction of flows	• "Lean" AND "Transportation Waste" • "Backtracking" AND "bypassing" • ("JUST-IN-TIME" OR "JIT") AND "Planning and Control" • "Kanban" AND "CONWIP" AND "POLCA" AND "Comparisons"
Section 3.3 – Facility planning,	• "Layout Design" AND "Facility Planning" • "Muther" AND "Systematic Layout Planning" • "Layout Performance" AND "Manufacturing"

F. New production concept results

F.1 Bin storage per station

Station	Number of small bins at production	Number of medium bins at production	Number of large bins at production
Starter BP	82	0	0
Epsilon BP	14	0	8
Sub 1 station	10	0	0
Smart Starter	12	0	6
Battery lid Assembly	10	0	0
PCB Support	6	2	0
Sub 2 station	16	14	0
Starter HE	104	0	0
Epsilon HE	22	0	8
Traction HE	10	7	3
105E	40	0	0
Total	**326**	**23**	**25**

Figure 7.18 - Bin storage per station

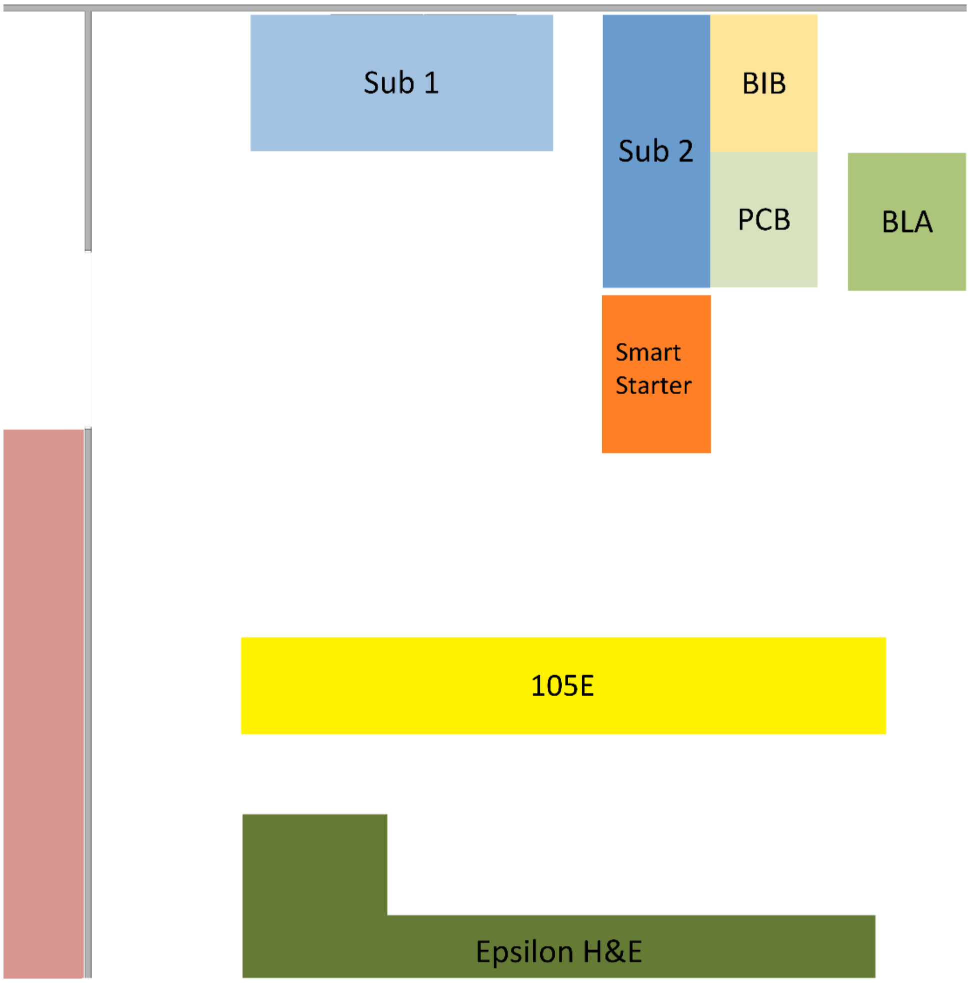
F.2 Weighted Average Cost of Capital

The weighted average cost of capital, often abbreviated as *WACC*, is the weighted average costs of a company's assets. The *WACC* is often used in firm to look for expansion opportunities or possible acquisitions. The WACC is calculated using formula F.1.

$$\mathrm{WACC} = \mathrm{V/E} * \mathrm{Re} + \mathrm{VD} * \mathrm{Rd} * (1 - \mathrm{Tc}) \qquad (\mathrm{F.1})$$

Where *Re* is the cost of equity; *Rd* is cost of debt; E is the market value of the firm's equity; *D* is the Market value of the firm's debt; *V* is the total market value of the firm's financing; and *Tc* is the corporate tax rate.

F.3 Placement of the 105E and Smart Starter in the current situation



G. Floorplans of the current situation

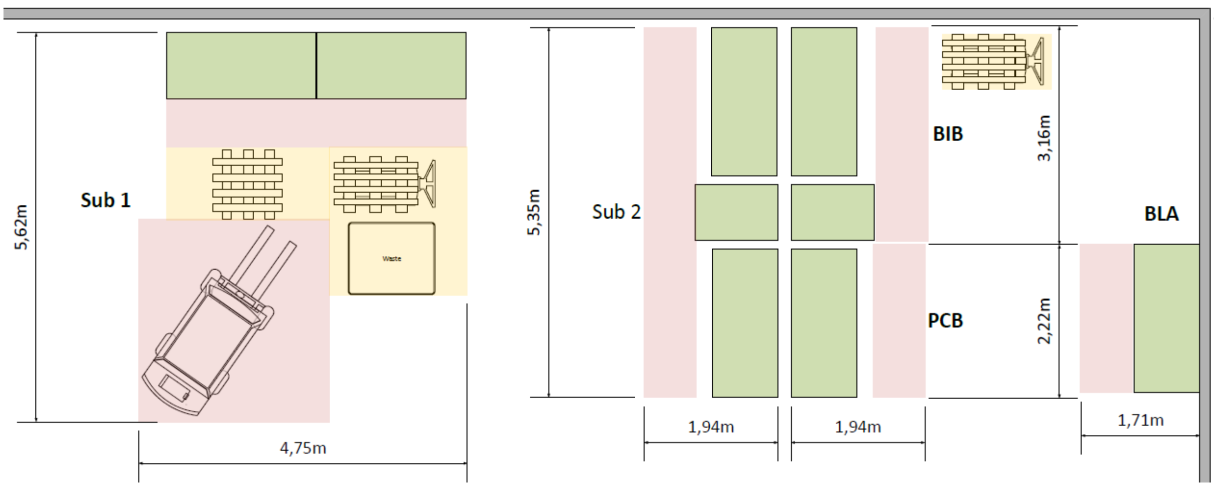


Figure 7.19 - Sub 1, Sub 2, BIB, PCB and BLA current floorplans

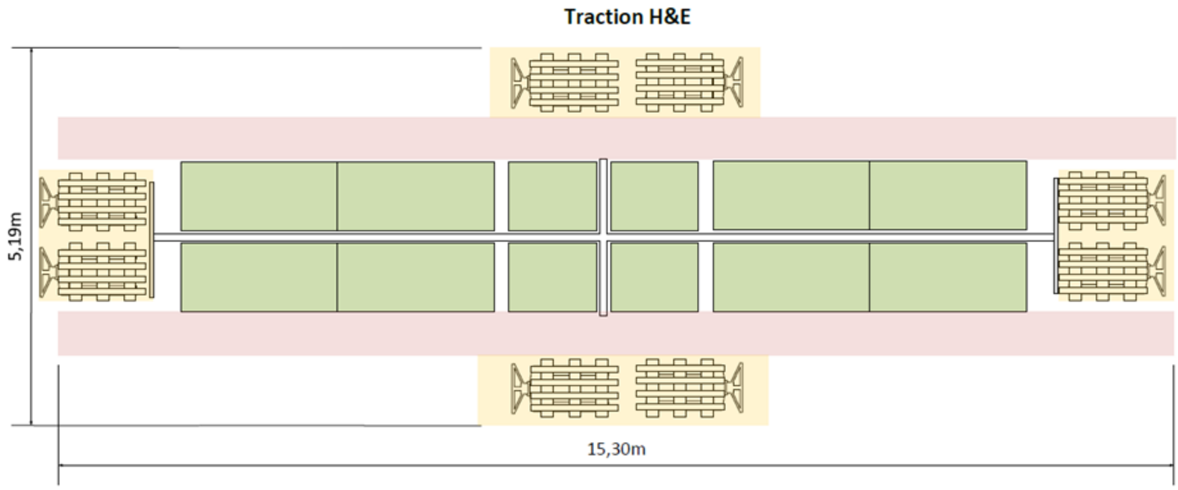


Figure 7.20 - Traction H&E current floorplan

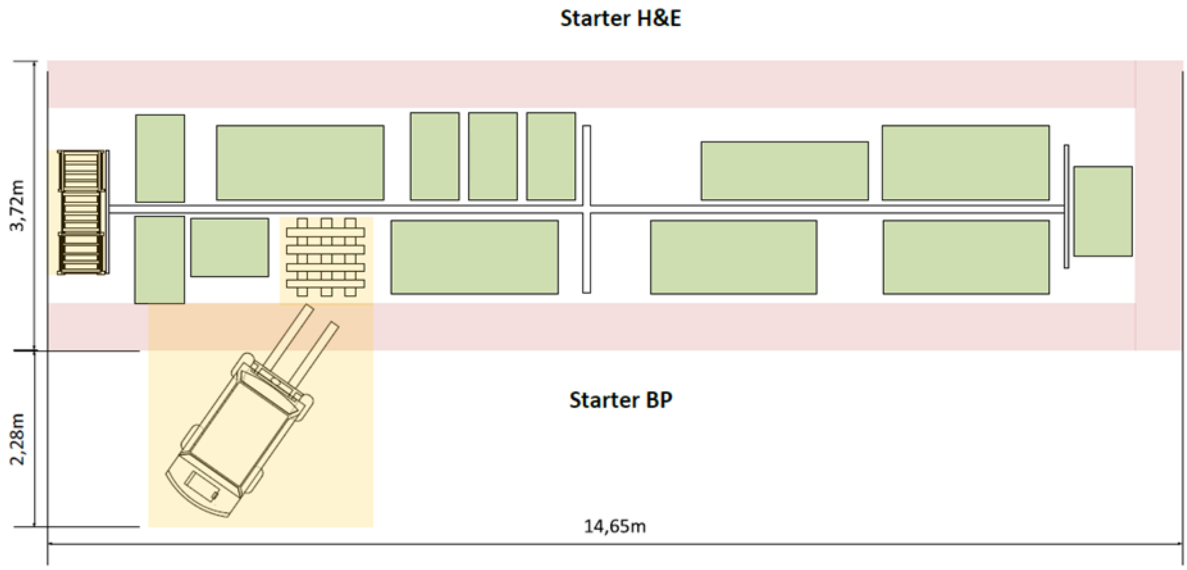


Figure 7.21 - Starter BP & Starter H&E stations current floorplans

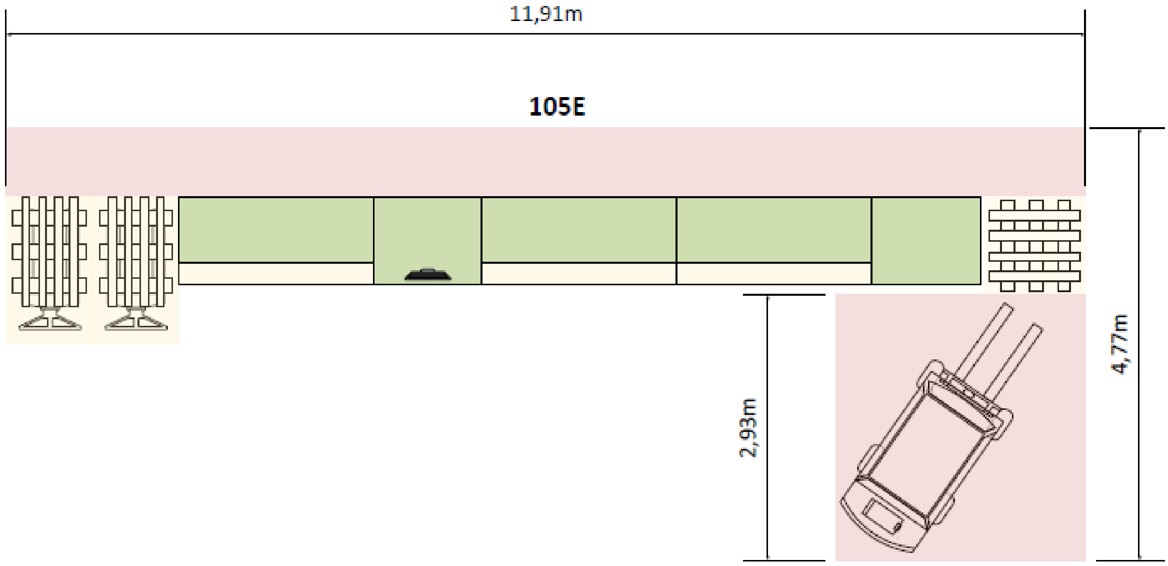


Figure 7.22 - 105E Station floorplan

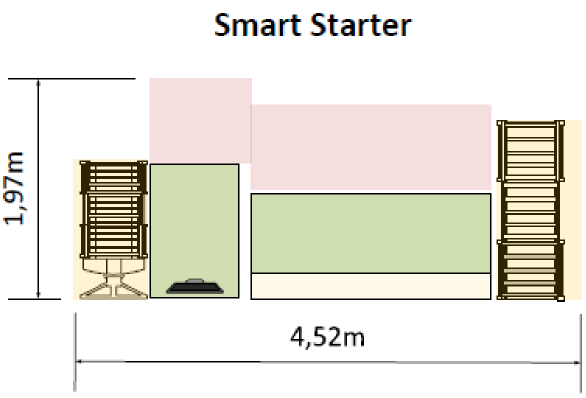


Figure 7.23 - Smart Starter floorplan

H. Layout Model

H.1 MIP model

In chapter 6 we discussed of using a MIP model for solving our layout problem. Unfortunately the free software that was available didn't support the size of our model. In the beginning of this research we identified 17 departments that where of importance. We could have simplified this problem by reducing the number of department to 6, by grouping the whole departments with the same end products. However, the free solvers could only handle 3 department groups. For that reason we turned to an alternative. Nevertheless, we introduce our custom MIP model:

Parameters:

B_x^L	be the start of the modifiable area (using *x*-coordinates),
B_x^U	be the length of the building (using *x*-coordinates),
B_y^L	be the start of the modifiable area (using *y*-coordinates),
B_y^U	be the width of the building (using *y*-coordinates),
A_i	be the area of the department *i,*
$L^u{}_i$	be the upper bound of department *i*'s length,
$L^l{}_i$	be the lower bound of department *i*'s length,
W_i^U	be the upper bound of department *i*'s width,
W_i^L	be the lower bound of department *i*'s width,
R_1	Y-coordinate of southern warehouse door
R_2	Y-coordinate of northern warehouse door
M	be a large number.

Decision variables:

α_i	be the x-coordinate of department *i*'s centroid,
β_i	be the *y*-coordinate of department *i*'s centroid,
x_i'	be the *x*-coordinate of department *i*'s left side,
x_i''	be the *x*-coordinate of department *i*'s right side,
y_i'	be the y-coordinate of department *i*'s top side,

y_i'' be the y-coordinate of department *i*'s bottom side,

z_{ij}^x be equal to 1 if department *i* is strictly to the east of department *j*, and 0 otherwise,

z_{ij}^y be equal to 1 if department *i* is strictly to the north of department *j*, and 0 otherwise,

S_i^1 be the downwards distance from department *i* to R_1,

S_i^2 be the upwards distance from department *i* to R_2,

S_j^1 be the downwards distance from department *j* to R_1,

S_j^2 be the upwards distance from department *j* to R_2,

$V_{ij}, W_{ij}, U_{ij}, N_{ij}$ be binary help-variables

$$Min\ z = \sum_i \sum_j f_{ij} c_{ij} \left(\left| \alpha_{ij}^{+} - \alpha_{ij}^{-} \right| + \left| \beta_i - \beta_j \right| + U_{ij} * Q_{ij} \right)$$

Subject to $L_i^l \leq (x_i'' - x_j') \leq L_j^u$		for all i
$W_i^l \leq (y_i'' - y_j') \leq W_j^u$		for all i
$(x_i'' - x_j')(y_i'' - y_j') = A_i$		for all i
$B_x^L \leq x_i' \leq x_i'' \leq B_x^U$	**New dimensions, fixed departments in 0 - B_x^L**	for all i, except 1, *
$0 \leq y_i' \leq y_i'' \leq B_y^U$		for all i, except 1, *
$\alpha_i = 0.5x_i' + 0.5x_i''$		for all i
$\beta_i = 0.5y_i' + 0.5y_i''$		for all i
$x_j'' \leq x_i' + M(1 - z_{ij}^x)$		for all i and j, $i \neq j$
$y_j'' \leq y_i' + M(1 - z_{ij}^y)$		for all i and j, $i \neq j$
$z_{ij}^x + z_{ji}^x + z_{ij}^y + z_{ji}^y \geq 1$		for all i and j, $i < j$
$\beta_i < R_1 + M * V_{ij}$	**If B>r then V=1 else V=?->0**	for i>2, j = 1, 2
$\beta_i > R_2 - M * W_{ij}$	**If B<R then W=1 else W=?->0**	for i>2, j = 1, 2
$\beta_j < R_1 + M * V_{ji}$	**If B>r then V=1 else V=?->0**	for j>2, i = 1, 2
$\beta_j > R_2 - M * W_{ji}$	**If B<R then W=1 else W=?->0**	for j>2, i = 1, 2

$V_{ij} * W_{ij} = U_{ij}$	If r<(Bi or Bj)<R then Uij =1 else 0	For all *i* and *j*
$S_i^2 = R_2 - \beta_i$	Length S2 calculation, when dep. *j* is fixed	for i>2
$S_i^1 = \beta_i - R_1$	Length S1 calculation, when dep. *j* is fixed	for i>2
$S_i^1 < S_i^2 + M * N_{ij}$	Check which Length is shorter, when dep. *j* is fixed	for i>2
$S_j^2 = R_2 - \beta_j$	Length S2 calculation, when dep. *i* is fixed	for j>2
$S_j^1 = \beta_j - R_1$	Length S1 calculation, when dep. *i* is fixed	for j>2
$S_j^1 < S_j^2 + M * N_{ij}$	Check which Length is shorter, when dep. *i* is fixed	for j>2
$Q_{ij} = S_i^1 * (\beta_j - R_1)(N_{ij} - 1) + S_i^2\,(R_1 - \beta_j)N_{ij}$	Set Q when dep. *j* is fixed	for i>2, $j = 1, 2$
$Q_{ij} = S_j^1 * (\beta_i - R_1)(N_{ij} - 1) + S_j^2\,(R_1 - \beta_i)N_{ij}$	Set Q when dep. *i* is fixed	for j>2, $i = 1, 2$
$\alpha_i, \beta_i \geq 0$		for all i
x_i', x_i'', y_i', y_i''		for all i
$z_{ij}^x, z_{ij}^y, V_{ij}, W_{ij}, U_{ij}, N_{ij}\ \ 0/1$ integer		for all i and j, $i \neq j$

H.2 Simulated Annealing

Often when optimization problems need a lot of computation time, some calculations could even take millions of years to complete. For these so-called NP-hard problems, heuristics are used to find a solution in finite time. Heuristic solutions, however, are often local optima: an optimum within a neighbour set. This contrasts with a global optimum, which is the optimal solution of all neighbour sets). In order to approximate the global optimum in finite time, we introduce Simulated Annealing. Simulated Annealing is a generic, probabilistic, heuristic optimization algorithm used to find an approximation of the global optimum of a given function in a large search space (Aarst & Korst, 1988). Although, simulated annealing still does not guarantee the absolute optimum, the search space exceeds that of a standard heuristic that only finds local optimum.

Simulated annealing uses a cooling schedule to find a broader spectrum of results. Normally when a heuristic performs for example a swap and the results is better than the current solution, the new swap gets accepted, this isn't any different with Simulated annealing. The difference lies in when not to accept a solution. When in a standard heuristic the result gets worse, it won't get accepted, the previously found result won't change. In simulated annealing, however, a worse solution can still be accepted. Simulated Annealing introduces a cooling parameter which is linked to a probability function. The probability function gives the chance of accepting a worse solution. The cooling parameter decreases over time, such that the probability of accepting a worse solution also decreases over time. The probability of accepting a worse solution also depends on how much worse the solution is, the higher the difference between the current and new result, the lower results gain higher probabilities. In formula H.1 the calculation of the probability function is given.

$$\chi(c) = e^{\frac{A-B}{c}} \tag{H.1}$$

Here *A* is the current solution and *B* is the new solution in case of minimization problems. Note that the probability is calculated when B is higher than A, thus A-B is always negative, which subsequently means χ becomes lower when *B-A* becomes more negative. In maximation problems, it should be the other way around. Next, *c* is the cooling parameter. The cooling parameter decreases over time by multiplying it each iteration with a factor α. Factor α depends on how many iterations (or computation time) one wants. The cooling parameter starts at a temperature (c_{start}) at which almost all (reasonable) solutions get accepted. Naturally, the cooling parameter also has a stopping point (c_{stop}) at which, the probability function approaches 0. Because of this, in the end, no worse solution gets accepted. With accepting worse solutions in the beginning of the algorithm, we search for an optimum in a larger search space.

H.3 Facility and Space-filling curve configuration

H.4 Results of 24 experiments

Scenario 1: 2019-2020			
Exp Nr	**Score**	**SFC**	**Algorithm**
1	28867.78	1	Group swap
2	29003.96	2	Group swap
3	28690.54	3	Group swap
4	28866.21	4	Group swap
5	29212.96	1	8 & 16 segment swap
6	29131.68	2	8 & 16 segment swap
7	28897.98	3	8 & 16 segment swap
8	29134.99	4	8 & 16 segment swap
9	29148.81	1	3-opt
10	29193.42	2	3-opt
11	29005.17	3	3-opt
12	29012.82	4	3-opt

2022-2023			
Exp Nr	**Score**	**SFC**	**Algorithm**
13	33648.95	1	Group swap
14	33648.68	2	Group swap
15	33475.06	3	Group swap
16	33479.66	4	Group swap
17	33622.65	1	8 & 16 segment swap
18	33659.5	2	8 & 16 segment swap
19	33462.99	3	8 & 16 segment swap
20	33760.88	4	8 & 16 segment swap
21	33920.87	1	3opt
22	33931.43	2	3opt
23	33949.57	3	3opt
24	33882.34	4	3opt

H.5 Relaxed layouts

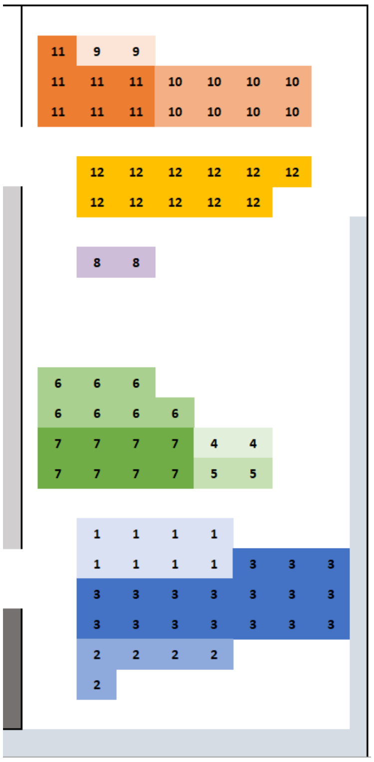


Figure 7.27 - Scenario 1: Best objective function (relaxed)

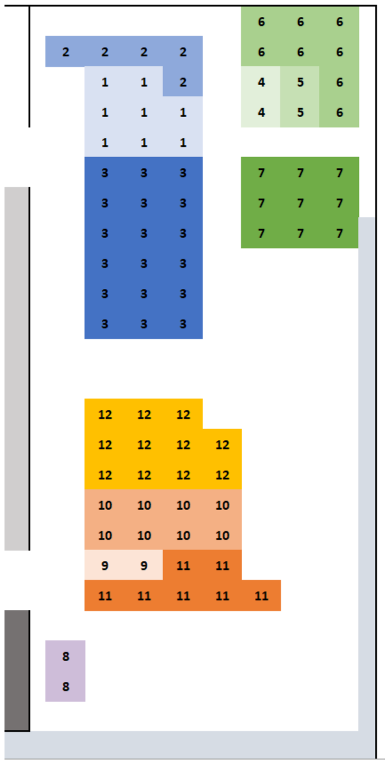


Figure 7.24 - Scenario 1: Layout chosen by Super B (relaxed)

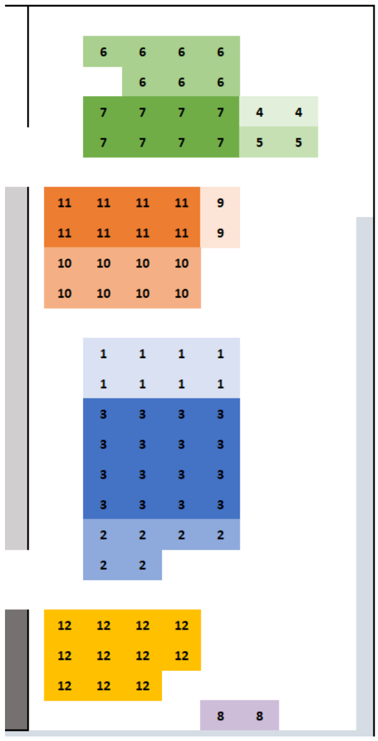


Figure 7.26 - Scenario 2: Best objective function layout (relaxed)

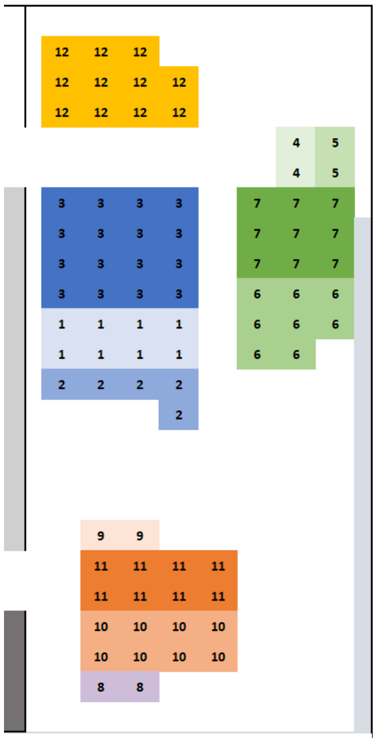
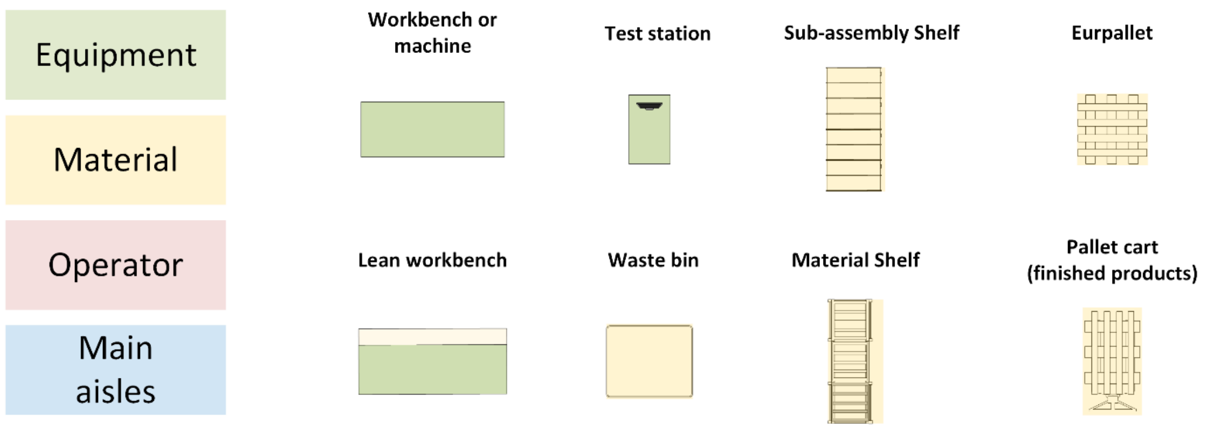


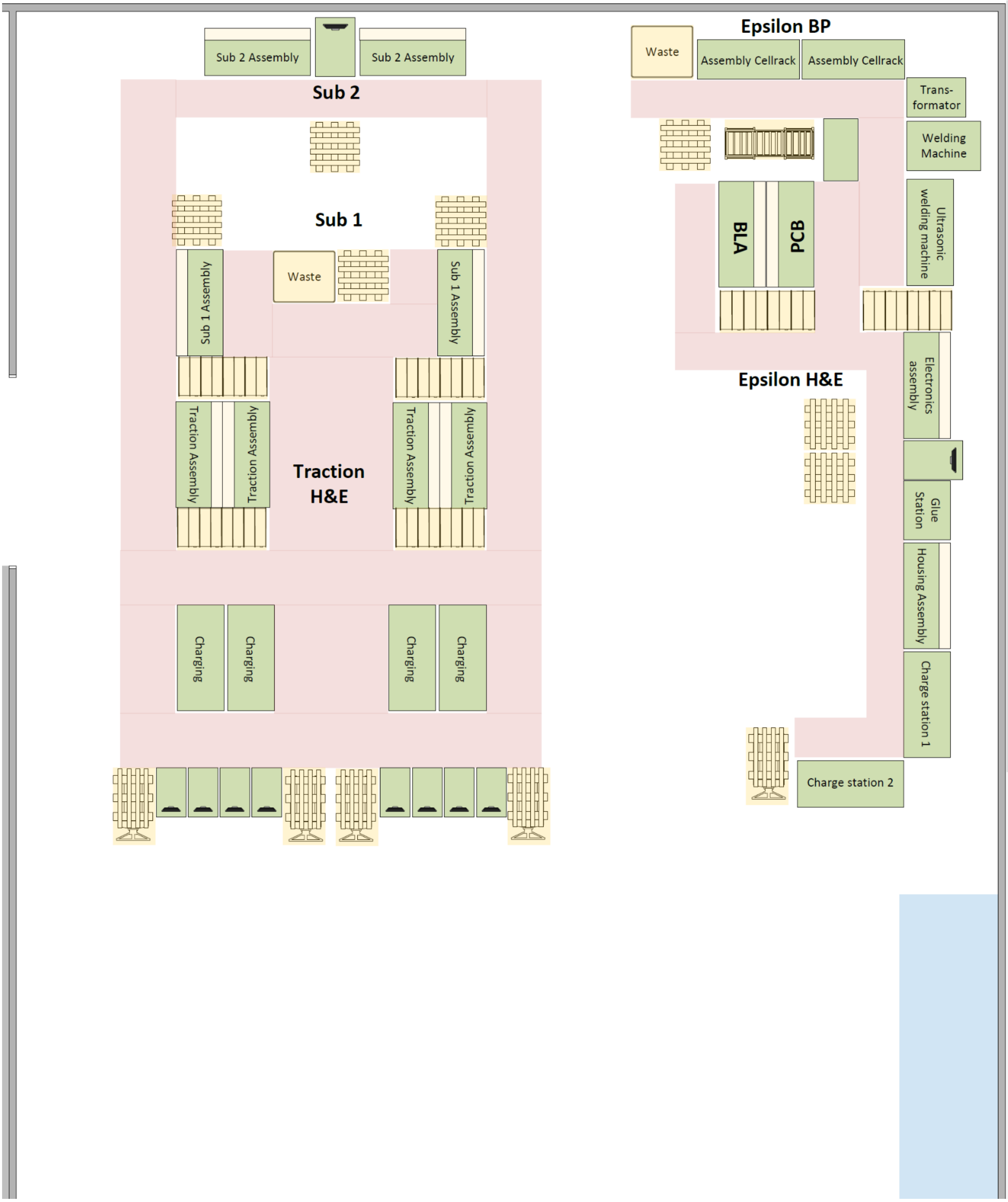
Figure 7.25 - Scenario 2: Layout chosen by Super B (relaxed)

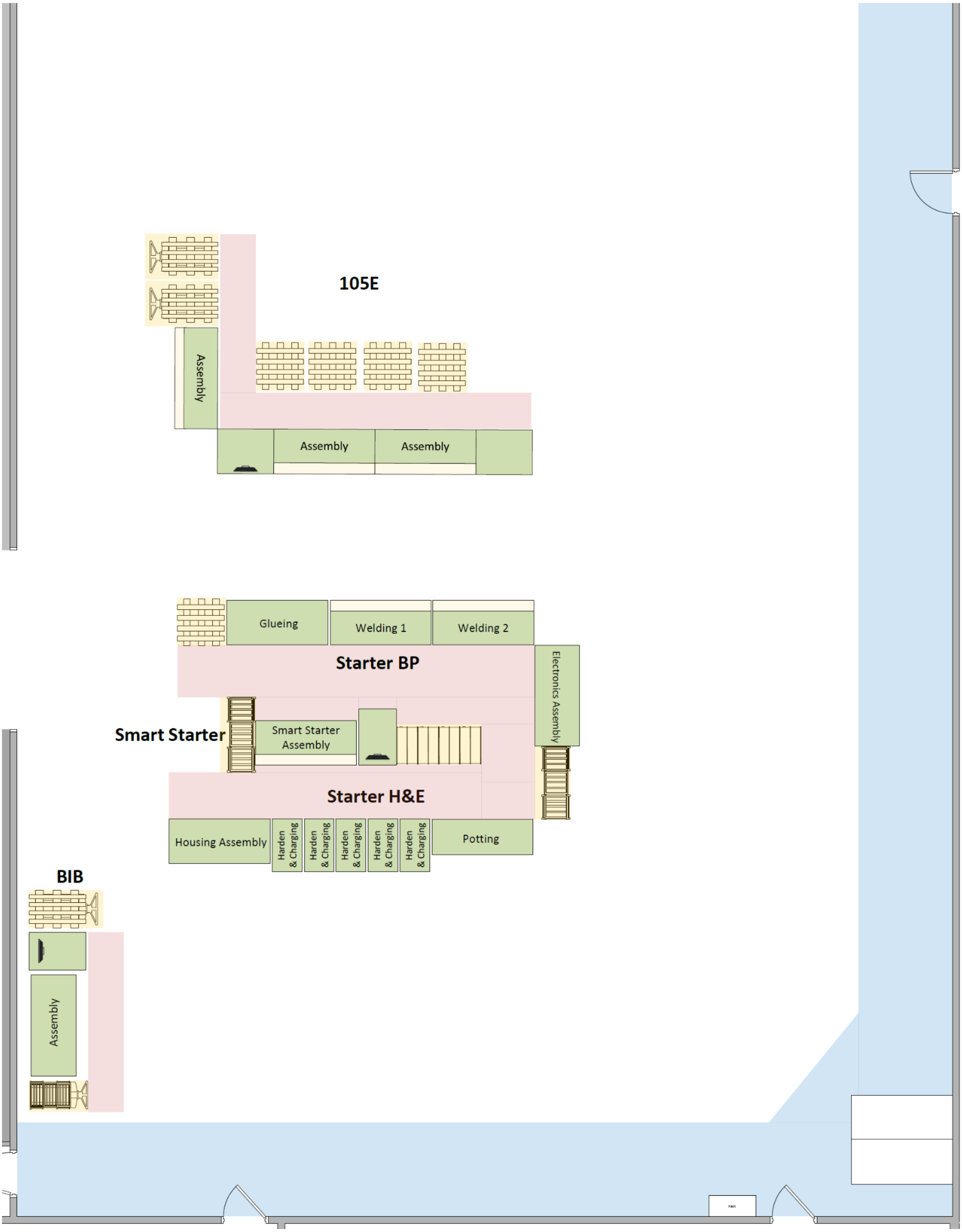
I. Detailed layouts

I.1 Detailed layouts legend

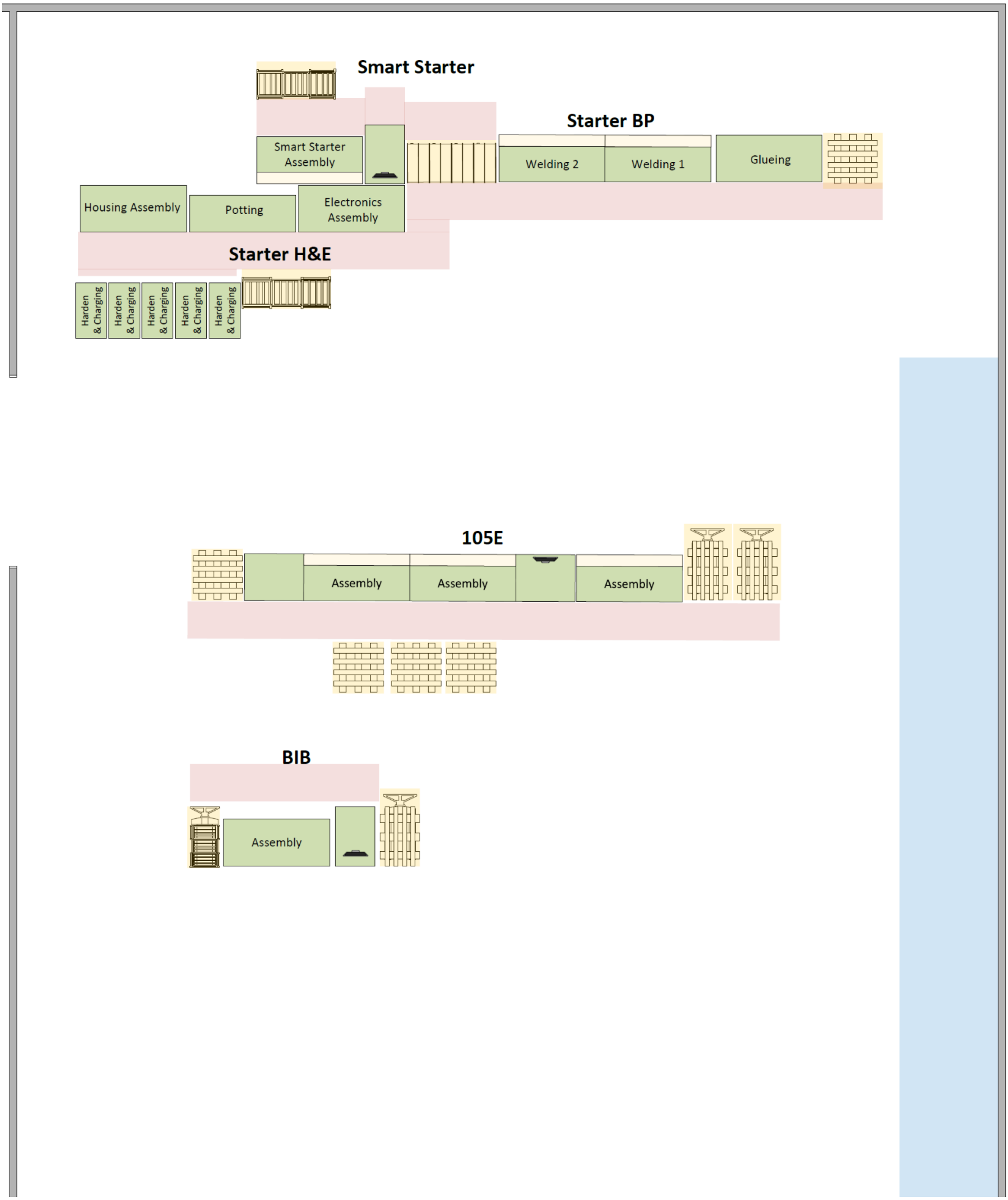


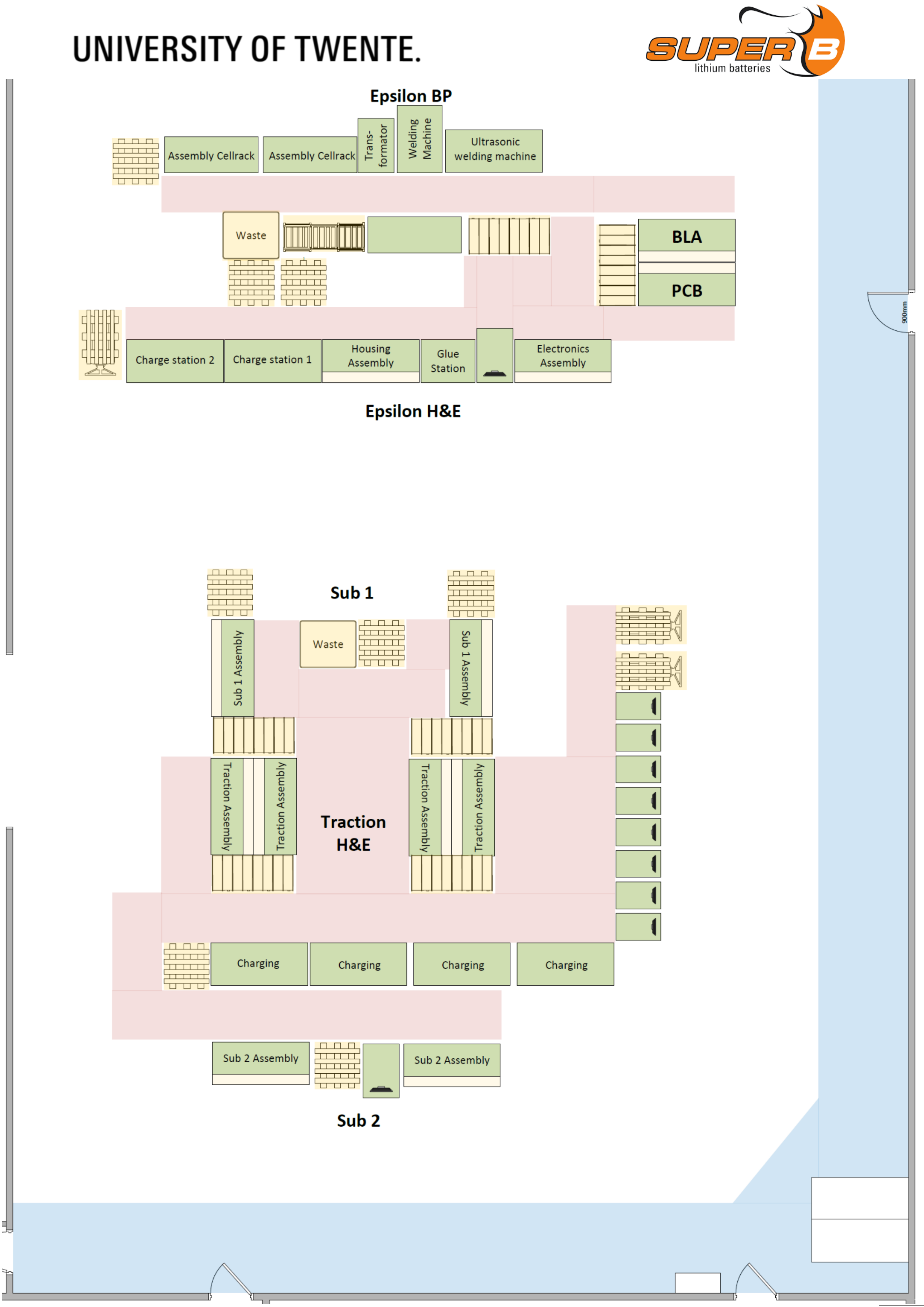
I.2 Scenario 1: Layout with the best objective function



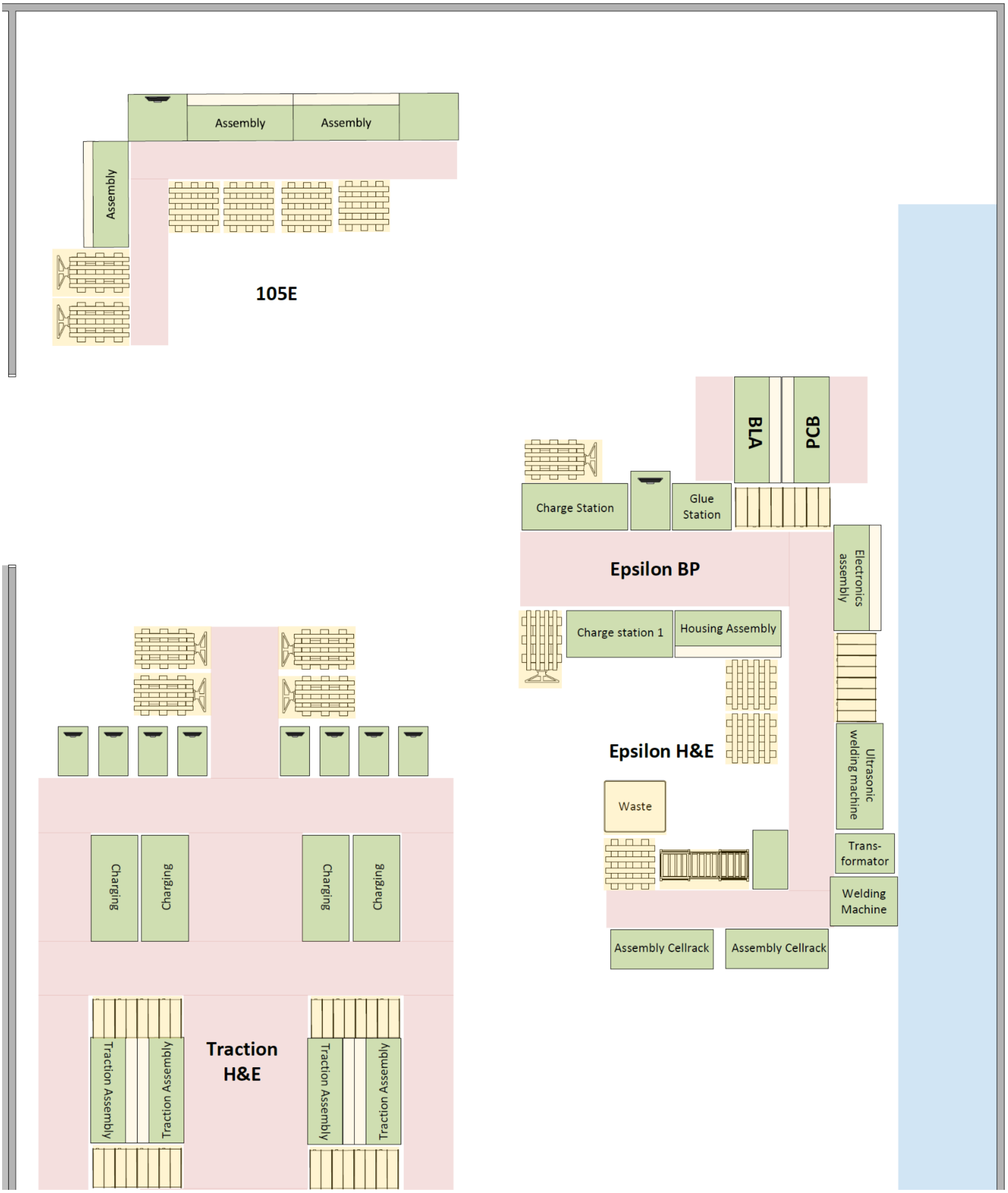

105E
Assembly
Assembly
Assembly
Glueing
Welding 1
Welding 2
Starter BP
Electronics Assembly
Smart Starter
Smart Starter Assembly
Starter H&E
Housing Assembly
Harden & Charging
Harden & Charging
Harden & Charging
Harden & Charging
Harden & Charging
Potting
BIB
Assembly

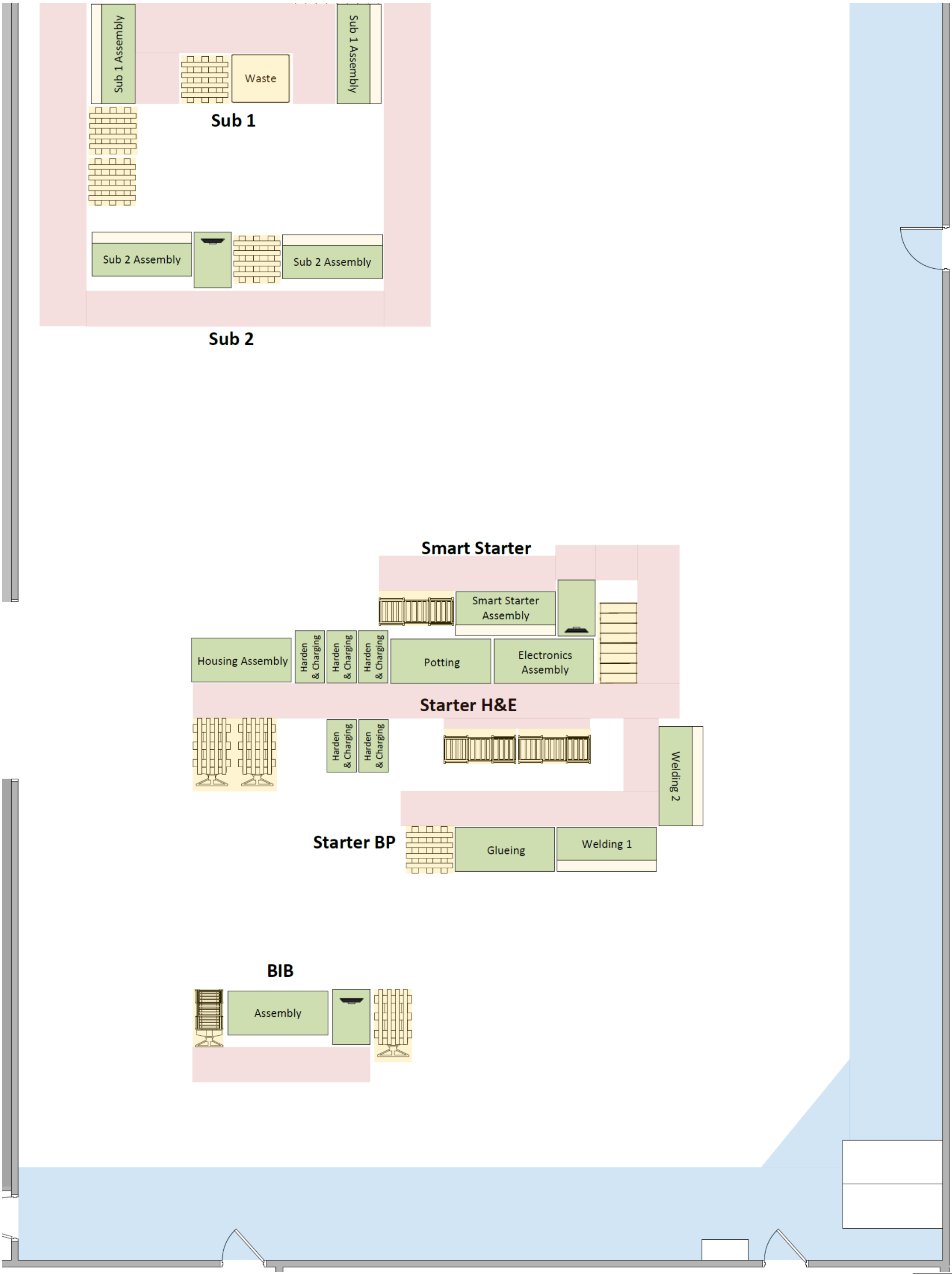
I.3 Scenario 1: Layout chosen by Super B



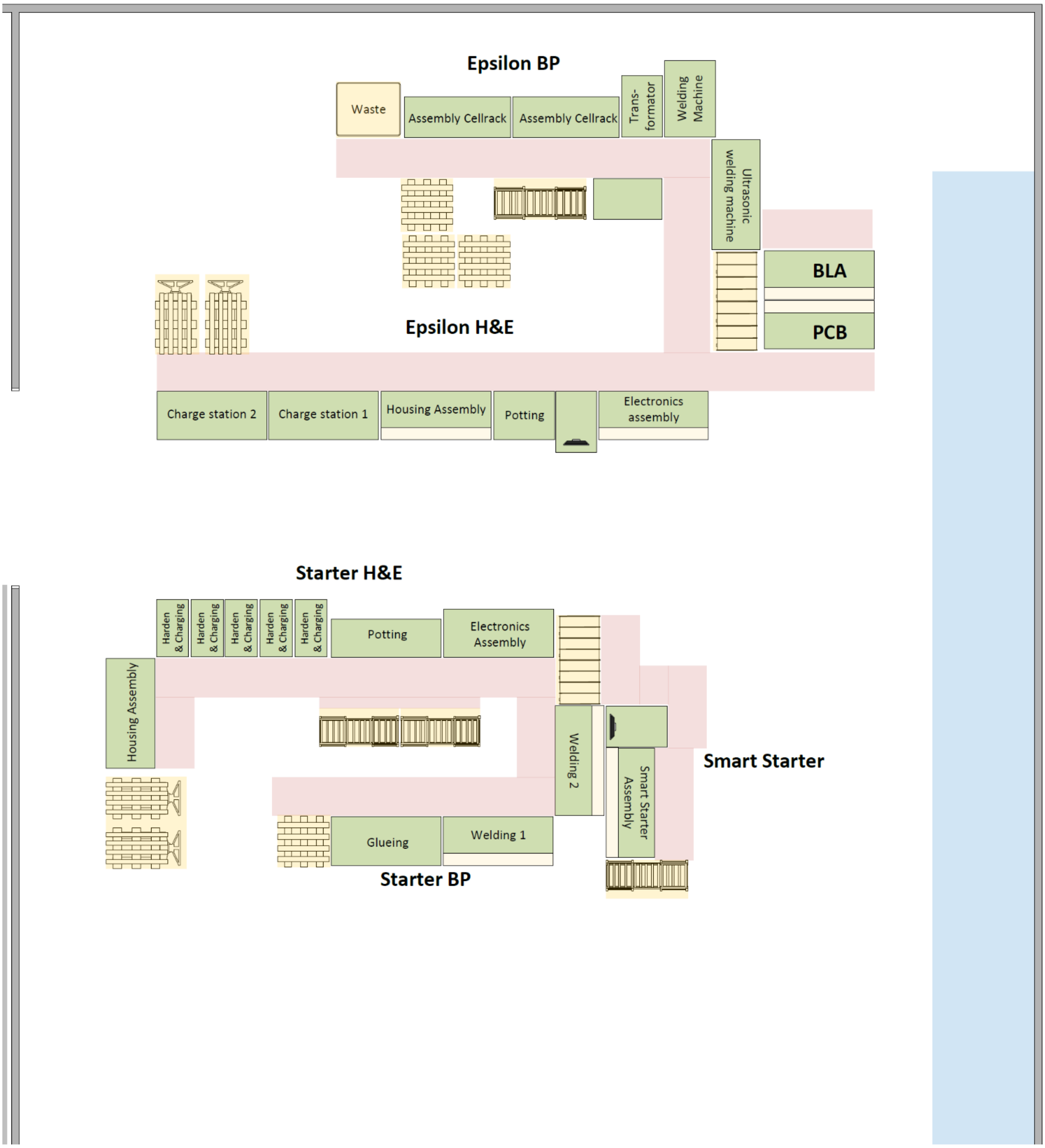

Epsilon BP
Assembly Cellrack
Assembly Cellrack
Trans-formator
Welding Machine
Ultrasonic welding machine
Waste
BLA
PCB
Charge station 2
Charge station 1
Housing Assembly
Glue Station
Electronics Assembly
Epsilon H&E
Sub 1
Sub 1 Assembly
Waste
Sub 1 Assembly
Traction Assembly
Traction Assembly
Traction H&E
Traction Assembly
Traction Assembly
Charging
Charging
Charging
Charging
Sub 2 Assembly
Sub 2 Assembly
Sub 2
900mm

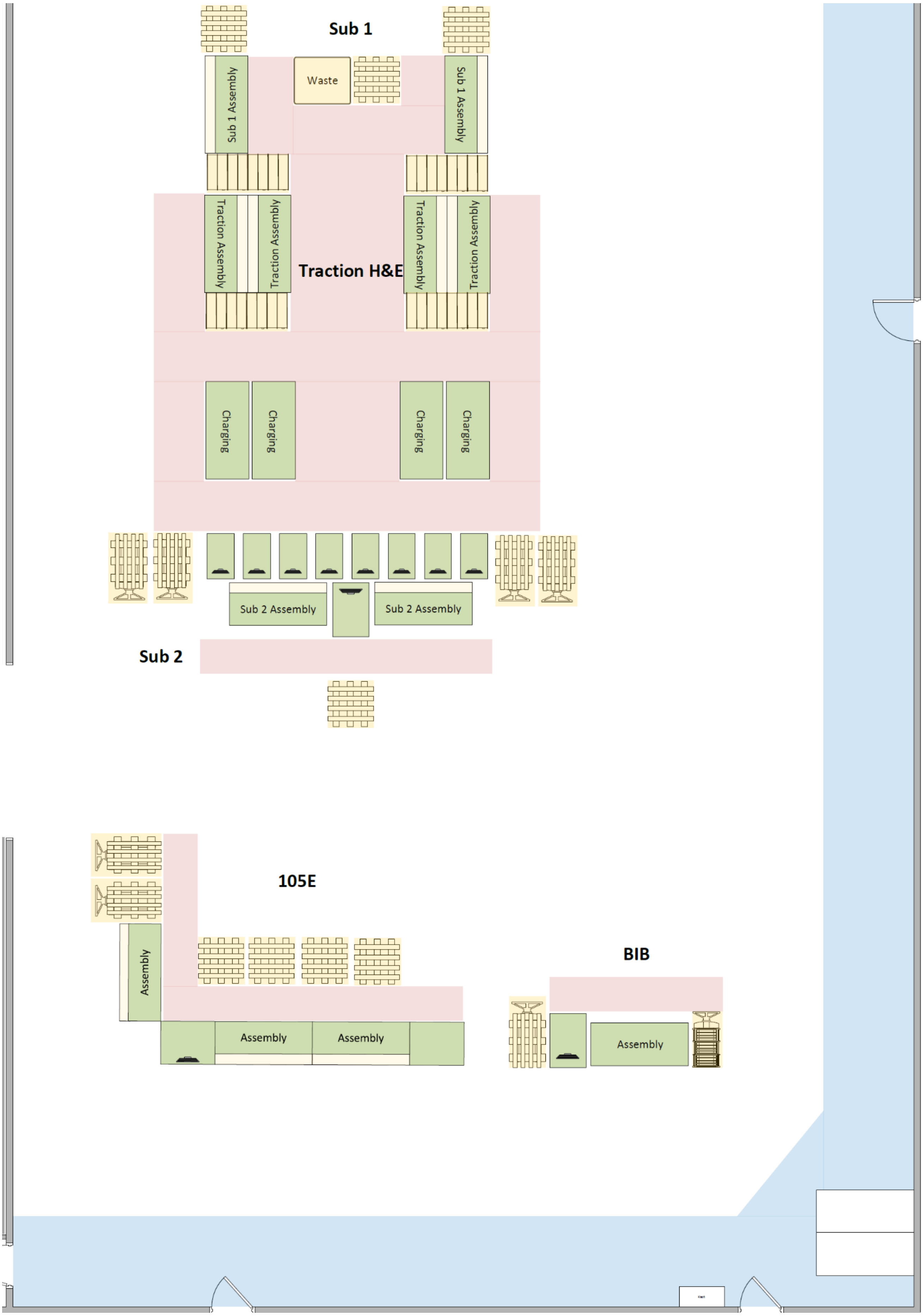
I.4 Scenario 2: Layout with the best objective function



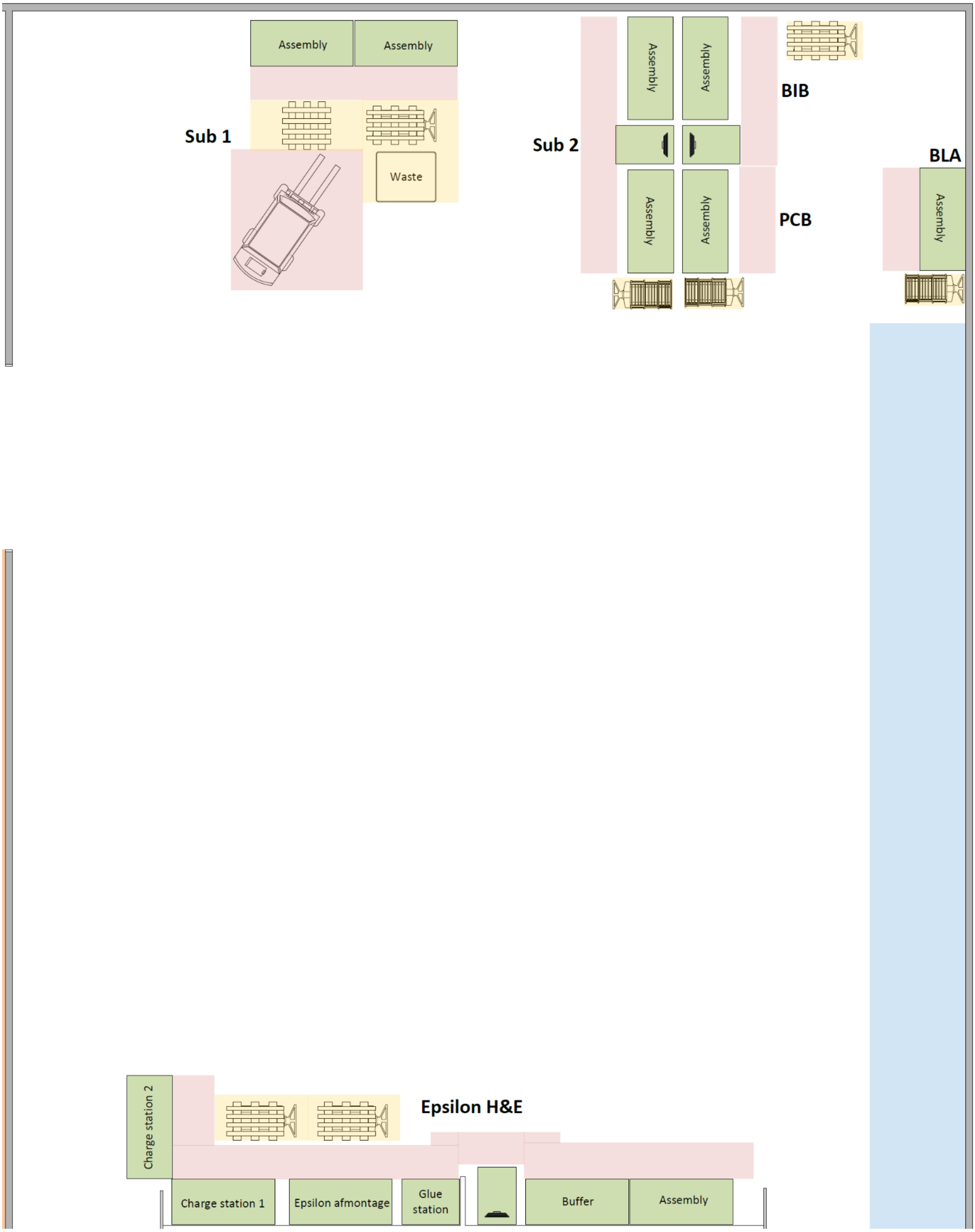

Sub 1 Assembly
Waste
Sub 1 Assembly
Sub 1
Sub 2 Assembly
Sub 2 Assembly
Sub 2
Smart Starter
Smart Starter Assembly
Housing Assembly
Harden & Charging
Harden & Charging
Harden & Charging
Potting
Electronics Assembly
Starter H&E
Harden & Charging
Harden & Charging
Welding 2
Starter BP
Glueing
Welding 1
BIB
Assembly

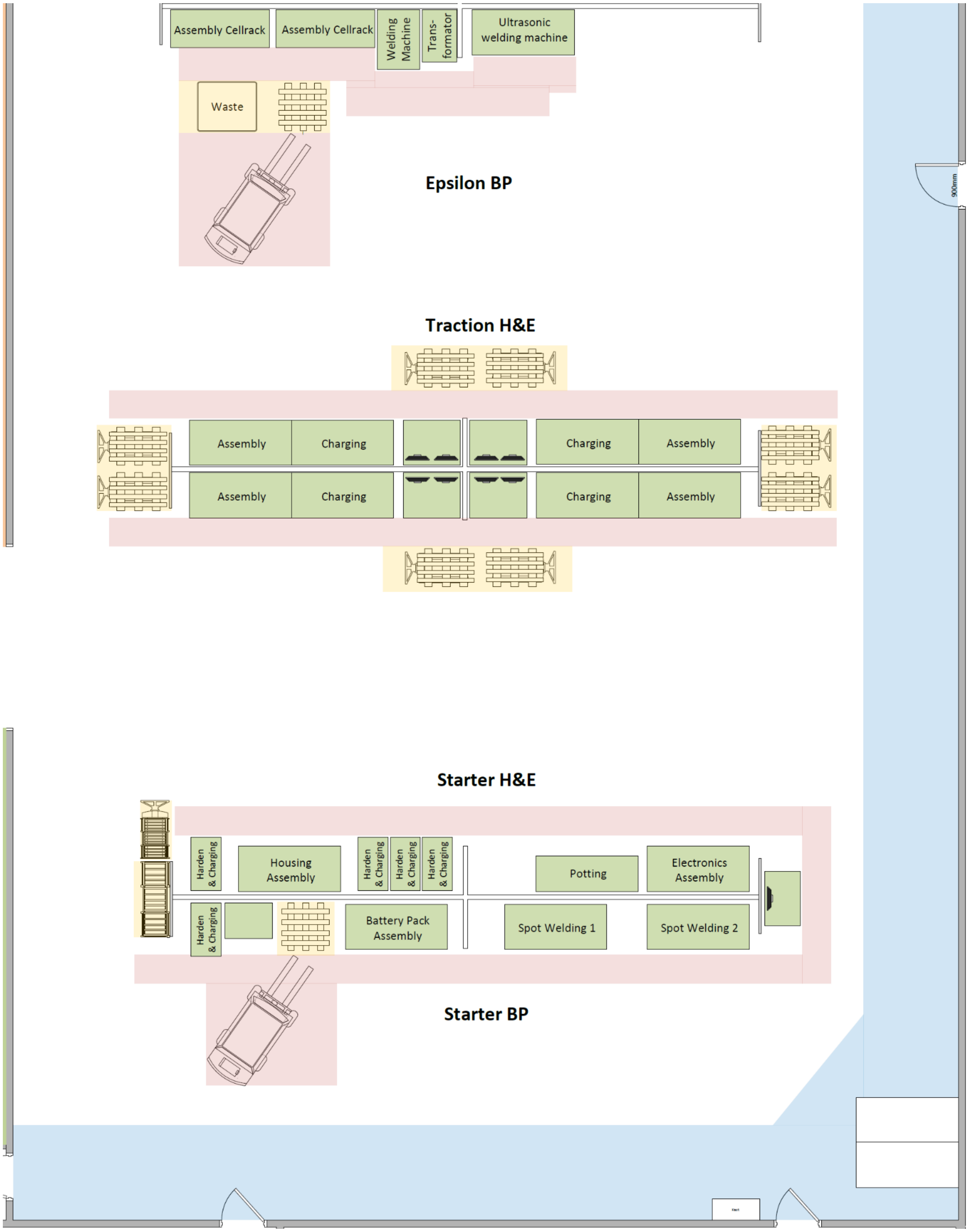
I.5 Scenario 2: Layout chosen by Super B




Sub 1
Waste
Sub 1 Assembly
Sub 1 Assembly
Traction Assembly
Traction Assembly
Traction H&E
Traction Assembly
Traction Assembly
Charging
Charging
Charging
Charging
Sub 2 Assembly
Sub 2 Assembly
Sub 2
105E
Assembly
Assembly
Assembly
BIB
Assembly

I.6 Current layout




Assembly Cellrack
Assembly Cellrack
Welding Machine
Trans-formator
Ultrasonic welding machine
Waste
Epsilon BP
Traction H&E
Assembly
Charging
Charging
Assembly
Assembly
Charging
Charging
Assembly
Starter H&E
Harden & Charging
Housing Assembly
Harden & Charging
Harden & Charging
Harden & Charging
Potting
Electronics Assembly
Harden & Charging
Battery Pack Assembly
Spot Welding 1
Spot Welding 2
Starter BP