POLITECNICO DI TORINO

Master of science program in MECHANICAL ENGINEERING

Master's Degree Thesis

Design and Simulation of battery swapping system for electric vehicles

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Contents

Abstract

As the economy develops and the people's living standards improve, the number of cars in the world have maintained rapid growth, which is threatening the ecological environment. Driven by the energy conservation policy, renewable energy generation will get rapid development. Thus, the electric car is the best complement to renewable energy. Growing of the electric car can not only satisfy the needs of people's travel but also promote energy conservation and emissions reduction, which can be the strategic direction of the development of the auto industry.

In this article, we will discuss a delay charging model: A part of batteries in day high electricity consumption period will not be charged until low electricity consumption period arrives. Thanks to low unit electricity cost in night, this strategy could decrease the operating cost and power grid load pressure.

This sizing and operation of this station, call Battery Swap Station (BSS), will be investigated in this work through a configurable simulation model able to generate different scenarios taking as a case study the city of Turin. By changing the number of charging bay and stored batteries, finally, find a proper warehouse design to satisfy the customers’ requirements.

The simulation model has been implemented in FlexSim, a 3D simulation modeling and analysis software. Series of experiments are then designed and simulated in order to show which factors could affect the performance of the station. Afterwards, several useful performance measures will be tracked and analyzed. Finally, through a series of simple standards, the most suitable solution is provided to the case study.

1. Introduction

The thesis focuses on the smart management of the batteries of electric cars arriving at the Battery Swap Station (BSS). A simulation-based approach has been used to better evaluate the performance measures of the system involved and to have suitable and more realistic criteria to encourage the automotive industry and private companies to invest in this field. The simulation model includes from when the discharged battery arrives at the station to when the charged battery comes out.

The thesis is composed of six chapters and it structured as follows:

Chapter 1

This chapter mainly introduces the concept and provided a brief description of the battery swap method, focus on analyzing the advantages and disadvantages of this method, Introduction to the development of the electric vehicle market and business models.

Chapter 2

This chapter mainly points out the current situation regarding battery swapping technologies, implementations, and techniques available today, taking into account the relevant studies and research in scientific literature.

Chapter 3

This chapter mainly contains the description of the scenario considered in this work to design and simulate. Moreover, some assumptions have been formulated for model building.

Chapter 4

This chapter mainly provides a comprehensive explanation of the model built in FlexSim simulation software, as well as the proposed plan of experiments and the performance measures observed.

Chapter 5

This chapter mainly highlights the results obtained by the simulations with regard to the benchmarks, feasibility and performance of the proposed model, finding also the best solution between different alternatives. At the end, a further improvement to the model is provided.

Chapter 6

This chapter mainly draws the conclusions, makes it clear what are the thesis findings and addresses proposals for future related developments and work ideas.

1.1 The electric Vehicle Market

As the report [1], Not only it's the key technology to reduce the air pollution in densely populated areas by using electric vehicles. But also in order to achieve energy diversification and reduce greenhouse gas emissions. There are many benefits of using electric vehicles, such as zero exhaust emissions, compare to the internal combustion engine vehicle it has higher efficiency, and the higher potential for reducing emissions combined with the low-carbon power sector. These goals have become the main driving force for countries to promote the construction of domestic power transmission systems. So far, there are17 countries have announced they would achieve zero-emission vehicles or phase out the internal combustion engine vehicle by 2050. France responded to this goal first to incorporate this intention into law in December 2019, with a time-Schule of 2040.

Policies related to electric vehicles are determined by the status of the electric vehicle market and technology. Drawing up the vehicle and its charger standards are prerequisites for electric vehicle widely promoting. In the early years, the public procurement schemes (such as schemes for buses and municipal vehicles) have the double benefit. On one hand, it can demonstrate the advanced technology to the public and, on the other hand, provide the opportunity for public authorities to lead by such example. Besides, they also allow the industry to produce and deliver huge number of orders to increase economies of scale, which the emerging economies can scale up the policy efforts for both new and second-hand vehicles.

Tax rates related to CO_2 emissions could be benefit for improving the electric vehicle promotion. Fiscal incentives which focusing on the vehicle purchase, as well as complementary measures (such as road toll discounts and low-emission regions) are quite effective to attract drivers and businesses to choose electric options. Meanwhile, local governments play an important role in implementing measures and proposing to enhance the value of electric vehicles. The mention of local low-emission and zero-emission regions could affect the purchase decisions far beyond than just those regions, which it may also influence the relative value of ICEs and electric powertrains.

Many car sellers offer some discount, like subsidy and tax reduction, for the customers want to but electric cars as well as support the plans which aim to deploy charging infrastructure. It's more and more common to see the encouraging schemes of charging facilities and the "EV-readiness" of buildings in the provisions of building codes to are becoming more common. Also, it is similar for mandates to build the charging infrastructure along road and refueling stations.

In 2019, the sales of electric cars topped 2.1 million globally, which is shown in fig.1.1.1, and it increases the stock to 7.2 million electric cars. Electric cars, which accounted for almost 2.6% of global vehicle sales and nearly 1% of global vehicle stock in 2019, generates around 40% of year-on-year increase. With the development of technological progress in the electrification of all kinds of vehicles and the market, electric vehicles are promoting significantly. In recent years, the meaningful policies have played an important role in stimulating the electric-vehicle promotion in the markets. In 2019, it could be realized that the policies which relying more on the regulatory and other structural measures now, including zero-emission vehicles and fuel economy standards, have shown an obviously signals to the automotive industry and consumers.

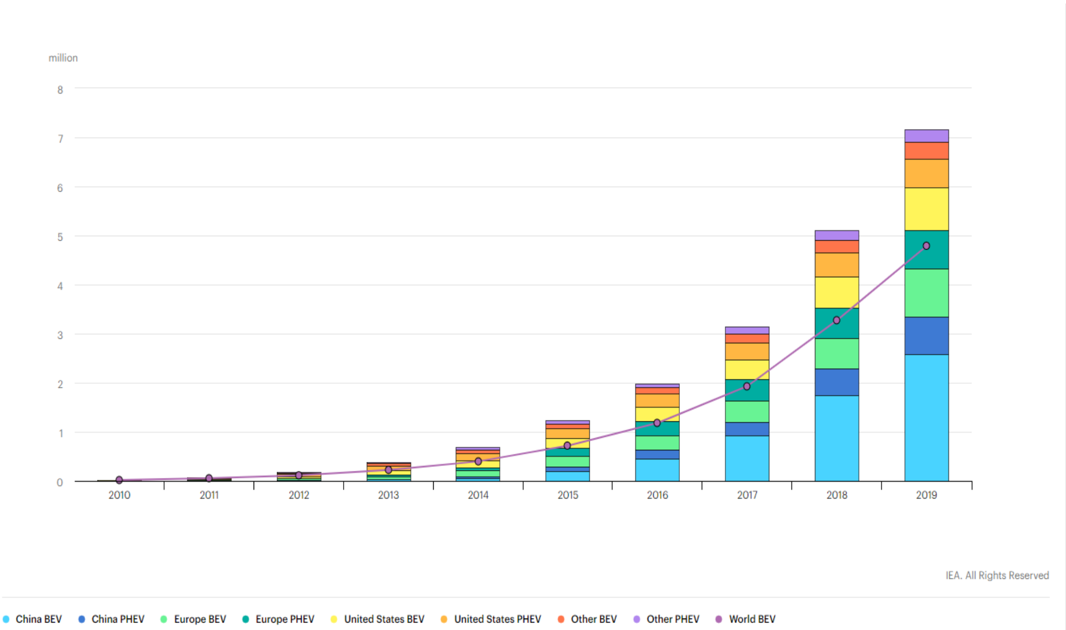

Fig.1.1.1 Sales of electric cars

In the first half year, after it entering the commercial markets, electric car sales increased rapidly. There were only about 17 000 electric vehicles around the world in 2010. While in 2019, the number had jumped to 7.2 million, in which nearly 47% of them were accounted in China. What's more, there are already nine countries owned more than 100 000 electric vehicles on the road and at least 20 countries owned the market shares over 1%.[2]

In 2019, the electric vehicle sales are 2.1 million which represent a 6% growth comparing with the previous year, but lower in year-on-year sales growth since 2016 with a percentage at least 30%. The reasons could be generated as follows:

- Contracted of Car markets. Total passenger car sales quantities were decreased in 2019 among many important countries. In the 2010s, some fast-growing EVs markets, such as China and India, had lower sales for all types of vehicles year by year. Under the situation of sluggish sales in 2019, the 2.6% market shares of electric vehicles in worldwide car sales have constituted a record. In particular, China (at 4.9%) and Europe (at 3.5%) both achieved new records in electric vehicle market shares this year.

- Purchase subsidies were reduced in the markets. China cut nearly a half of subsidies of electric car purchasing due to the change of policy in 2019 which is a step of a gradual weaken process of direct incentives set out since 2016. The US federal tax credit program was also executed for many electric vehicle producers such as General Motors and Tesla, which the tax credit is applicable up to a 200 000 sales cap for each company. These actions have contributed to a significant decrease in electric vehicle sales in China the United States over the year. With almost 90% of global electric vehicle sales, China, Europe and the United States, all made a great influence to EVs global sales and which overshadowed the 50% sales increase in Europe in 2019, thus it's indeed slow the growth trend.

- Consumers' expectations of further technology improvements. Nowadays, consumers' role in the electric car market is evolving from the adopters (only few people accept it) or technophile purchasers in the early stage to modern adopters (it's already common in our life). The significant improvements in technologies and a richer variety of electric car moldings in the markets have stimulated customers;' purchase decisions all the time. Some certain EVs' battery pack owned a higher energy density in 2018-19 versions than 2012 version, which the increasing is around 20~100%. Furthermore, with the increasing performance, the battery costs have decreased more than 85% since 2010. The delivery of new popular models such as the Tesla Model 3 caused a huge sales increase in 2018 among some key markets such as the United States. The automakers have shown a diversified concept of electric cars and many of which are expected in later years. For the next five years, automakers plan to publish nearly 200 new electric car models, with the influence of the improvements in technologies and cost reductions, consumers would be placed in the position that being attracted by these products, however, wondering if it would be a good way to wait the "latest model".

What's more, the Covid-19 pandemic have affected global electric vehicle markets. Based on sales data, the passenger car market would have a big shrink until the waves leave. Considering the situations, we are facing, the markets and industry earn the supporting policies. Particularly in China and Europe, their markets have both national and local subsidy schemes in place, in which, China has extended its subsidy scheme until 2022. Besides, China and Europe also recently published strengthened and extended New Energy Vehicle and CO2 emissions laws respectively. Finally, there are signals show that recovery measures for the Covid-19 will continue to focus on vehicle efficiency performance in general, particular in electrification field.

1.2 Charging EV's Battery Pack

Meanwhile, as the adoption rate of EVs is increasing, the demand of the fast and convenient energy refueling services is growing. There is no doubt that, the refueling method is a key in EVs. Main EVs refueling technologies are performed by some charging methods:

Plug-in method.

Also called wire charging method which is the most mature charging method. With the development of EVs, the charging piles are becoming more and more common around the world. The principle of wire charging is the same to the way people charging the phone, connect the battery in EVs with power grid through the wire and plug. The grid is a high voltage AC source, the current is converted to DC through AC/DC and then adjust voltage by DC/DC, finally transmit to batteries for charging.

The most obviously advantage of plug-in method is the easy technology and low cost of infrastructures. However, the customers have to cost 30 mins to several hours for charging in parking condition. Although the fast-charging technology has significantly shortened the time required, but the high charging current during fast charging also affect the life of batteries.

Wireless charging method [3]

It uses the principle of transformer as shown in *fig 1.2.1* and *fig1.2.2.* in transmitting side, AC mains from the grid is converted into high frequency AC through AC/DC and DC/AC converters. And in receiving sides, the receiving coil, typically mounted underneath the vehicle, converts the oscillating magnetic flux fields to high frequency AC and then converted to a stable DC supply, which is used by the on-board batteries.

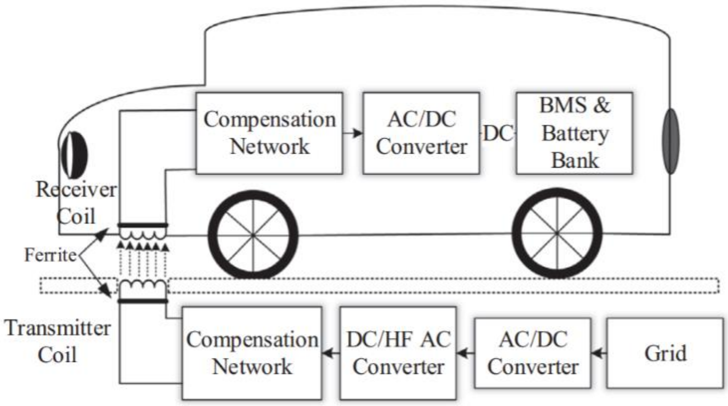

Fig.1.2.1Basic block diagram of static wireless charging system for EVs

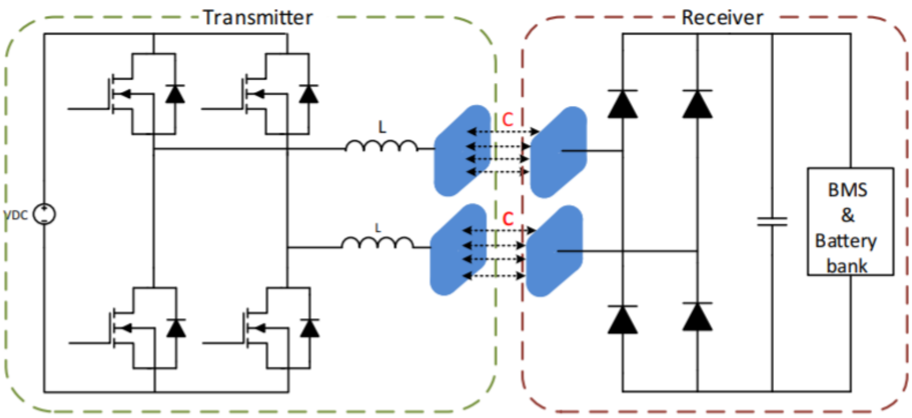

Fig.1.2.2 Schematic diagram of Wireless Power Transfer.

Nowadays, the wireless method has many achieving technologies, such as Capacitive wireless power transfer and Inductive power transfer. Comparing with plug-in method, wireless charging method have more advantages in the simplicity and reliability. While the wireless method also has the limitation which they can only be utilized when the car is parked or in stationary modes, such as in car parks, garages, or at traffic signals. It still has some challenges, such as electromagnetic compatibility issues, limited power transfer, bulky structures, shorter range, and higher efficiency.

Battery-swapping method.

Compared to the long charging time of existing charging methods (usually in hours), with the battery-swapping method, an EV can swap its depleted battery (DB) for a fully-charged battery (FB) one within several minutes [4]. The swapped DBs can be gathered and recharged at a centralized battery charging station (BCS), which thus forms a gigantic battery energy storage system. It is believed that if appropriately planned and managed, the battery-swapping technology can not only benefit EV owners with a fast energy refueling service [5], but it can also provide enormous flexibility for grid operators to perform critical tasks such as load balancing and renewable energy integration, thus reducing carbon emissions [6]and improving the efficiency and stability of power systems [7].

Although the Battery swapping method has great potential, there are many aspects should be discussed before it is popularized. Different from the other two method, besides the technology problems, the operating strategies, the construction planning and some other commercial issues are also very important in achieving process. And these has been popular questions for studying in recent years.

Internationally, the reference standard for charging stations (wired or inductive) is defined by the International Electrotechnical Commission (IEC) and is the IEC 61851-1 standard. This regulation specifies the general characteristics of charging systems, including charging and connection modes and safety requirements.

Nowadays, in the current market, Li-Ion batteries have the biggest market segment in equipping electric vehicles. Moderate energy consumption (14.7 kWh/100 km), continuous decline of the cost price, advanced manufacturing technology, increased cycle life, low weight and high energy storage potential make Li-Ion batteries an optimal choice in this field.

Figure 1.2.3 presents a comparative market price evaluation of different electric vehicles, depending on battery capacity:

Renault Twizzy	Li-Ion Battery	Capacity: 6.1 kWh	Power: 4 kW/5 CP	Price: 6750 €
Hyundai Ioniq	Li-Ion Battery	Capacity: 28 kWh	Power: 88 kW/118 CP	Price: 29500 €
Nissan Leaf	Li-Ion Battery	Capacity: 30 kWh	Power: 80 kW/107 CP	Price: 30680 €
VW E-Golf	Li-Ion Battery	Capacity: 24.2 kWh	Power: 100 kW/136CP	Price: 37590 €
Tesla Model S	Li-Ion Battery	Capacity: 100 kWh	Power: 193 kW/259CP	Price: 123000€

Figure 1.2.3 Comparative evaluation of different electric vehicle market cost.

There are mainly two charge sources for EV battery: Alternating current (AC), which the AC source usually generates from the distributed power grid. Direct current (DC), which the DC source usually generates by an DC generator or AC source with rectifiers. (Figure 1.2.4).

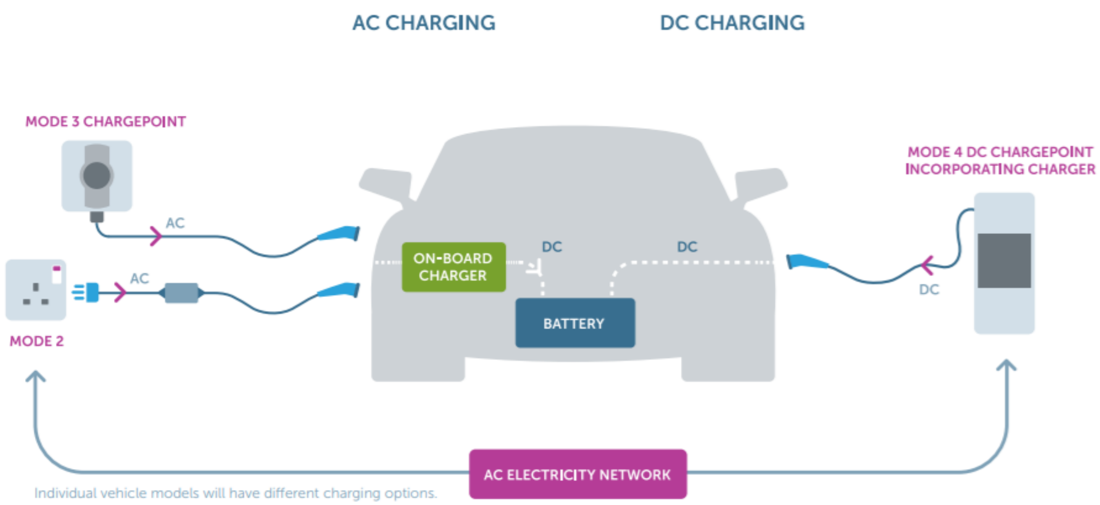

Figure 1.2.4. Charging equipment for AC and DC types[8]

The AC source, comparing with DC source, is a low power charging system. Usually, the power of AC charging system would be lower than 22kW. Considering the vehicle battery could only be charged directly by DC, an AC/DC conversion block is required to convert alternative current to direct current. The AC/DC conversion block usually consist of a rectifier that achieving a function of converting, a DC/DC convertor for reducing the charging voltage to a proper value for battery and some other parts like fuse. In this way, the charging station acts like a gasoline station. The AC charging can be both single-phase source (usually the voltage is 230V) or three-phase source (usually the voltage is 400V). Generally, the chargers integrated in EVs are not all the same, some accept higher powers (e.g. 22 kW - 32A 400V) and others accept lower powers (e.g. 3.7 kW - 16A 230V).

Besides, the effective charging power is not only judged by the source power, in fact, it depends on both the power of the source and the maximum power accepted by the on-board charging system. For example, considering the AC source max power is 40kW, if the source is used to charge a low power accept charging system (e.g. 3.7kW) the max power for charging process would be 3.7 kW. And the limits of the accept power for charging system usually depends on the precision electronic components, like Triode.

The DC source, plays a role of fast charging system, generally will have a charging power furthermore than AC system. This charging methods is more complex and expensive due to its high operating power and high charging current. Although DC generates a fast-charging process, in order to avoid overstressing the battery and extend the life of battery, the charging sometimes will be limited to 80% of battery capacity.

As it is mentioned above, the charging time is very important, which it depends on many factors. In detail, the charging time firstly affects by charging rate of system, which it is calculated from the current and the voltage. Second, the capacity of battery is another main factor represents how much energy store in the battery. The other factors include temperature, the system resistance have smaller influence on it.

According to the factors and parameters of the system, we can estimate the charging time for completely charging a battery.

$$\overbrace{\frac{UBC\ (kWh) - ABC(kWh)}{MPBC\ (kW)}}^{\text{Amount of charge required (kWh)}} = ECT\ (hrs)$$

Where:

UBC is the Usable Battery Capacity

ABC is the Actual Battery Capacity

MPBC is the Maximum Power of the Battery Charger

ECT is the Estimated Charging time

Usually, we do not talk about how much quantity of energy (kWh) it's already charged, instead, State of Charge (SoC) is used to present the percentage of available electrical energy exist in battery. The battery pack of an electric car is never used 100%. The usable capacity is less than the full capacity of the battery (it corresponds to about 90% of the total capacity) due to safety reasons such as maintain a correct battery temperature.

Also, the charging rate does not always behave constantly or at its maximum rate. Considering the two different charging phases: constant current charging and constant voltage charging. Constant current charging phase charges the battery fast with high power, and when SoC is about 90%, it would be constant voltage charge and the charging speed will decrease. Charge same SoC, the latter phase will cost more time. So, 90% is also a proper value to decrease the charge time.

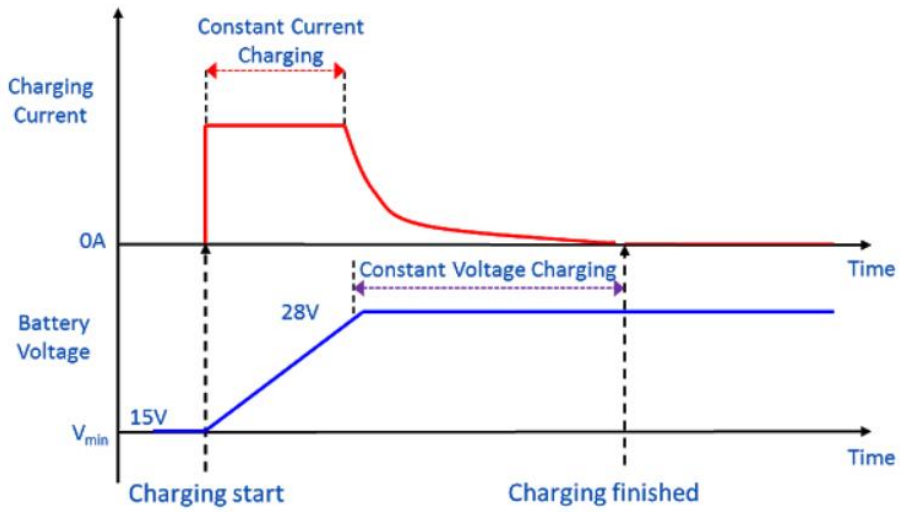

Figure 1.2.5. Constant current charge phase and Constant voltage charge phase.

Although EVs all have these factors that affect time cost for charging the battery, the impact of each factor is different for different kind of vehicle make and model. Indeed, since battery pack sizes vary considerably between EVs, charge times will vary accordingly. According to the calculation from Locardo[9], we can have a general view about charging time for some common vehicles.

Brand and Model	Number of Battery Pack Cells	Nominal capacity [Ah] & Voltage [V] of each cells	Battery Pack Weight [kg]	Battery Pack Capacity [kWh]	Energy Density [Wh/kg]	Maximum power of the on-board battery charger [kW]	Estimated Charging Times [hrs] for a full charge (0% → 100%)
Renault Zoe Z.E. R110 40	192 in 96s2p configuration	63.4 & 3.8	305	45.6 (available 41)	150.0	Single-phase: up to 7.4; Three-phase: up to 22	2.3 kW -> 24; 3.7 kW -> 14; 7.4 kW -> 7; 11 kW -> 4; 22 kW -> 2
Renault Fluence Z.E.	192 (96s2p configuration) in 48 modules	65.0 & 7.5	290	23.4 (available 22)	80.7	Single-phase: up to 3.7	2.3 kW -> 9.6; 3.7 kW -> 5.9
Nissan Leaf	192 in 96s2p configuration arranged into 24 modules	32.5 & 3.8	209	40.0	188.0	Single-phase: up to 7.4	2.3 kW -> 17.4; 3.7 kW -> 10.8; 7.4 kW -> 5.4
Tesla Model 3	4416 in 96s46p configuration	5.0 & 4.2	480	92.0 (available 75)	191.7	Single-phase: up to 7.4; Three-phase: up to 11	2.3 kW -> 32; 3.7 kW -> 20; 7.4 kW -> 10; 11 kW -> 6.8
Tesla Model S	7104 (6s74p configuration) in 16 modules	3.0 & 3.8	540	81.0 (available 75)	150.0	Single-phase: up to 3.7; Three-phase: up to 11	2.3 kW -> 30; 3.7 kW -> 19; 11 kW -> 6.3
Audi e-tron 55	432 in 36 modules	60.0 & 3.3	700	95.0 (available 83.6)	135.0	Single-phase: up to 7.4; Three-phase: up to 11	2.3 kW -> 41; 3.7 kW -> 25.6; 7.4 kW -> 12.8; 11 kW -> 8.6
BMW i3	96	120.0 & 3.7	278	42.6 (available 42.2)	153.2	Single-phase: up to 7.4; Three-phase: up to 11	2.3 kW -> 16.5; 3.7 kW -> 10.2; 7.4 kW -> 5.1; 11 kW -> 3.4

Figure 1.2.6. Summary of battery packs parameters with charging time[9]

1.3 Motivation and critical issues

In the current charge scheme, we mainly have two ways:

Slow Charging [10]:

Slow charging is typically associated with overnight charging. This is a definition easy to grasp that translates into a six to eight-hour period. Slow charging makes use of the EV or PHEV onboard charger, which is sized based on input voltage from the grid. For example, a 120V, 15A (80%) service would supply a 1.4kW charger, while a 240V, 32A service would supply a 6.6kW charger.

How does this translate into recharging the vehicle battery pack? A PHEV with a 5kWh battery pack, for example, would have a 1.4kW on-board charger that allows complete recharge on the order of five hours. An EV with a 40kWh battery pack might have a 6.6kW charger, which allows complete recharging on the order of six to eight hours, depending on thermal considerations and charge algorithms for the battery chemistry.

Fast Charging [10]:

Fast charging could be defined as any scheme other than slow charging. But the real definition, or set of definitions, is much more complex. *Fig1.3.1* lists a few of the more commonly used terms, which include fast charge, rapid charge, and quick charge. The California Air Resources Board (ARB), in their Zero Emissions Vehicle (ZEV) mandate program, lists a certification requirement for fast charging as a ten-minute charge that enables the vehicle to travel 100 miles.

Type of Charge	Charger Power Level, kW		
	Heavy Duty	SUV/Sedan	Small Sedan
Fast Charge, 10 minutes, 100% SOC	500	250	125
Rapid Charge, 15 minutes, 60% SOC	250	125	60
Quick Charge, 60 minutes, 70% SOC	75	35	20
Plug-In Hybrid, 30 Minutes	40	20	10

Fig1.3.1 Power levels of DC Charging

According to the research [11],[12],[13], fast charge has faster charging speed while sacrifices the life of battery packs. Meanwhile, slow charge benefits to the battery packs' life but cost more time, which the long charge time will make users dissatisfied. As we can see both two charge type have its disadvantages, the development of charging technology is still facing a lot of challenges.

For the power system operation, large-scale electric vehicle access has both positive and negative impacts. Access to a large number of electric vehicles may cause the load to increase significantly in certain periods. If the vehicle charging time focuses on the peak load periods, it would be more negative in reliable operation of the grid. EV charging disorder may also cause raising power system losses, the decline of power quality, peak load increasing, and other adverse effects.

The uncertainty of the EVs pattern brings challenges to the safe and reliable operation of the power system. Meanwhile, the particular active behaviors and energy storage of EVs offer power systems favorable conditions in achieving renewable energy consumptive and load shifting. Recent studies have focused on EVs in these three areas: the electric vehicle battery demand law, charging load regularity, and active space, which play roles in EVs' large-scale access on the effect of the power systems. On the other hand, the massive popularity of EVs relies on a sound power supply network, but before the widespread of EVs, there exists some uncertainty on the service capacity of centralized stationing site after filling in a power station in investment services and on the profitability after various types of investment services equipment. Such problems also affect the investment enthusiasm of EVs service facilities and slow down the service network construction, which adversely brings a negative impact on the development of the electric vehicle industry.

However, these are just some of the issues and technical challenges concerning current battery swap technology that researchers have to deal with in near future.

1.4 Business Model

Electric vehicles (EVs) have been deemed as being the future of mobility both by auto industry experts as well as major original equipment manufacturers (OEMs) globally. General Motors (GM) announced that it will release more than twenty new models by 2023; Daimler AG (Mercedes Benz parent company) announced that all the models available will be electrified by 2022; Ford Motor Co. announced 40 electrified models by 2022; several other automakers have committed to an all-electric future[14]. In addition to the original equipment manufacturers' (OEMs') commitments to an all-electric future, government agencies across the world have also set various zero emission mandates. The California Air Resource Board (CARB), Zero Emission Vehicle (ZEV) regulation has a mandate to reduce emissions level by 40% in 2030 in comparison to the level in 1990, and 80% by 2050 through regulations and ZEV credits for automakers that produce a significant number of electrified vehicles. China's New Energy Vehicle (NEV) mandate is similar in implementation to CARB's policies, requiring 2.5% of vehicles sold to be ZEVs by 2018 and 8% by 2025. Norway and the Netherlands have also committed to 100% EVs by 2025 and 2030, respectively. According to [14], the EV market share is expected to grow from roughly 1% today to about 30% in Europe and around 15% in the U.S. by 2025, totaling 130 million by 2030 globally.

The following will introduce a more typical company that uses battery exchange technology.

1.4.1 Company of Better Place

"Better Place" was a venture-backed international company which developed and sold battery-charging and battery-swapping services for electric vehicles. Its formal headquarters was set in Palo Alto, California, and the mainly planning and operations were based on the Israel team, which the founder of Better Place and the investors were all live in the Israel.

Fig 1.4.1 company of 'batter place'

Better Place implemented a special business model. Under the model, customers purchase commodities known as driving distance which is similar to the mobile phone fee and suit from which customers contract for minutes of airtime and other service. The initial cost of an electric vehicles might also include a gift which customers will be subsidized by the ongoing unit distance revenue contract just as mobile handset purchases are subsidized. Better Place aims to enable electric vehicles to be sold as a price less than the average value of gasoline car sold in the US[15], or the advantages of electric vehicles in the market would be minimal. For example, the Prius hybrid series had been sold in market over 13 years with a price which the price is $4,000 more than the average price of other gasoline cars while the series had captured only less than 2% of the worldwide market[16].

1.4.1.1 Batter Place business model

The Better Place approach (called BPA below) aims to make manufacturing and sales of different electric cars separately from the standardized batteries[17] , which it's just like the way that the petrol vehicles are sold separately from fuel. Petrol would be bought a few times a month when needed and, similarly, the BPA would cover electric "fuel" costs per month which including the price of battery, daily charging and battery swaps. BPA allow customers to pay for battery costs in a gradually way, this cost includes the part of battery body cost, degradation, maintenance, quality, technology advancement and anything else related. In the details, each payment would cover battery pack renting, charging and swap infrastructure, purchasing sustainable electricity, profits, and the cost of investor capital[18]. All battery problems would be handled by BPA stores which would then summarize the costs and sent the bill to their customers monthly to support all the infrastructure operating.

The BPA electric car charging infrastructure network is built based on a smart grid software platform which using Intel Atom processors and .NET Framework or other comparable vendors. This platform was first in the world on its application field and which it enables BPA system to manage the charging tasks for thousands of electric vehicles simultaneously with a strategy automatically time-delay recharging to avoid the peak demand hours of electricity in a day, preventing overload and unstable of electrical grid of the host country[19]. According to Agassi, with the help of smart software that monitored and managed all the recharging of electric cars connected with BPA system[20], it is possible to provide electricity for millions of electric vehicles without installing extra electricity generator or transmission line. An analysis of this business model and some further study and considerations was later developed by the University of Denmark[21].

BPA encouraged governments to promote use of international standards and open access for recharging which available for all kinds of charging networks to facilitate competition[22]. However, the standardization works such as SAE J1772, had not yet an apparent development in global consensus. BPA displayed "Charge Spot" refueling stations that used a connector with the same configuration as SAE J1772-2009 but housed in a non-standard plug[23]. They also displayed a “wall mounted” type charging station which using IEC 62196 Type 2 receptacle[24][25]. What’s more, the switching process of battery pack outside of BPA's network was not allowed. BPA company said it had pre-sold enough contracts in Israel which these contracts could make sure its first deployed network profitable once it is launching[26].

1.4.1.2 Battery-Swapping Stations

With battery switching stations, which also called battery-swap stations (BSS), established around cities, drivers could drive the electric vehicles with an unlimited driving range by recharging the batteries for long-distance trips[27]. The QuickDrop battery swapping system enables Renault Fluence Z.E.'s battery, which is the only vehicle deployed in the BPA network, to be swapped within approximately three minutes at BSS[28]. The actual robotic battery-swapping operation would cost about five minutes in such a station[29][30]. While each BSS would cost $500,000[31] in general as its basic cost, the CEO of Better Place, Shai Agassi, still said that this price would be only a half comparing with a typical petroleum station[32].

In order to enjoy the battery swapping station, the customers would have to be confirmed the qualifications according to their membership card. The remaining process, such as swapping, moving forward was fully automated, driver could stay in the vehicle when the swapping work is being executing and it’s similar to going through a car wash.[33]

In 2010, Better Place operated a demonstration BSS in Tokyo which allowing three kinds of specially equipped taxis to swapping their depleted battery pack with a fully charged one(160 km) within 59.1 seconds on average[34]. Better Place also used the same technology to swap batteries for F-16 jet fighter aircraft [35].

Better Place battery swapping stations could support multiple types of battery pack for all kinds of electric vehicles as long as the swapping window of battery pack is under the car[36]. It is recorded that a battery swapping station could use only 15 batteries to had the ability to support batteries for 2,500 EV's[37]. Better Place claimed it had BSS installation teams which one team could install one battery swapping station within just two days[38] with 25 miles distance in every route[39] and, at the same cost, it will cost 7 days for a petroleum station in the United States. Better Place also claimed it could cover all area of the United States with battery swapping stations and other required infrastructure[40].

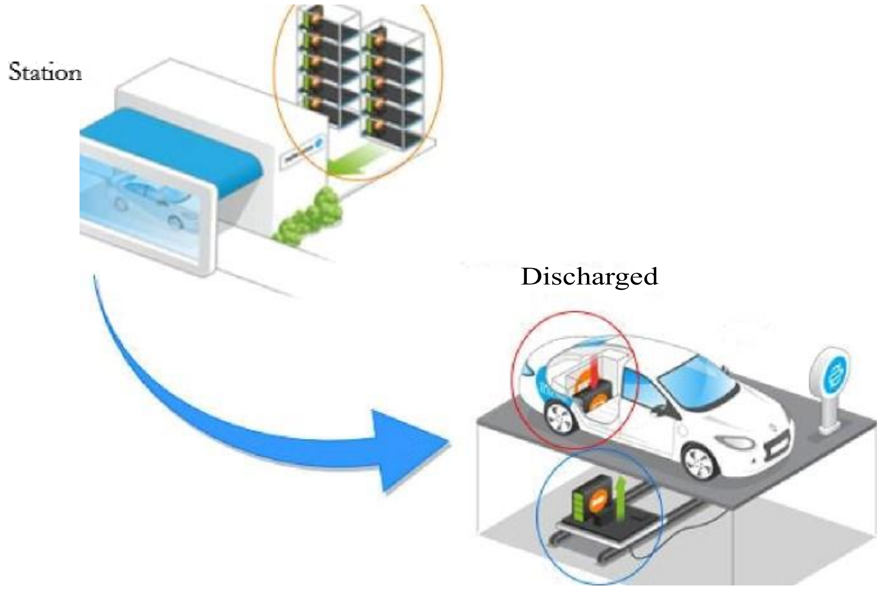

Fig 1.4.1.2.1Better Place's conceptual design of a BSS

Fig 1.4.1.2.2Better Place's battery switching Station in Israel

Fig 1.4.1.2.3 Better Place's electric car BSS at Amsterdam's airport

2. Battery Swap System Development

Following different criteria and points of view, many studies have been carried out and many others are currently underway dedicated to the study and analysis of this alternative strategy to the traditional recharge of the battery in electric cars, in order to understand whether it is a feasible solution.

This section is intended to investigate the battery swap system's players involved (the EV owner and the station owner), how the battery swap procedure takes place in EVs and all the related aspects, following the most recent developments published in scientific literature.

2.1 Case I

One classic research done by Xiao qi Tan and his team[41] mainly introduces the question about BCS scheduling (BCSS): Given the electricity price (e.g., the day-ahead market) and FB demand at known epochs during a fixed time horizon (e.g., a day), how should the BCS operator minimize the total charging cost by controlling the loading/unloading decisions and the charging rates of all charge bays (CBs) to satisfy the FB demand with warehoused FBs in the dynamic FB inventory.

The related system model as follow:

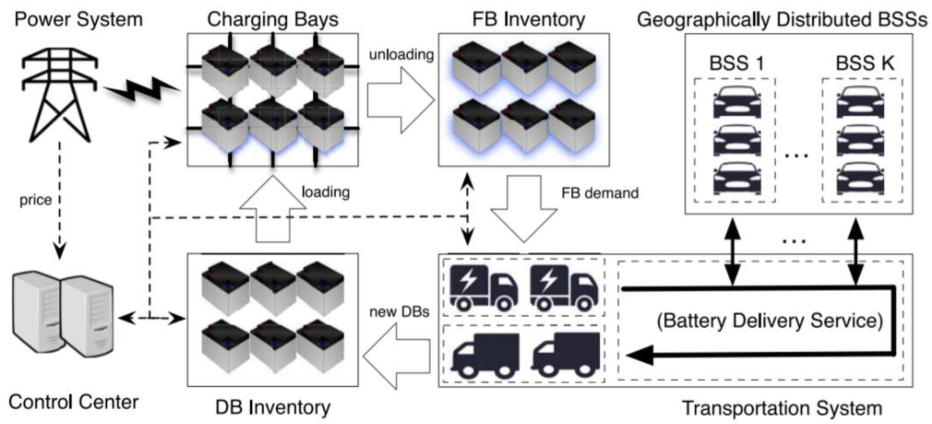

Fig.2.1.1.1 The system model of a centralized BCS and multiple geographically distributed BSSs. The centralized BCS is comprised of four components: the FB Inventory, the DB Inventory, the Control Center, and the Charging Bays.

Then by considering the BCSS problem as a mixed-integer problem (MIP), has a highly decomposable structure when fixing the binary decision variables. Therefore, the generalized Benders decomposition (GBD) is applied to solve the BCSS problem in an iterative manner. Finally, the algorithm gives a strategy to fit the demands.

2.2 Case II

Another research done by *Sujie Shao*[42] and his team support a new vision in battery swapping operation. Different from a station, they combine the battery swapping technology and delivery service, a battery swapping van is used which can carry tens of fully charged batteries and drive to an EV to swap a battery within a relatively short fixed period of time according to the appointment on app. The whole structure is shown in *Fig 2.1.2.1* below.

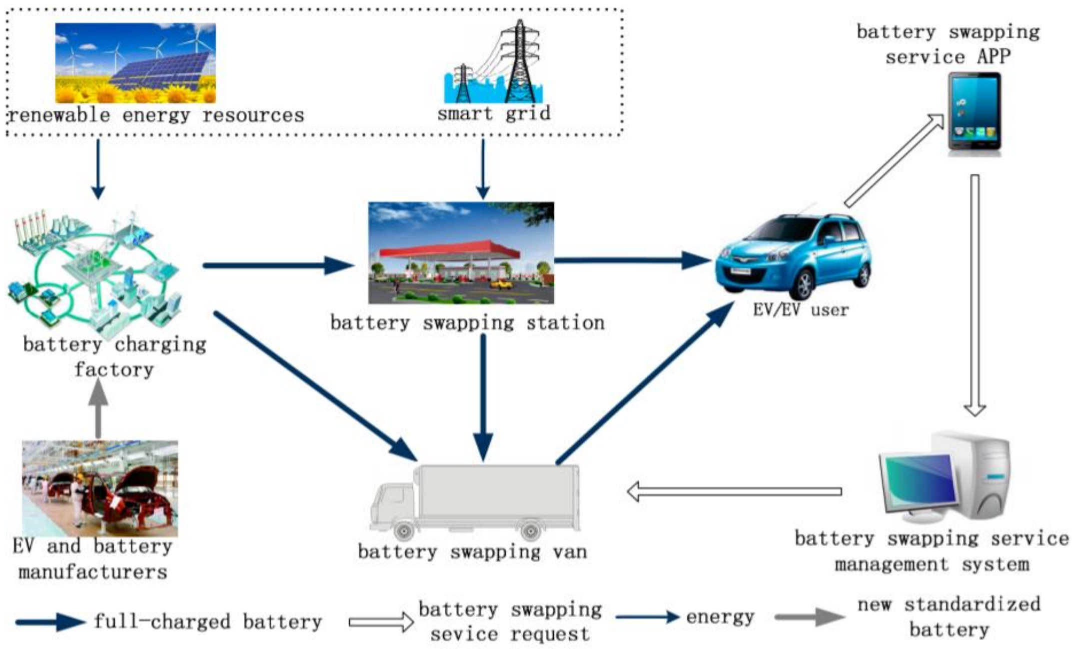

Fig.2.1.2.1 EV battery swapping structure based on battery swapping van

The literature tries to make a strategy for vans to improve the efficiency and effectiveness of battery swapping service and propose a minimum waiting time based on priority and satisfaction Energies scheduling strategy (MWT-PS) to distinguish and schedule the battery swapping requests.

First, the authors define the battery swapping service request and set its priority according to the State of Charge (SOC). Second, authors establish a battery swapping service request queuing model according to the specific battery swapping service mode based on a battery swapping van. Then discuss the satisfaction of EV users based on waiting time and request priority and establish the scheduling model. Finally, the MWT-PS is proposed based on the abovementioned analysis.

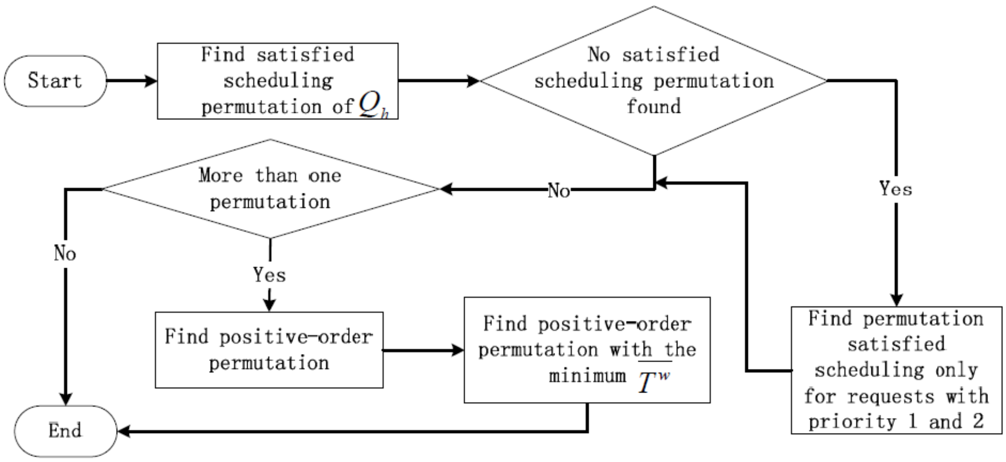

Fig 2.1.2.2 MWT-PS scheduling strategy

2.1 Case III

Besides, a concept of micro-grip is introduced by *Mushfiqur R. Sarker* and his team[43] . The article defines three possible energy transportation paths: Battery-to-battery (B2B); Battery-to-grid (B2G); Grid-to-battery (G2B). They are shown in *Fig.2.1.3.1* below.

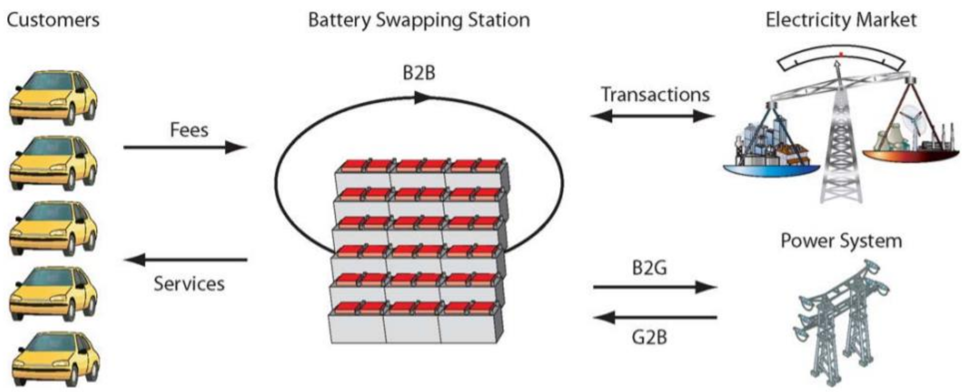

Fig.2.1.3.1 BSS interactions with customers, market, and the power system.

The concept is to establish an energy dump station, buying the electric energy from power grid when it is cheap, save the energy in the micro-grid and charging the battery when it is needed. The batteries perform a role of medium in transportation.

By taking numerical analysis, finally, the author calculates the relative profit by using this model and verifies the feasibility.

3. Scenario Definition

So far, we have introduced 3 popular business models. Each of them has a special and brillliant innovation to cater to the market and improve the performance of station . In this part, we will discuss another interesting case: Delay charging model. The modeling of a service station for battery swapping and a hypothesis of solution of use of this technology will be formulated as well as the model development process will be illustrated. And then, the validity and the effectiveness of the proposed model will be proof by a set of concrete scenarios.

3.1 Motivation and Delay charing model

Considering the electricity consumption of power grid in a city during a day, it's obviously that the grid load varies, or we could say quite different according to time. It could be generally divided as two period: high electricity consumption period and low electricity consumption period. During high electricity consumption period, obviously, there are many different features comparing with low electricity consumption period, the mainly two points as shown below:

1. Unit cost of electricity is higher due to customers' intensive usage and market segmentation.
2. Power grid load is heavier due to intensive usage. This condition will lead to unstable power supply, which it could damage the charging batteries and decrease the batteries life.

It seems that, for a BSS, charing the battery in the night has many benifits. However, limited by the customer flow in the night, the tranditional Charging strategy is hard to utilize the advantages of "night time charging". That's why "Delay charging model" is mentioned.

Delay charging model or strategy, as it is shown, aim to delay charge the batteries until night time (low electricity consumption period), thus enjoying the benifits of higher charging safty, lower dissipation in charging and low electricity price. Besides, it could have a more uniform charging time distribution in a day, in some cases, could deal with the workforce shortage problems during busy hours, improve the service quality.

Of course, if all the batteries are charged in the night, meanwhile, the customer in the day should be satisfied, that will requir a very big battery reserve ready for swapping which is unworthy. So, choosing a proportion of batteries delay charged at low electricity consumption period is a avaliable strategy. Thus, the number of batteries which would be charged at day time (high electricity consumption period) is the main factor to determine whether the Full Charged Batteries (FBs) could satisfy the customers' needs. Besides, the number of batteries which would be charged only at night time (low electricity consumption period) will also make differece. So, we need to find a proper number of batteries and proper ratio of batteries charged at day time, they should consider both the operating cost and basic cost effect.

3.2 Model Building

According to the case mentioned above, the focus would be the development of a model for a BSS based on the configuration and discrete events modelling of a battery storage site to allow the management of EVs' battery using swap mode. The aim is to evaluate the performance of the battery swap system through the design and simulation of a BSS model as realistic and accurate as possible in a scenario where EVs are a widespread resource. The city of Turin will be taken as a case study.

In order to make the simulation more realistic, we can consider two types of battery, one for standard travel range and another for long travel range. Considering the most sold vehicle, let's take Renault Zoe R110 Z.E. 40[10] (capacity: 41kWh) as an example for standard range battery and Tesla Model 3 Long Range[10] (capacity: 75kWh) for long range battery.

Fig 3.2.1 Renault Zoe R100 Z.E.40 and its battery pack

Fig 3.2.2 Tesla Model 3 Long Range and its battery pack

To simulate the customer flow, we can take the vehicle on road as an example. Fig 3.2.3 and Fig 3.4.5[44] show the distribution of the number of vehicles circulating in Turin at different times of the day and the distribution of the number of kilometers travelled on the city network over 24 hours respectively.

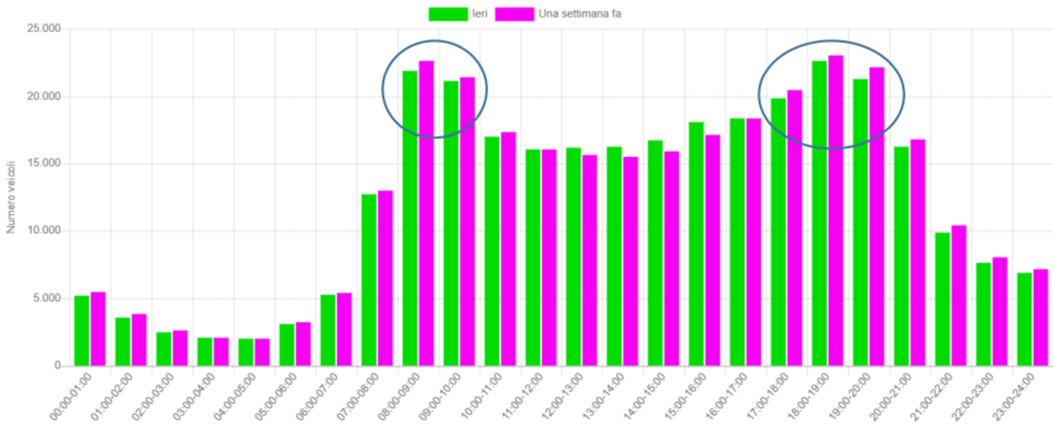

Fig 3.2.3 Vehicles Distribution on road in different time slots in Turin

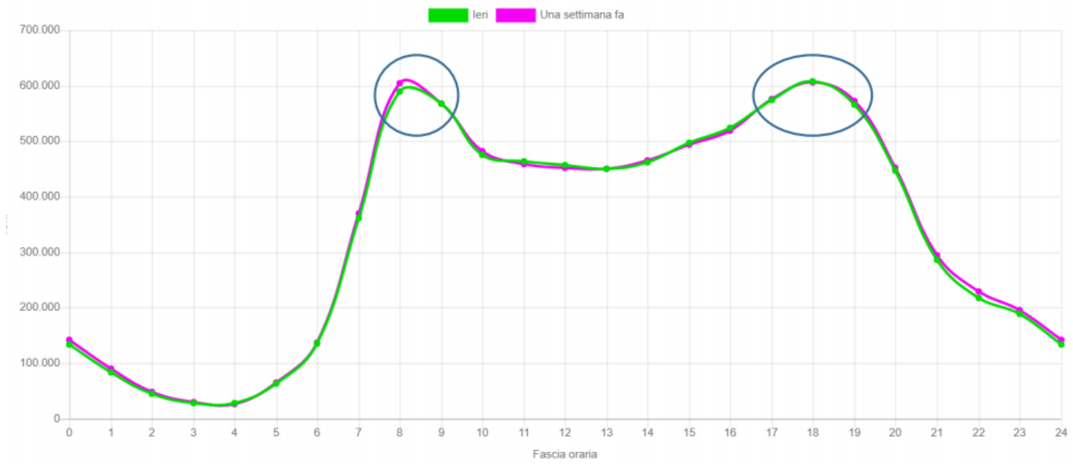

Fig 3.2.4 Kilometers Distribution covered by vehicles in different time slots in Turin

By examining these distributions, the peak hours are from 08:00 to 09:00 in the morning and from 17:00 to 19:00 in the evening. From the data, the total number of kilometers travelled each day is thus about 8 million, while the total number of vehicles in circulation is about 320 thousand, which represents roughly 44% of the total vehicle fleet in Turin. At this point, given both the kilometers travelled and the vehicles in circulation every hour, it is possible to derive the numbers of electric cars. Knowing that the car fleet in Turin is 576 571, which corresponds to 80% of the vehicle fleet, the same percentage could be used to estimate the number of cars in circulation every hour.

Assuming, in an ideal scenario, all circulating cars are full electric and using only the two types of batteries mentioned above. It is estimated on average the kilometers travelled by each car before recharging. Since Tesla Model 3's range is greater than that of the Renault Zoe, the entire electric cars fleet will be divided into 34% Tesla Model 3 and 66% Renault Zoe respectively. Afterwards, through a weighted average it is possible to know on a erage how many electric cars will need to recharge the battery every hour over a 24-hour period in Turin and dividing the kilometers covered at each hour by the average kilometers travelled before recharging the EV's battery.

At this point, given the large number of electric cars that may need to recharge the battery, so serveral battery swap stations in Turin should be considered. Also, according to the reaserch mentioned in [10], the remaining capacity percentage of battery when customer begin charging distribution is shown in fig 3.2.5. As we can see, the most common value is 20% ~ 25%, we can assume that the distribution follows a lognormal distribution.

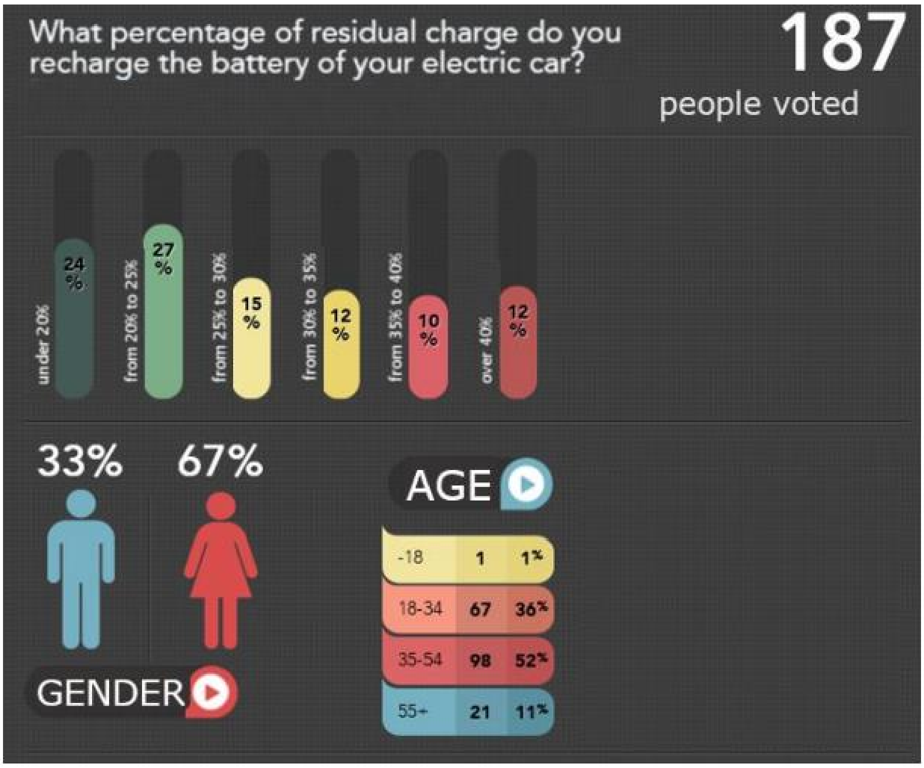

Fig 3.2.5 residual percentage when drivers charge the batteries

In BSS, a warehouse is needed to store and recharge the exchanged batteries. To simplyfied the model, considering the warehouse is designed to have 6 levels each bay, during simulation, we only change the number of bays rather than levels. Each slot could only put one battery. The maximum charging power used by the chargers will be kept fixed at 22 kW (for avoiding damage due to fast charges) and each battery pack will be recharged to a maximum SoC percentage of 90% (as mentioned above).

3.3 Model assumptions

To simplify the simulation model and make it reasonable, we have made some hypothesis as follows:

1. The model considers only private EVs;
2. The station will open 24 hours a day;
3. The station can serve a maximum number of EVs equal to the number of battery swap workstations at a time;
4. The battery packs for all incoming EVs can be of two different capacities and types, but of standard dimensions;
5. The principle "first-in first-out" is used to serve EVs according to their arrival time;
6. Each location in the warehouse is able to accommodate only one battery regardless of the type or the capacity of the latter
7. The number of battery chargers available is equal to the number of batteries the warehouse can hold
8. The battery's State Of Health (SoH) parameter will not be taken into consideration;
9. No breakdown and recovery times for objects in the model has been considered;
10. Costumers will accept all SoC levels batteries even if it's not a FBs.

The other parameters are shown below

Table 3.3.1 Model parameters

Parameter		Value
RACK		
Rack Size (meters)	Width of Bays	2
	Height of Levels	1
VEHICLES		
Task Executors Speed (m /s)	AGV (x-axis)	2
	ASRS(x-axis)	1
Swapping Bay		
Number of swapping bays	Waiting Queue	2
	Swapping Bay	2

What's more, we need to discuss the effect no only for energy, essentially, the operating cost. That means we need to know the electricity price in the day time and in the night time, of course that's why we discuss about delay model, and then we can calculate the total cost per day.

From the websit such as Inc.Iren, there are no exactly price for large commercail electricity business. We can only know an average price for commercail usage which is about 0.184 Euro/kWh. For further assumption, we consider the Chinese electricity market condition, which the the day time generatly will be 1.5~2 times comparing with night time. Chinese electricity price is cheaper than Europe, while we can assum that they have the same trend on it. So, considering the average price mentioned above, we could assum that the day time electricity price for our model is 0.242 Euro/kWh and 0.121 Euro/kWh at night. For reference case, the electricity price is always 0.242 Euro/kWh. By doing so, we could continue our work.

4. Methodology

After determining the estimation methods and some assumptions, now it's possible to develop the simulation model for the Turin Urban Infrastructure. The model and the simulation process would be done through the software Flexsim, the creation of model would be discussed in this part. The model allows to simulate the BSS under various conditions with some configurable elements offered by software. And the stochastic behavior of the system considered as well as its performance will be also investigated.

4.1 Discrete event simulation

To simulate the behaviors of a real system or model, we need to build and define the relationships between different elements and modes. It's possible to predict the performance of the system. To do so, there are many different types of model used to simulate, according to different features, they could be classified as follows:

According to the continuous of process:

1. Continuous Models: the system state will vary continuously with time;
2. Discrete Models: system state will vary only at a certain time step or when special event happen.

According to the system condition:

1. Static Models: system is presented at a special time period or in steady state;
2. Dynamic Models: the system varies depends on time.

According to randomness of system:

1. Deterministic Models: the system does not consider the probability distribution;
2. Stochastic Models: the system should consider the probability due to the randomness.

By using simulation software, the models usually are discrete, dynamic and stochastic so called Discrete-Event simulation (DES) models, which the models are particularly used to analysis high-level automation of plants and industry process.

In a discrete-event model, the system is characterized in every moment of time by a set of variables called state variables, by events which modify the value of at least one of the state variables, by entities (single elements of the system) and their attributes, by resources and by activities (operations of known duration) and delays.

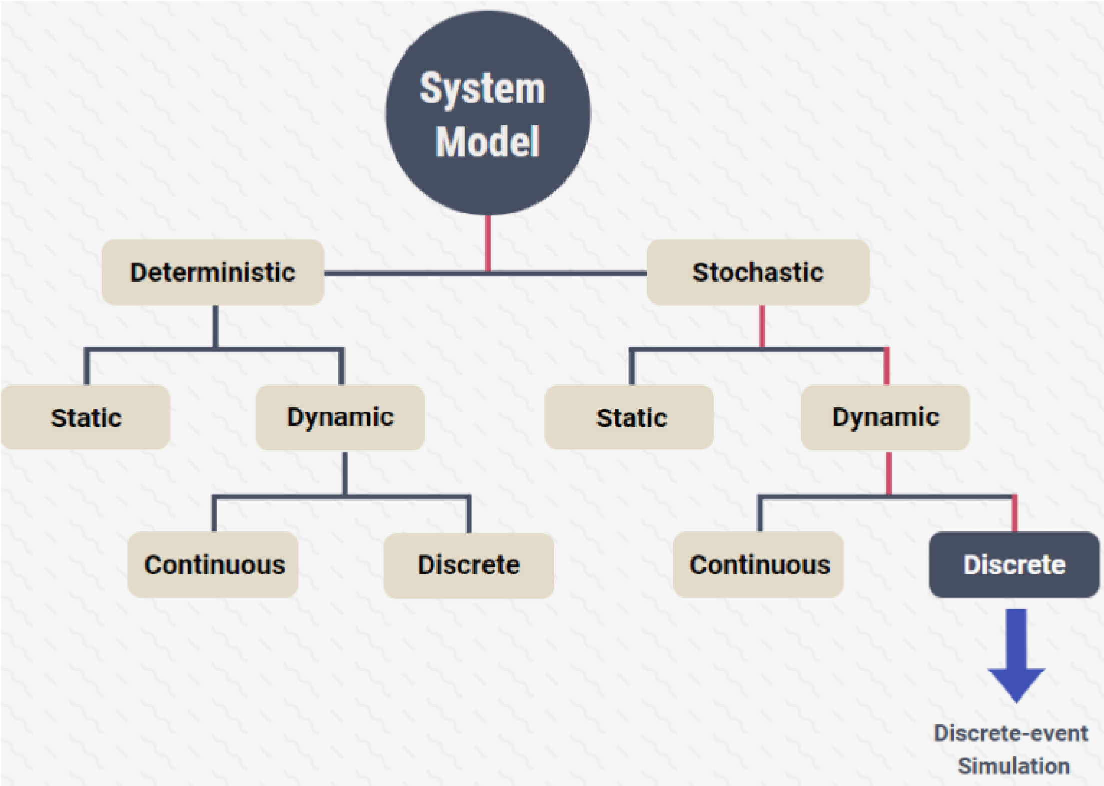

Fig 4.1.1 Classification of model

4.2 Simulation Software

From this perspective, among several commercial DES software that perform manufacturing simulations as shown in fig 4.2.1), Flexsim has been chosen to visualize, analyze and improve the behavior of the considered system for real-world processes and applications as a more concrete way. By using Flexsim, it is possible to easily create the simulation model and achieve the final goal of this analysis, which is to better understand what conditions and processes optimize the RSS system as well as the advantages and disadvantages that a company can derive from its implementation.

Criteria Groups	Comparison Criteria	Simulation Software Tools				
		AnyLogic	Arena	Flexsim	Plant Simulation	Witness
Hardware and Software	Coding aspects	****	***	**	****	**
	Software compatibility	***	**	***	****	***
	User support	****	**	****	****	***
General features	Purpose	General	General	General	General	General
	Experience required	***	****	**	***	**
	Ease of use	***	**	**	***	****
Modelling assistance	On-line help	****	**	****	***	**
	Library and templates	***	**	****	****	***
	Comprehensiveness of prompting	***	**	***	***	***
Simulation capabilities	Visual aspects	****	**	*****	****	***
	Efficiency	****	**	****	****	***
	Testability	****	***	****	****	***
	Experimentation facilities	***	***	****	****	***
Input / Output	Statistical data	****	***	****	****	****
	Input/output capabilities	****	***	****	*****	****
	Manufacturing capabilities	****	**	****	****	*****
	Analysis capabilities	***	***	****	****	***

Fig 4.2.1 Comparation of commercial software of system simulation

Flexsim is 3D simulation software that models, simulates, predicts, and visualizes business systems in a variety of industries: manufacturing, material handling, healthcare, warehousing, mining, logistics, and more. It's a powerful yet easy-to-use software package that implements a C-like language called FlexScript and it has been designed with an open architecture to integrate with C++ as well. The main features of this simulation software comprise the use of:

1. A highly realistic 3D graphics simulation to see any actions that occur during the simulation and to confirm whether the system is working or not as it was intended to (visual validation).
2. 2. A model layout that exploits drag-and-drop controls to arrange resources and 3D objects used in model building directly into the 3D environment.
3. A model building with: a). a standard object library set and a drop-down lists to customize objects, events, functionalities and system properties; b). a process flow using activity blocks to build system logic.
4. 4. A full suite of analysis features that includes a list of graphical interfaces, predefined or customized by the user, called dashboards to better visualize data of interest from running simulation and the possibility of collecting and exporting data to other calculation applications like Excel spreadsheet (statistical validation).
5. Two optimization tools (Experimenter & Optimizer) in order to simulate multiple scenarios in which input variable fi1es and performance indicators are different, make the test possible choices and compare the results of the solutions.

All these functionalities make this software very complete, allowing to easily control and modify the simulation model from multiple perspectives.

For our thesis, we choose the 20.0.0 version for working.

4.3 Flexsim environment

The FlexSim user interface is divided into several part, as shown in Figure 4.3.1. The 3D model area is located in the center panel in FlexSim, the library (and the toolbox) in the left panel, the properties and the process flow view in the right side and the script console in the bottom panel. In the FlexSim reference system, the x-axis (in red) corresponds to the horizontal axis, the z-axis (in blue) coincides with the vertical axis and the y-axis (in green) represents the depth. On these axes task executors (like AGV and ASRS) can travel.

The 3D model field, that is the main workspace, is where, by means of animations and 3D graphics, the whole system is visualized and validated. The library includes all the objects, divided into categories or classes that have a high level of customization and can be used to both build the 3D simulation model and to create activity blocks in the process flow. In the properties section, the most important details (features, values, labels, etc.) about the objects present in the simulation model are given. The script window is useful to execute FlexScript code in order to obtain information or configure the simulation model without running the model. Moreover, in the script console the code can be debugged. Lastly, there is the process flow interface that allows to create and to build the overall logic of the simulation system that is the basis of the operation of the simulation model.

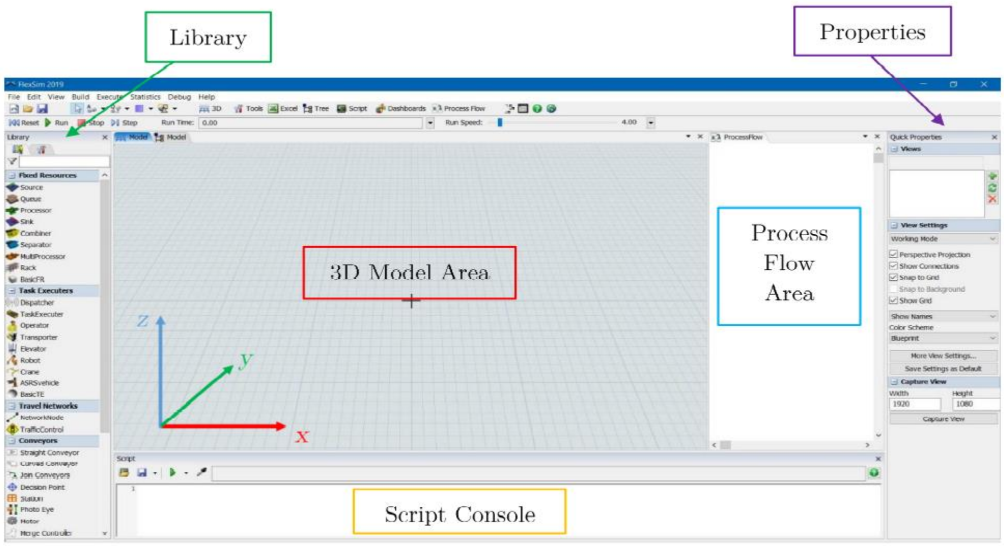

Fig 4.3.1 Flexsim users' interface

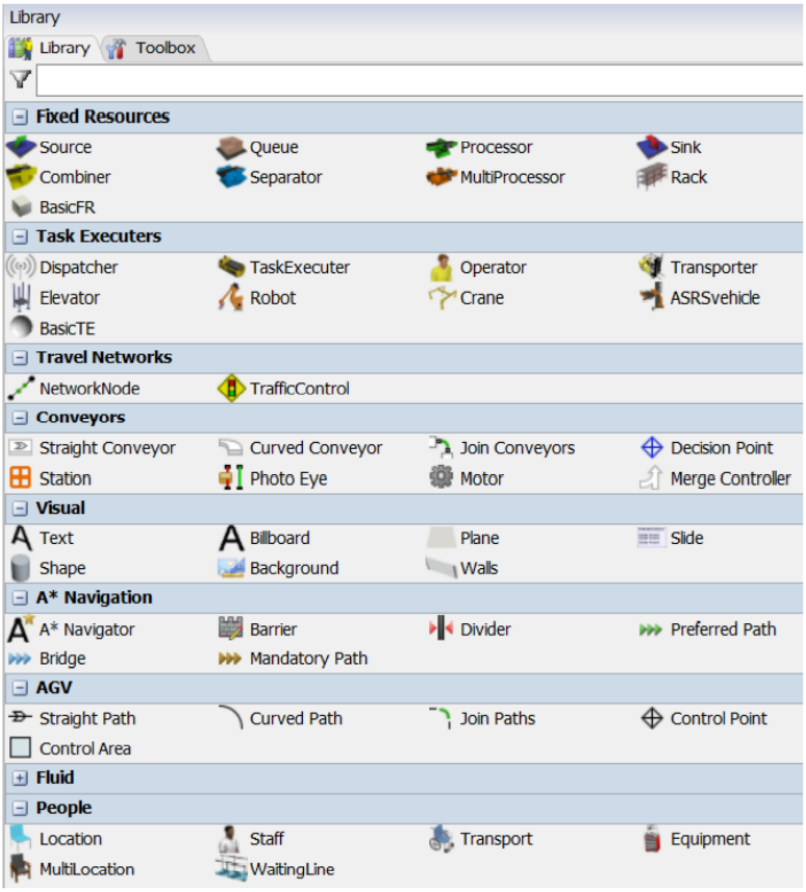

Fig 4.3.2 Flexsim object library

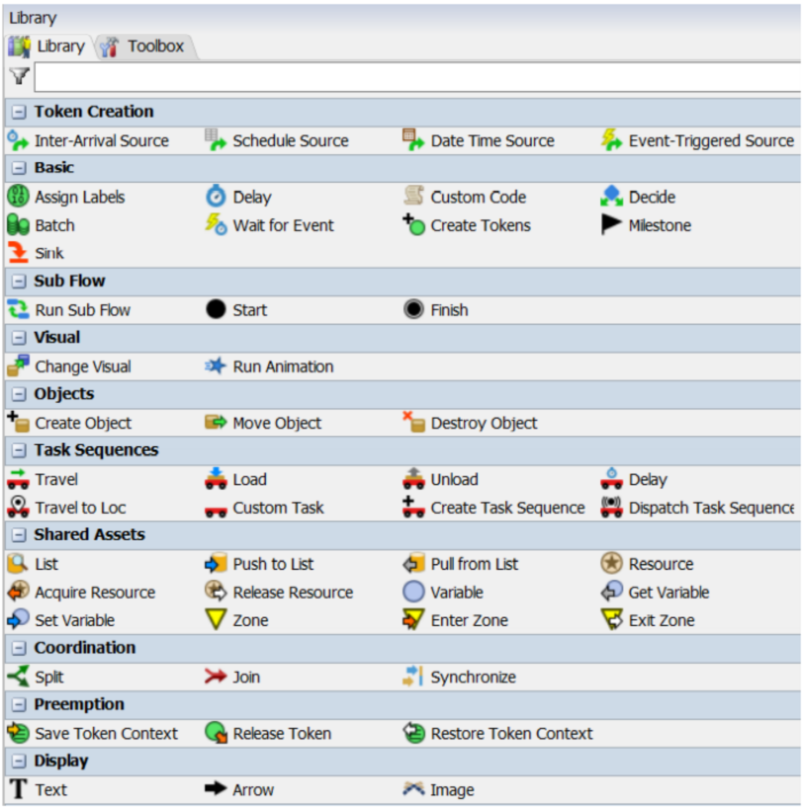

Fig 4.3.3 Flexsim process flow library

The process flow tool has a flow chart-like visuals where is possible to create blocks that represent tasks, activities or resources. The main elements of a process flow are tokens, activities and shared assets. Tokens represent the simulation status and are essentially flow items moving from one activity to the next. Moreover, they are specified by a green circle and identify the position and activity that the item should perform in the model. Each token contains basic information such as ID, name and labels in order to identify and store custom data.

Tokens in this model are associated with battery packs in such a way that, by tracking token information, it is possible to keep track of every battery pack in the system. Activities are the logical operations in the process flow and are linked to each other with connectors. A set of activities can be grouped together into a single stacked block creating sequence of steps.

Shared assets are essentially limited resources that tokens can release or claim at specific points in the process flow. Whenever a shared asset is unavailable, the token that requests it has to wait for that resource to become available in order to move on to the next activity. Shared assets can be of three different types including resources, lists and zones, which correspond to limited supply of resources, lists and statistical information respectively.

4.4 Model building

There are two main parts in the model. First one includes all necessary simulation objects with their connections, corresponding parameters, labels and initial values have been created directly in the 3D model area. Also, it still be possible to make manual changes to the model in order to simulate and test situations that are even more complex. The second one is generally a process flow in which the rules of operation of the system are collected to present the logic process in working.

Most of the values or parameters assigned to objects in the model are dynamic and can be changed in the simulation in order to make the model as flexible as possible for future changes. For this reason, several of the customizable parameters in the model have been saved as global variables. Among these, there are the maximum battery charge level, expressed as a percentage, in the rack called MaxLevelRackSoC. The SoC update rate for the batteries in the warehouse called Updating Time. The time required to remove the battery or insert it into the car called DelayTime. And the time it takes a customer to leave the station once served so call Departure time. In this paragraph, the general layout of the model is outlined, highlighting all the objects involved.

For simulating the system, we need focus on the main parts and its features and then there are six types of objects should be used which made available by the software, can be identified in the model and each of them is described in the next pages:

1. Two Sources (Fixed Resource) to generate the incoming battery packs during simulation time (SourceBattery) and the battery packs available in the rack at startup (SourceRack).
2. Two Queue (Fixed Resource) to model the customers' waiting queue (WaitingQueue) and the battery swap bay (SwapBay) where the AGV exchanges the discharged battery for a charge, and two more queue for storage (StoringBay) and retrieval (RetrievalBay) operations.
3. A Sink (Fixed Resource) to represents the customers' exit from the station with new battery (OutBatery).
4. An AGV (Automated Guided Vehicle) and an ASRS (Automated Storage and Retrieval System) Vehicle (Task Executer) for transporting and moving batteries.
5. A Rack (Fixed Resource) to store and charge the battery packs know as Battery Warehouse.
6. An AGV network (AGV) to provide a set of paths that will be followed by the vehicle, which the paths also have function to represent the distance.

Let’s talk the objects according to the battery “flow” in the system.

First of all, the source battery object simulates the customers coming to the BSS with battery waiting to be swapped. The arrival style of source can be set as “inter-arrival time” for using a customer arrival time table. The Flowitem class could be set as “Hourly Rate, Custom Daily Repeat” for setting the customers coming in each hour.

Interval Variability: Constant Rate | Stream: getstream(cu | Std Dev: 20 %

Table: Locally_Defined_Table

Days: 1

	Day 1
0:00 - 1:00	6
1:00 - 2:00	3
2:00 - 3:00	2
3:00 - 4:00	2
4:00 - 5:00	4
5:00 - 6:00	8
6:00 - 7:00	23
7:00 - 8:00	37
8:00 - 9:00	35
9:00 - 10:00	30
10:00 - 11:00	28
11:00 - 12:00	28
12:00 - 13:00	27
13:00 - 14:00	28
14:00 - 15:00	30
15:00 - 16:00	26
16:00 - 17:00	36
17:00 - 18:00	38
18:00 - 19:00	35
19:00 - 20:00	27
20:00 - 21:00	17
21:00 - 22:00	13
22:00 - 23:00	11
23:00 - 24:00	10

Fig 4.4.1 Customer coming rate table

Then a creation trigger would be set to achieve a special process when a battery coming to the system. As it shown below, the parameter of battery including “Type”, “SoC”, “Serial number”, “Color in model” and the state would be created.

Labels		Labels	
Type	1	Type	1
SoC	22.36	SoC	90
ToSwap	1	ToSwap	0
Capacity	41	Capacity	41
State	1	State	-1
MaxSoCTime	-1	MaxSoCTime	0

Fig 4.4.2 example of label created in trigger

It’s worth to explain that “ToSwap = 1” represents the battery is waiting for storing while “ToSwap = 0” represents the battery have been stored. “State” represents the state of the batteries. There would be three number for this label: “-1” strands the battery have been full charged and already in the warehouse, “0” represents the swapped full charged battery, “1” represents the batteries in charging. And the “MaxSoCTime = -1” represents the battery haven’t been charged, “0” means in charging, otherwise the number will represent the time when the battery is full charged.

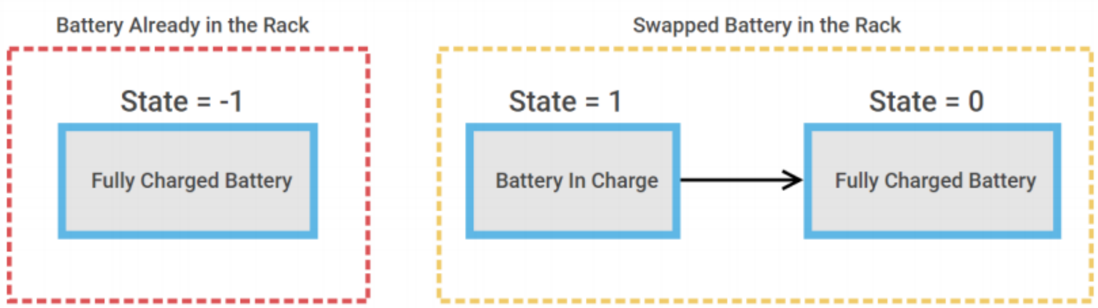

Fig 4.4.3 Meaning of the number of "State"

The code could be seen as follow:

```
Object current = ownerobject(c);
Object item = param(1);
int rownumber = param(2); //row number of the schedule/sequence table

{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"Type"/**/;
Variant value = /** \nValue: *//***tag:value*//**/bernoulli(66, 1, 2, getstream(current))/**/;

involved.labels.assert(labelname).value = value;
} // ******* PickOption End ******* //

{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"SoC"/**/;
Variant value = /** \nValue: *//***tag:value*//**/lognormalmeanstdev(20, 20, getstream(current))/**/;

involved.labels.assert(labelname).value = value;
} // ******* PickOption End ******* //

{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"ToSwap"/**/;
Variant value = /** \nValue: *//***tag:value*//**/1/**/;

involved.labels.assert(labelname).value = value;
} // ******* PickOption End ******* //
```

```
{ // ************* PickOption Start ************* //
/***popup:SetObjectColor*/
/**Set Object Color*/
Object object = /** \nObject: *//***tag:object*//**/item/**/;
object.color = /** \nColor: *//***tag:color*/ /**/Color.byNumber(item.Type)/**/;
} // ******* PickOption End ******* //

{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"Capacity"/**/;

Array vetttipo = Table.query("SELECT ARRAY_AGG(Type) FROM TypeTable")[1][1];
Array vettcap = Table.query("SELECT ARRAY_AGG(Capacity) FROM TypeTable")[1][1];

for (int i=1; i<= numType; i++){
		if (item.Type == vetttipo[i])
			involved.labels.assert(labelname).value = vettcap[i];
}
} // ******* PickOption End ******* //

{ // ************* PickOption Start ************* //
/***popup:SetName*/
/**Set Name*/

treenode involved = /** \nObject: *//***tag:object*//**/item/**/;
string name = /** \nName: *//***tag:name*//**/"Battery " + string.fromNum(nameBattery+1)/**/;

involved.name = name;
nameBattery++;
} // ******* PickOption End ******* //
{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"State"/**/;
Variant value = /** \nValue: *//***tag:value*//**/1/**/;

involved.labels.assert(labelname).value = value;
} // ******* PickOption End ******* //
{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
```

```
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"MaxSoCTime"/**/;
Variant value = /** \nValue: *//***tag:value*//**/-1/**/;

involved.labels.assert(labelname).value = value;
}
// ******* PickOption End ******* //
```

The type of batteries, as it mentioned above, the probability of two types of batteries coming could be regard as following the Bernoulli distribution, with 66% probability for 44 kWh battery and 34% probability for 75 kWh. Also the SoC follows the lognormal statistical distribution with average value is 25% .

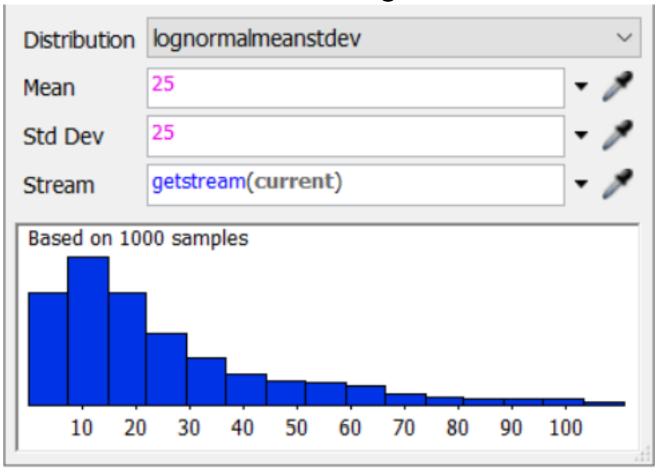

Fig 4.4.4 SoC follows the lognormal statistical distribution

In other side, SourceRack generates the batteries inside warehouse initial. The Arrival Style should be set as Arrival Schedule to build an array about two types batteries. The number of batteries would be changed according to warehouse size. Also, the creation trigger will create related parameters for these batteries.

Arrivals 2 Labels 1

	ArrivalTime	ItemName	Quantity	Type
Arrival0	0		60	1
Arrival2	0		30	2

Fig 4.4.5 SourceRack setting

Then after the customer (battery) coming, it will entry the waiting queue. The coming battery will wait here due to there are only two ports for AGV to swap the battery with one capacity per time. The trigger should record the Start Waiting time and End Waiting time for calculating the Waiting time. The “Reevaluate Sendto on

Downstream Availability" box is checked in order to consider to push to list every time a downstream object becomes available. The output logic of this queue is set to FIFO (First in First Out).

Next, the battery would be swapped in two swapping bays. Its maximum content is set as one since the swapping bay can serve one customer at a time. In the Input group of the flow tab, the pull strategy checkbox is selected because it should pull from WaitingBattery list the battery that has been waiting the longest first so that following FIFO strategy as explained above. This queue has a binary label called "Busy" that is used essentially to engage the queue during the entire battery swap procedure and to not allow other batteries, waiting to be served, to enter. Every time an item enters in this object from the WaitingQueue, the OnEntry Trigger is activated and the Busy label is set to one. To simplify the model, we consider the battery swapping process cost same time in repeating work.

Then, the swapped battery would be transfer to storing bay by AGV. As we mentioned above, the AGVs have been set the paths and loading/uploading position. Besides, the max speed, acceleration, deceleration, loading/unloading time should be set. AGV's task sequence is described in Process Flow, aiming to control the work to two AGV's.

The StoringBay will have a trigger, when battery dropped off in the bay, simultaneously, the "ToSwap" label of the item is changed to zero because the battery has been swapped and will be stored in the rack, by means of the ASRS, where it will be charged.

The Rack or called warehouse is where battery storing and charging. The size of the warehouse is an important parameter which contains number of bays, number of levels, slots per bay and slot size. The size of warehouse should match the number of batteries initially stored set by SourceRack, the number of levels would keep as 6 during simulation and only number of bays would be modified to change the warehouse size. The exit battery would be chosen in random bay and level as it is the right type and has the max SoC comparing with other batteries. The battery in the warehouse will be considered as charging if its SoC hasn't reached 90%. Considering the Delay charging model, the SoCupdating code should distinguish which batteries' SoC should be updated (charging) and which are not (delay). Also, in the code and warehouse trigger, it should record the key parameters like energy consumption in the day/night, SoC when battery exit. These parameters would be used for final discussion to judge whether the system is proper.

The SoC calculation code shown as follow:

```
/**Custom Code*/
//treenode tree = model().find("BatteryWarehouse");
//Object obj = tree;
//int dimensionrack = obj.subnodes.length;
//return rackgetcellcontent(obj,1,1);

Object obj = model().find("BatteryWarehouse");
int dimensionrack = obj.subnodes.length;
Table table = Table("WaitTable");

Array captot = Array (dimensionrack);
Array charge = Array (dimensionrack);
Array carica = Array (dimensionrack);
Array tempori = Array (dimensionrack);
Array chargedsoc = Array (dimensionrack);
Array bay = Array(dimensionrack);
Array level = Array(dimensionrack);
double sum = 0;
double sumd = 0;
double sumdd = 0;


for (int i=1; i <= dimensionrack; i++){
    captot [i] = obj.subnodes[i].labels["Capacity"].value;
    charge [i] = obj.subnodes[i].labels["StoringSoC"].value;
    tempori [i] = obj.subnodes[i].labels["EntryTime"].value;
    carica [i] = obj.subnodes[i].labels["SoC"].value;
}
// funzione che restituisce i nuovi valori di SoC in base alla potenza
fornita dal caricatore
Array finale = NewSoC(captot, charge, tempori, carica).clone();

// aggiorna tutte le SoC nel magazzino
for (int i=1; i <= dimensionrack; i++){
    obj.subnodes[i].labels.assert("SoC").value = finale[i];
```

```
    bay [i] = rackgetbayofitem(obj, obj.subnodes[i]);
    level [i] = rackgetlevelofitem(obj, obj.subnodes[i]);
    // sono al max
    if (obj.subnodes[i].labels["SoC"].value == MaxLevelRackSoC &&
tempori[i] != 0 && table[level[i]][bay[i]] == 0){
        obj.subnodes[i].labels.assert("State").value = 0;
        obj.subnodes[i].labels.assert("MaxSoCTime").value = time();
        table[level[i]][bay[i]]++;
        }
    if (obj.subnodes[i].labels.assert("Energy").value == 0){
        obj.subnodes[i].labels.assert("DayEnergy").value = 0;
    }
    sum += obj.subnodes[i].labels.assert("Energy").value;
    sumd += obj.subnodes[i].labels.assert("DayEnergy").value;
    sumdd += obj.subnodes[i].labels.assert("DoC").value;

}

TotEnergy = sum;
TotDayEnergy = sumd;
TomaxEnergy = sumdd;
```

Inside, the "NewSoC" code:

```
/ /**Custom Code*/
/* Custom Code*/

// captot param(1);
// charge param(2);
// tempori param(3);
// carica param(4);

Object obj = model().find("BatteryWarehouse");
int dimensionrack = obj.subnodes.length;
Array age = Array (dimensionrack);
Array per = Array (dimensionrack);
Array daricaricare = Array (dimensionrack);
Array bay = Array(dimensionrack);
Array level = Array(dimensionrack);
Array sctime = Array(dimensionrack);
Array csoc = Array(dimensionrack);

double ava = dimensionrack * ratio;

for (int i=1; i <= dimensionrack; i++){
```

```
    if (param(4)[i] < MaxLevelRackSoC){
        bay [i] = rackgetbayofitem(obj, obj.subnodes[i]);
        level [i] = rackgetlevelofitem(obj, obj.subnodes[i]);
        if ( (level[i]-1)*10+bay[i] <= ava){
            sctime[i] = param(3)[i];
            obj.subnodes[i].labels.assert("csoc").value = 0;
        }
        else{
            if (param(3)[i] < 25200){
                if (time() < 25200){
                    sctime[i] = param(3)[i];
                    obj.subnodes[i].labels.assert("csoc").value = 0;
                }
                else if (time() > 82800){
                    sctime[i] = 82800;
                    obj.subnodes[i].labels.assert("csoc").value = csoc[i];
                }
                else{
                    obj.subnodes[i].labels.assert("csoc").value = param(4)[i]
- param(2)[i];
                    sctime[i] = time();
                }
            }
            else if (param(3)[i] > 82800){
                obj.subnodes[i].labels.assert("csoc").value = 0;
                sctime[i] = param(3)[i];
            }
            else{
                obj.subnodes[i].labels.assert("csoc").value = 0;
                if (time() >82800){
                    sctime[i] = 82800;
                }
                else{
                    sctime[i] = time();
                }
            }
        }
        age [i] = time() - sctime[i];
        per [i]= (param(1)[i] -
(age[i]/3600)*Table("PowerTable")[level[i]][bay[i]])/param(1)[i];
        obj.subnodes[i].labels.assert("Energy").value =
Table("PowerTable")[level[i]][bay[i]]*age[i]/3600+obj.subnodes[i].labels.ass
ert("csoc").value/100*param(1)[i];
        if (param(3)[i]<25200 && time()>25200 && (level[i]-1)*10+bay[i] <=
```

```
ava){
            obj.subnodes[i].labels.assert("DayEnergy").value =
Table("PowerTable")[level[i]][bay[i]]*(time()-25200)/3600;
        }
        else if (param(3)[i]>25200 && time()<82800 && (level[i]-1)*10+bay[i]
<= ava){
            obj.subnodes[i].labels.assert("DayEnergy").value =
Table("PowerTable")[level[i]][bay[i]]*age[i]/3600;
        }
        else if (param(3)<82800 && time()>82800 && (level[i]-1)*10+bay[i] <=
ava){
            obj.subnodes[i].labels.assert("DayEnergy").value =
Table("PowerTable")[level[i]][bay[i]]*(82800-param(3)[i])/3600;
        }
        else{
            obj.subnodes[i].labels.assert("DayEnergy").value = 0;
        }
        daricaricare [i] = 1 - per[i];
        param(4)[i] = param(2)[i] + daricaricare[i]*100 +
obj.subnodes[i].labels.assert("csoc").value;
        obj.subnodes[i].labels.assert("DoC").value = (MaxLevelRackSoC -
param(4)[i])/100 * param(1)[i];
    }
    else
    param(4)[i] = MaxLevelRackSoC;
}
return param(4);
```

It's worth to explain that in delay model, we have to consider all the possible condition for battery charge. In the code, we have divided them as follows:

1. The batteries could be charged at day time;
2. The batteries couldn't be charged at day time, it comes and finish charging process before 7:00;
3. The batteries couldn't be charged at day time, it comes before 7:00, but finish charging during day time;
4. The batteries couldn't be charged at day time, it comes before 7:00, finish charging after 23:00 (stop charging during day time);
5. The batteries couldn't be charged at day time, it comes and finish charging during day time;
6. The batteries couldn't be charged at day time, it comes during day time, but finish charging after 23:00 (stop charging during day time);
7. The batteries couldn't be charged at day time, it comes and finish charging during night time.

The calculation show be considered different condition and them, all the batteries provided would be counted their energy consumption as “AddEnergy”, all the batteries stored in warehouse would be counted there energy consumption as “TotEnergy”. Besides, considering in a new day, all the batteries should be full charged to reach the initial condition (the time is enough), the energy will be used to full charged them would be counted as “TomaxEnergy”. The total energy consumption per day is the sum of these three parameters. Also, in the day time, code counts the energy consumption timely. Finally, the night time energy consumption is the difference between them.

Considering the other side, when battery is swapped in the swapping bay, at the same time, the ASRS would transmit the FBs (even it may not be full charged in model, for simplified call, the batteries exit the warehouse are called FBs) to RetrievalBay, which is a queue used as a transport location for AGV to catch the FBs.

The AGV transmit the FBs to swapping bay and a sink called OutBattery object is used to standard the customer leave BSS with swapped battery or could say “battery destroyed”. When last customer leave, the trigger would be executed and the label of SwapBay would be set to “0” means that the bay is free, allowing next customer enter the swapping bay from waiting queue. Besides, for tracing the leaving batteries, a BatteryTable and a CustomersTable are built and the items will show the related parameters of the batteries.

The Tigger of Sink is shown below:

```
/**Custom Code*/
Object current = ownerobject(c);
Object item = param(1);
int port = param(2);

Object baia1 = model().find("SwapBay");
Object baia2 = model().find("SwapBay2");
Table table = Table("BatteryTable");
Table table1 = Table("CustomersTable");
int riga = current.labels["Exit"].value;

if (item.Queue == 1)
baia1.labels.assert("Busy").value = 0;

if (item.Queue == 2)
baia2.labels.assert("Busy").value = 0;
```

```
// update CustomersTable
table1.addRow(riga);
table1.setRowHeader(riga,"Customer " + string.fromNum(numCustomer));
table1.cell(riga,1).value = item.StartWait;
table1.cell(riga,2).value = item.EndWait;
table1.cell(riga,3).value = item.StartService;
table1.cell(riga,4).value = item.EndService;
table1.cell(riga,5).value = item.EndWait-item.StartWait;
table1.cell(riga,6).value = item.EndService-item.StartService;
table1.cell(riga,7).value = table1.cell(riga,5).value + table1.cell(riga,6).value;

numCustomer++;

// Update BatteryTable
table.addRow(riga);
table.setRowHeader(riga,"Battery " + string.fromNum(numBattery));
table.cell(riga,1).value = item.Type;
table.cell(riga,2).value = item.Capacity;
table.cell(riga,3).value = item.StoringSoC;
table.cell(riga,4).value = item.SoC;
table.cell(riga,5).value = item.EntryTime;
table.cell(riga,6).value = item.MaxSoCTime;
table.cell(riga,7).value = item.OutTime;
table.cell(riga,8).value = item.State;
table.cell(riga,9).value = item.Energy;
table.cell(riga,10).value = item.OutTime-item.EntryTime;

if (item.MaxSoCTime != -1){
	table.cell(riga,11).value = item.OutTime-item.MaxSoCTime;
	table.cell(riga,12).value = item.MaxSoCTime-item.EntryTime;
}
else{
	table.cell(riga,11).value = 0;
	table.cell(riga,12).value = item.OutTime-item.EntryTime;
}
table.cell(riga,13).value = item.DayEnergy;
numBattery++;
current.labels.assert("Exit").value+= 1;
```

Finally, we could build this complex model. The 3D presentation is shown in Fig 4.4.6:

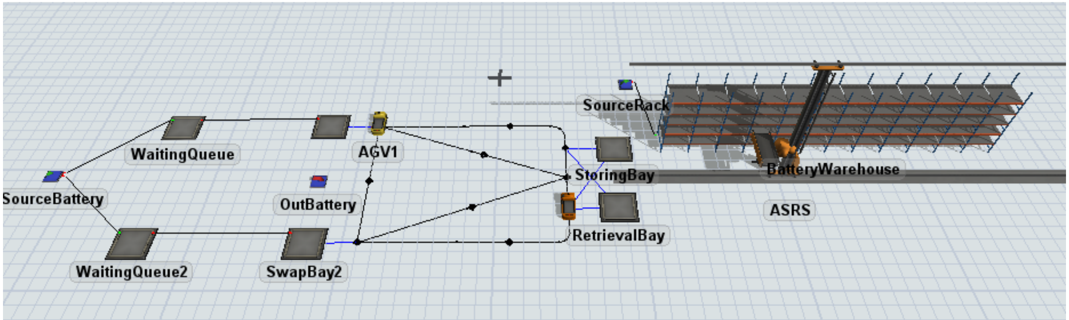

Fig 4.4.6 3D model of Battery swapping station

Before activating the model, a reset process is needed for repeat simulation. The OnModelReset Trigger is executed when model is reset to initialize the objects and global variebles. The code is shown below:

```
/* Reset Code */
Object obj = model().find("BatteryWarehouse");

// Reset TypeTable
Table table = Table("TypeTable");
table.clear();
table.setColHeader(1, "Type");
table.setColHeader(2, "Capacity");
table.setSize(numType, 2);
int tip = 1;
int cap = 41;

for (int i=1; i<=numType; i++){
        table.cell(i,1).value = tip;
        table.cell(i,2).value = cap;
        tip++;
        cap+=34;
}
// Reset BatteryTable
Table table1 = Table("BatteryTable");
table1.clear();
table1.setSize(0,13);
table1.setColHeader(1, "Type");
table1.setColHeader(2, "Capacity");
table1.setColHeader(3, "StoringSoC");
table1.setColHeader(4, "SoC");
table1.setColHeader(5, "EntryTime");
table1.setColHeader(6, "MaxSoCTime");
```

```
table1.setColHeader(7, "OutTime");
table1.setColHeader(8, "State");
table1.setColHeader(9, "Energy");
table1.setColHeader(10, "StayTime");
table1.setColHeader(11, "StayTimeToMax");
table1.setColHeader(12, "ChargingTime");
table1.setColHeader(13, "DayEnergy");
// Reset CustomersTable
Table table0 = Table("CustomersTable");
table0.clear();
table0.setSize(0,7);
table0.setColHeader(1, "StartWait");
table0.setColHeader(2, "EndWait");
table0.setColHeader(3, "StartService");
table0.setColHeader(4, "EndService");
table0.setColHeader(5, "TimeOfWait");
table0.setColHeader(6, "TimeOfService");
table0.setColHeader(7, "TimeInStation");
// Reset WaitTable & PowerTable
Table table2 = Table("WaitTable");
Table table3 = Table("PowerTable");
table2.clear();
int bay = rackgetnrofbays(obj);
int level = rackgetnroflevels(obj);
table2.setSize(level,bay);
table3.setSize(level,bay);
int dimension1 = 1;
for (int i=1; i<=level; i++){
	table2.setRowHeader(i, "Level " + string.fromNum(dimension1));
	table3.setRowHeader(i, "Level " + string.fromNum(dimension1));
	dimension1++;
}
int dimension2 = 1;
for (int i=1; i<=bay; i++){
	table2.setColHeader(i, "Bay " + string.fromNum(dimension2));
	table3.setColHeader(i, "Bay " + string.fromNum(dimension2));
	dimension2++;
}
for (int i=1; i<=level; i++){
	for (int j=1; j<=bay; j++){
		table2.cell(i,j).value = 0;
		table3.cell(i,j).value = 22;
	}
}
```

4.5 Process Flow

Most of the logic has been integrated into the 3D model as pointed out before, while the logic associated with the vehicles tasks was built in the process flow tool. This is because transportation tasks are more efficient than using the standard 3D operating logic as it can handle customization much better (see FlexSim documentation). The process flow is divided into sections depending on the functions performed. These sections are called containers and are suitable to visualize and keep activities organized. The Process Flow of the model is illustrated in the following figure (Fig 4.5.1), in which it is possible to see the decision-making logic applied.

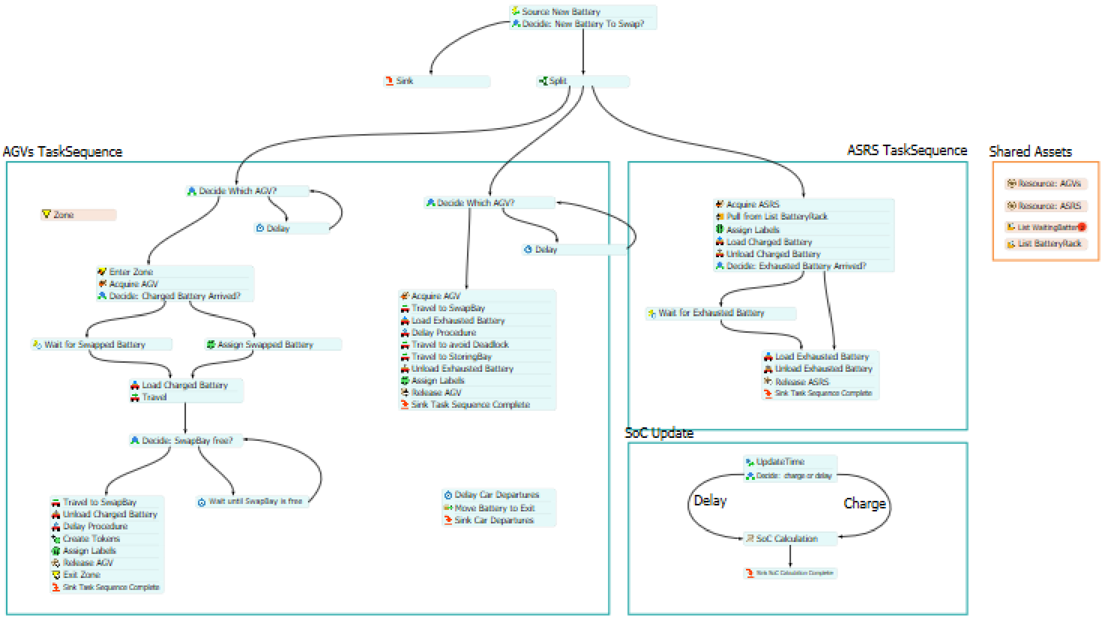

Fig 4.5.1 Process flow diagram

In the share assets, the Resource blocks and the List blocks could be found. The resources represent the available task executors, for example the AGV and ASRS vehicle. The two lists blocks here are connect to the global lists called BatteryRack and WaitingBattery, which two lists act as databases for every battery in the system for data searching and recording. The first list contains all the data related to the batteries currently stored inside the warehouse already seen before, such as time of entry, type, capacity, location in the rack, etc. Whenever a battery is retrieved from the rack, it would be removed from the list, meanwhile, each time a battery enters the rack, it will be added to the list. While the second list hold the information about the batteries arriving at the station and in WaitingQueue currently waiting to be served. The list entries are updated every time a new item joins or leave the WaitingQueue.

The event-triggered source New Battery Arrived monitors the entry of the SwapBay queue and creates a token once a battery enters it. The token represents the battery swap request and it will be associated with that specific battery. The decide activity New Battery Swap Request is used to determine whether the battery needs to be replaced or not (i.e. if the battery has already been replaced and is waiting to leave the station). The token is then split in order to acquire simultaneously both the AGV resource and the ASRS resource and in such a way as to manage the operations for the two vehicles in two separate branches. And the two task executors can begin their task sequences.

For ASRS, as it performs the store/retrieval cycle that consist in pulling from the BatteryRack list the charged battery that will be swapped with the discharged one, thus inserted in the car. If there is no FBs, the most charged battery (with the highest SoC) with the same type of battery required would be selected from the list according to the logic discussed above. The selection of the battery from the rack has been optimized in such a way as to take first the charged batteries present in the warehouse at the beginning of the simulation and, if all these work donw, among those that have been exchanged and have reached the maximum charge, the one that has longest reached its maximum charge. This process can minimize the time a charged battery stays in the warehouse. Moreover, to reduce service times, the puller (ASRS) will take not only the most charged battery but also the one closest to the position in which it is located (i.e. the battery at the shortest distance). Once the battery is selected, it will be picked up by ASRS and placed in RetrievalBay. After the retrieval cycle is completed, the ASRS performs the storage cycle taking the exhausted battery from the StoringBay (if it is present) and then put the battery in the warehouse slot as the same location of the retrieved battery. At the end of this cycle, the battery is pushed to the BatteryRack list to store the battery’s information and the ASRS resource is released. The task code is shown below:

```
Variant value = param(1);
Variant puller = param(2);
treenode entry = param(3);
double pushTime = param(4);

if (!objectexists(puller))
	return -1;
treenode ASRS = puller.ASRS;
updatelocations(value);
updatelocations(up(puller));

/**Straight-Line Distance From Resource to Puller*/
double height = getvarnum(ASRS, "forkresetheight");
double x1 = vectorprojectx(value, 0.5 * xsize(value), -0.5 * ysize(value), 0, model());
double y1 = vectorprojecty(value, 0.5 * xsize(value), -0.5 * ysize(value), 0, model());
double z1 = vectorprojectz(value, 0.5 * xsize(value), -0.5 * ysize(value), 0, model());
double x2 = vectorprojectx(ASRS, 0.5 * xsize(ASRS), -0.5 * ysize(ASRS), height, model());
double y2 = vectorprojecty(ASRS, 0.5 * xsize(ASRS), -0.5 * ysize(ASRS), height, model());
double z2 = vectorprojectz(ASRS, 0.5 * xsize(ASRS), -0.5 * ysize(ASRS), height, model());

return sqrt(sqr(x1 - x2) + sqr(y1 - y2) + sqr(z1 - z2));
```

Then considering the AGV task. Once the AGV resource is acquired, it travels to SwapBay to swap the battery and picks up the battery. After a delay that represents the time it takes the automated mechanism to perform all procedures to remove the empty battery from underneath the car, it transports the battery depositing it to StoringBay. At the same time, the AGV picks up the charged battery from the RetrievalBay (if it is present) and travels back to SwapBay to insert the charged battery into the car (also in this case there is a delay for the automatic procedure). Then AGV resource is freed.

An extra delay is added (Delay Car Departures) and represent the customer that get the car started and leave the station. Finally, the battery is moved to the OutBattery sink and it is stored in the Battery table to track key parameters for simulation.

4.6 Plan of Experiments

After building the simulation model and the logic relation of the whole system, a series of experiments would be carried out in order to simulate the behavior and result in different operating conditions, which the aim is to discuss the performance of the BSS model with related variables and understand the most significant factors in the model. Discuss what's the impact of variables and finally, if possible, find a proper variables combination to satisfy the requirements as much as possible.

In the model, the variables include:

1. The size of the warehouse and the number of stored two types batteries;
2. The ratio that related to the number of batteries could be charged at daily time.

Consider the assumption made above, the max content of items and the number of batteries stored should be varies simultaneously with warehouse size.

The Table below concludes the variables combination:

Table 4.6.1

Variables	Experiment value	
Warehouse size (only changes the number of bays)	10*6	
	12*6	
	14*6	
Max content of items of warehouse	60 (related)	
	72 (related)	
	84 (related)	
Initial stored batteries inside the warehouse	Type 1 (44 kWh)	Type 2 (75kWh)
	40 (related)	20 (related)
	48 (related)	24 (related)
	56 (related)	28 (related)
Ratio of batteries could be charged at daily time	20%	
	30%	
	40%	
	50%	
	60%	
	70%	
	100% (ref)	

Finally, we have 21 combinations shown in Table 4.6.2:

Table 4.6.2

No. of Case	Ratio	Warehouse size
1	20%	10*6
2		12*6
3		14*6
4	30%	10*6
5		12*6
6		14*6
7	40%	10*6
8		12*6
9		14*6
10	50%	10*6
11		12*6
12		14*6
13	60%	10*6
14		12*6
15		14*6
16	70%	10*6
17		12*6
18		14*6
19	100%	10*6
20		12*6
21		14*6

By using Flexsim Experimenter tool, it's possible to simulate the system with more than one case per time and each case could repeat several times to obtain a set of statistical data defined by user. In our model, we consider one day (24 hours, 86400 seconds) as a repeat cycle for simulation and one seconds as time step. Let's consider 5 replications for each case. However, the number of bays of warehouse could not be changed by experimenter tool, we need to change the size and other related variables manually.

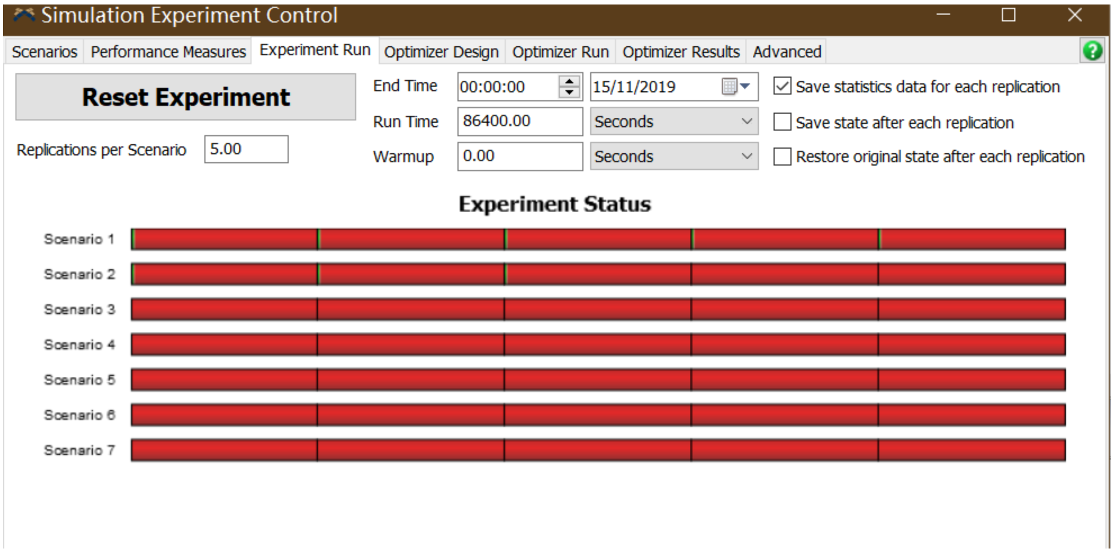

Fig 4.6.1 Experimenter tool interface

4.7 Collection Methodology of Results

Through the study and evaluation about the characteristics of the system (with the analysis of performance), the optimal values of the parameters of interest are defined and the critical points (bottlenecks) of the built model are determined. The parameters and performance measures observed, that have been tracked and collected from each simulation experiment. These parameters are related to:

- Average value and standard deviation for Customer Waiting Time, customers are considered as "constant coming rate and they will leave only if the service finish". Thus, the customer waiting time would be an important indicator presents the customers' satisfaction.
- Average value and standard deviation for Service Time, from this parameter, we can know whether our system could offer a quick service for customers.
- Average value and standard deviation for Battery Charge Level Provided, another important parameter to discuss whether the customer requirements are satisfied. Since our model assume that not full charged batteries would also be given, this value would present whether the number of charge bays could handle the busy time requirement.
- Total energy required by the station per day, which the value indicate the energy consumption per day.
- Total energy required by the station in day time per day, which the value is the energy consumption during period of 7:00 ~ 23:00, indicate the high electricity consumption period energy cost.
- Total energy required by the station in day night per day, which the value is the energy consumption during period of 23:00 ~ 7:00 (2^{nd} day), indicate the low electricity consumption period energy cost.
- Number of Full Charged Batteries. In real cases, only FBs could be

changed to customers, so this would be a parameter used to discuss the variables combination is better or worse.

Besides, there are some other measurements as shown in Fig 4.7.1, they would be considered if necessary.

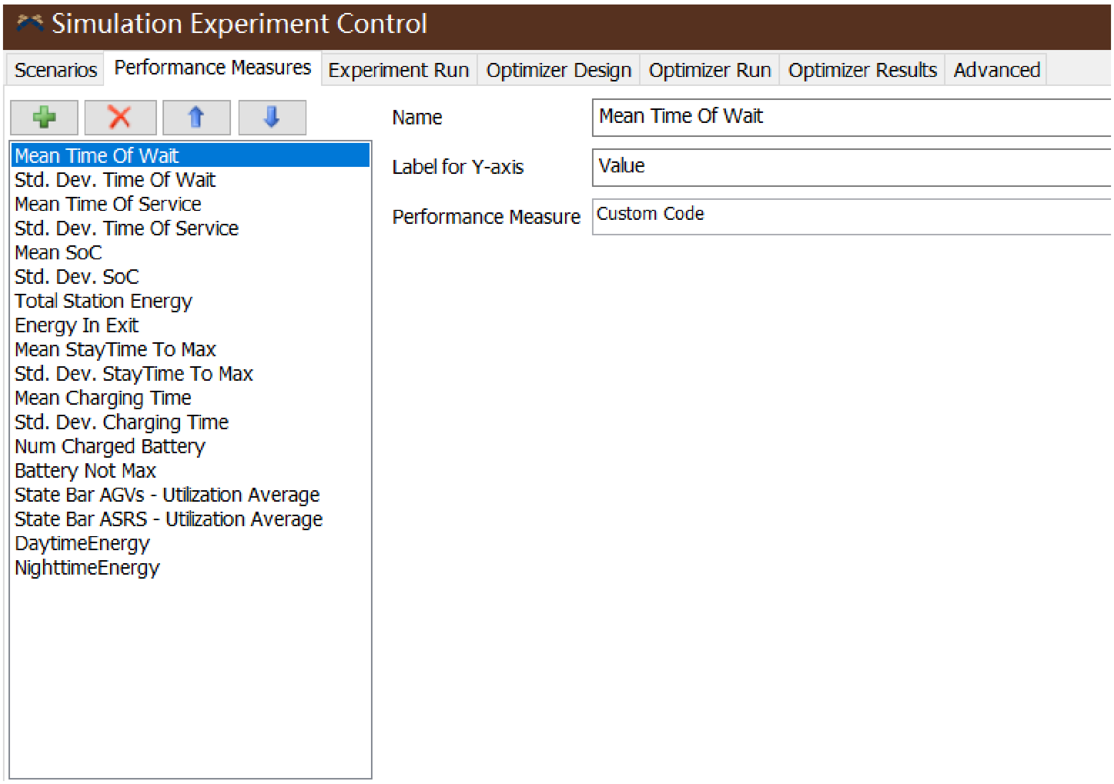

Fig 4.7.1 Performance measures

The data collection has been carried out by storing a series of significant moments of time, in which a certain action takes place. All items' information will be accessible in the form of global table at the end of the simulation as mentioned above. Fig 4.7.2 shows the global table "BatteryTable" that contains data about batteries leaving the station, inside which the parameters are:

- Type: the battery type;
- Capacity: the battery capacity (in kWh);
- StoringSoC: the battery SoC level when it entered the warehouse (in %);
- SoC: the battery charge level when it left the warehouse (in %);
- EntryTime: the time when the battery enters the warehouse (in sec);
- MaxSoCTime: the time when the battery reaches its maximum charge (in sec if it's not "0" or "-1");

- OutTime: the time when the battery leaves the warehouse (in sec);
- State: the battery status;
- Energy: the energy used to recharge the battery (in kWh);
- STayTimeToMax: the dwell time of fully charged battery in the warehouse, in other words is the difference between OntTime and MaxSoCTime (in sec);
- Charging Time: the time when the battery has been in charge in the warehouse, that is to say the difference between OutTime and EntryTime for the batteries that have not reached their maximum charge and between MaxSoCTime and EntryTime for the batteries that have reached the maximum charge (in sec).

Model | PowerTable | TypeTable | BatteryTable | CustomersTable | WaitTable | ASRS

	Type	Capacity	StoringSoC	SoC	EntryTime	MaxSoCTime	OutTime	State	Energy	StayTime	StayTimeToM	ChargingTime	Da
Battery 73	2	75	90	90	0	0	27843.50	-1	0	27843.50	27843.50	0	
Battery 74	1	41	90	90	0	0	27958.74	-1	0	27958.74	27958.74	0	
Battery 75	2	75	90	90	0	0	28049.09	-1	0	28049.09	28049.09	0	
Battery 76	1	41	90	90	0	0	28159.93	-1	0	28159.93	28159.93	0	
Battery 77	1	41	90	90	0	0	28259.32	-1	0	28259.32	28259.32	0	
Battery 78	1	41	90	90	0	0	28372.85	-1	0	28372.85	28372.85	0	
Battery 79	1	41	90	90	0	0	28480.59	-1	0	28480.59	28480.59	0	
Battery 80	1	41	90	90	0	0	28600.18	-1	0	28600.18	28600.18	0	
Battery 81	1	41	90	90	0	0	28712.27	-1	0	28712.27	28712.27	0	
Battery 82	1	41	34.38	90	695.77	4427.20	28818.81	0	22.80	28123.05	24391.61	3731.43	
Battery 83	1	41	16.48	90	1888.18	6821.00	28922.54	0	30.14	27034.35	22101.54	4932.82	
Battery 84	1	41	5.85	90	1298.68	6944.80	29012.89	0	34.50	27714.21	22068.09	5646.12	
Battery 85	1	41	9.96	90	2492.18	7862.10	29128.07	0	32.82	26635.89	21265.97	5369.92	
Battery 86	1	41	34.50	90	4900.18	8624.10	29224.42	0	22.76	24324.24	20600.32	3723.92	
Battery 87	1	41	5.63	90	3696.39	9357.30	29341.54	0	34.59	25645.15	19984.24	5660.91	
Battery 88	2	75	90	90	0	0	29451.89	-1	0	29451.89	29451.89	0	
Battery 89	2	75	90	90	0	0	29536.75	-1	0	29536.75	29536.75	0	
Battery 90	2	75	90	90	0	0	29668.91	-1	0	29668.91	29668.91	0	
Battery 91	1	41	21.23	90	6104.18	10717.80	29755.26	0	28.19	23651.07	19037.46	4613.62	
Battery 92	1	41	7.57	90	9108.18	14639.00	29861.60	0	33.80	20753.42	15222.60	5530.82	
Battery 93	2	75	3.94	90	3105.23	13667.00	29981.00	0	64.54	26875.77	16314.00	10561.77	
Battery 94	1	41	10.85	90	10912.18	16222.60	30088.39	0	32.45	19176.20	13865.79	5310.42	
Battery 95	2	75	30.18	90	7304.53	14645.80	30204.74	0	44.86	22900.20	15558.94	7341.27	

Fig 4.7.2 Data example in BatteryTable

And in the CustomerTable, other useful parameters would be recorded:

- StartWait. the time when the customer starts waiting for his turn (in sec);
- EndWait. the time when the customer's turn has come (in sec);
- StartService. the time when the customer starts to be served (in sec);
- EndService: the time when the customer was served (in sec);
- TimeOfWait: the time elapsed from when the customer enters the station to when he is served, which is the difference between EndWait and StartWait (in sec);

- TimeOfService: the actual customer service time, that is the difference between EndService and StartService. (in sec);

Model | PowerTable | TypeTable | BatteryTable | CustomersTable | WaitTable | ASRS

	StartWait	EndWait	StartService	EndService	TimeOfWait	TimeOfServic	TimeInStatior
Customer 65	26951.35	26951.35	26951.35	27059.06	0	107.70	107.70
Customer 66	26854.05	26991.97	26991.97	27167.30	137.92	175.33	313.24
Customer 67	27145.95	27145.95	27145.95	27257.04	0	111.09	111.09
Customer 68	27048.65	27187.30	27187.30	27371.29	138.65	183.99	322.64
Customer 69	27340.54	27340.54	27340.54	27445.13	0	104.59	104.59
Customer 70	27243.24	27391.29	27391.29	27585.77	148.04	194.48	342.52
Customer 71	27535.14	27535.14	27535.14	27692.05	0	156.91	156.91
Customer 72	27437.84	27605.77	27605.77	27767.80	167.93	162.03	329.96
Customer 73	27729.73	27729.73	27729.73	27915.15	0	185.42	185.42
Customer 74	27632.43	27787.80	27787.80	28021.90	155.37	234.10	389.47
Customer 75	27924.32	27935.15	27935.15	28106.84	10.83	171.69	182.52
Customer 76	27827.03	28041.90	28041.90	28225.09	214.87	183.19	398.06
Customer 77	28021.62	28126.84	28126.84	28327.07	105.22	200.23	305.45
Customer 78	28118.92	28245.09	28245.09	28440.01	126.17	194.93	321.09
Customer 79	28216.22	28347.07	28347.07	28552.25	130.85	205.18	336.03
Customer 80	28313.51	28460.01	28460.01	28667.34	146.50	207.33	353.83
Customer 81	28410.81	28572.25	28572.25	28783.92	161.44	211.68	373.11
Customer 82	28508.11	28687.34	28687.34	28881.18	179.23	193.84	373.07
Customer 83	28605.41	28803.92	28803.92	28988.29	198.52	184.37	382.88
Customer 84	28702.70	28901.18	28901.18	29076.05	198.48	174.87	373.34

Fig 4.7.3 Data example in CustomerTable

After a set of experiments simulation finishing, all the related parameters would be recorded and calculated according to the code and parameters we need.

5. Results and Discussion

After all the simulation finishing, we could export the results and do the post-process to better compare the different combination for discussing the pros and cons and their trend according to the variables.

5.1 Waiting Time

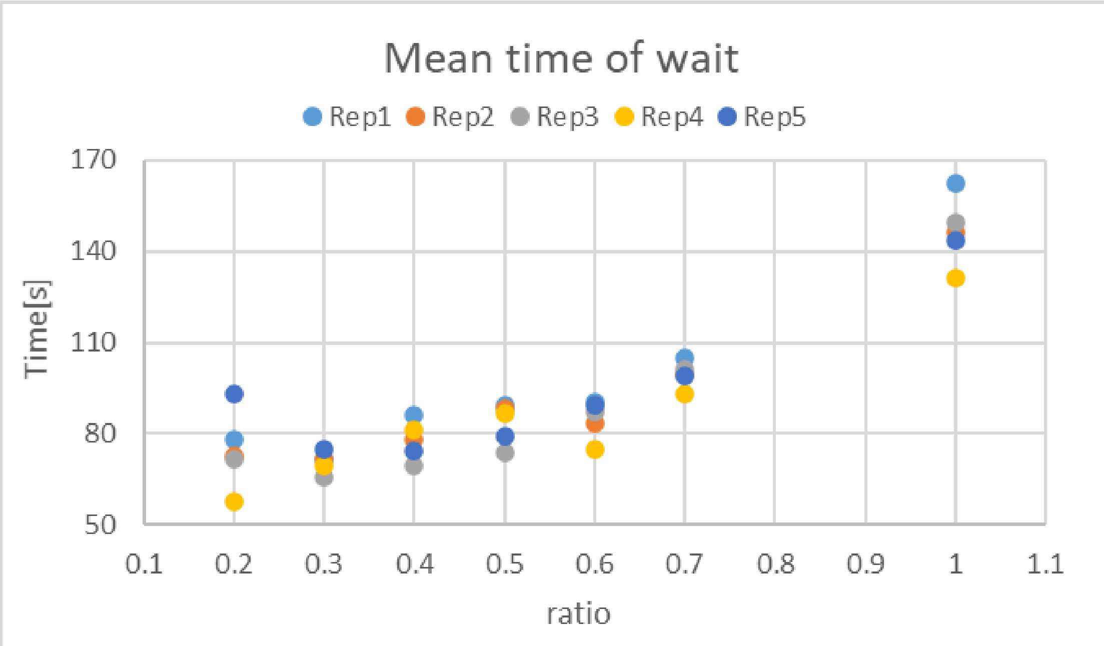

*Fig 5.1.1 Mean time of wait with warehouse size 10*6*

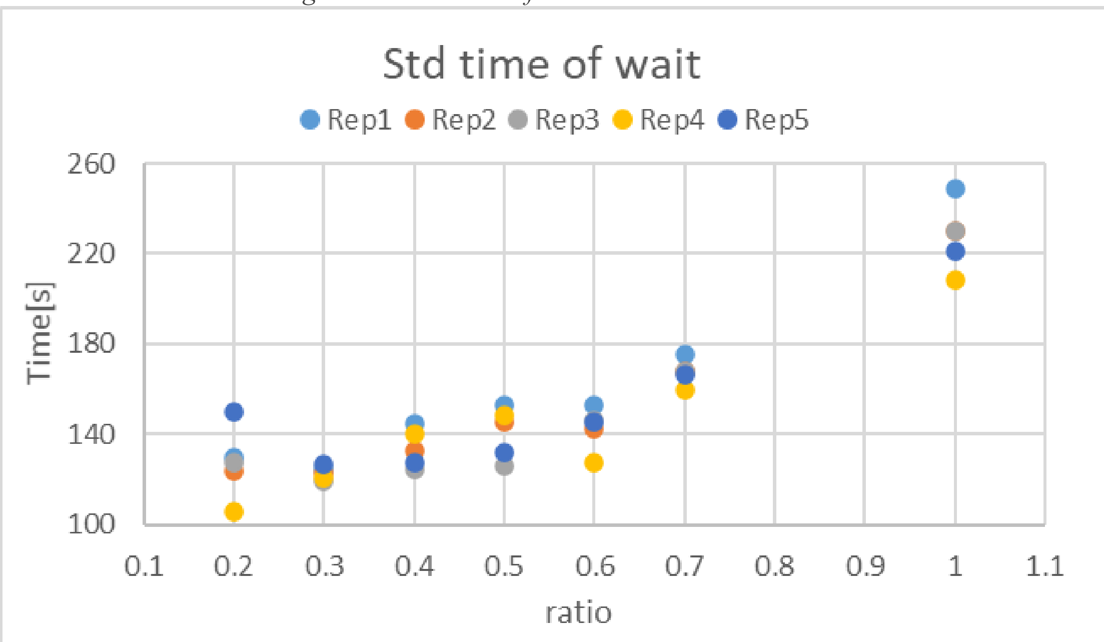

*Fig 5.1.2 Std time of wait with warehouse size 10*6*

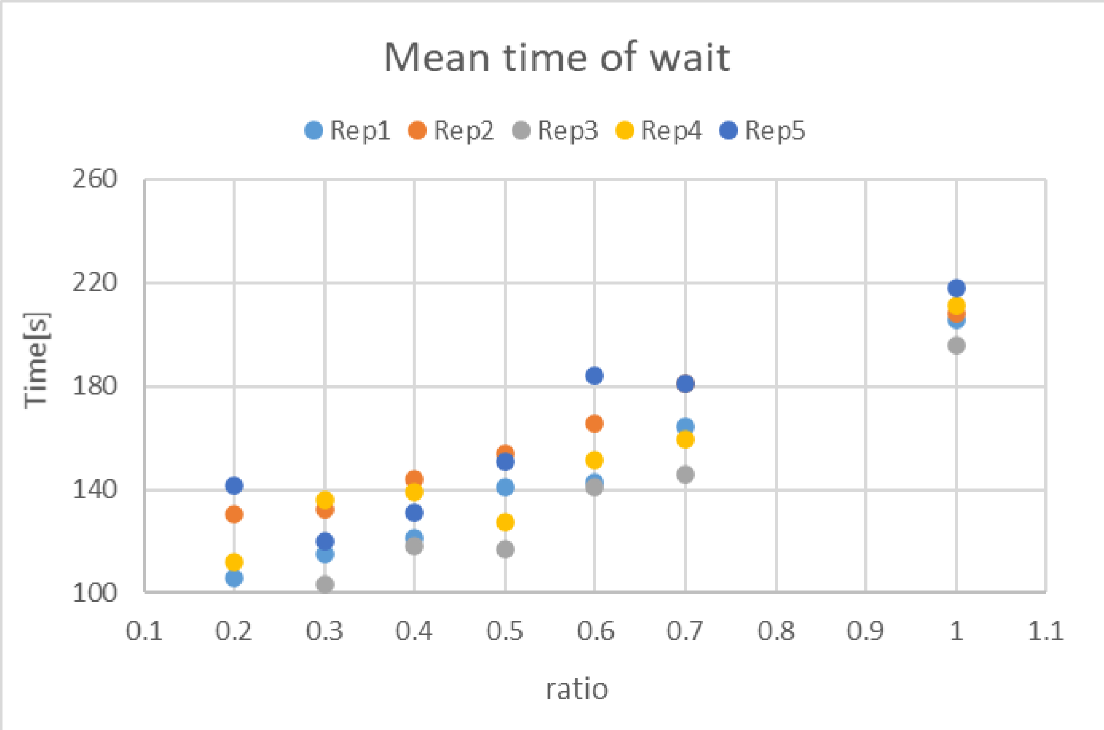

*Fig 5.1.3 Mean time of wait with warehouse size 12*6*

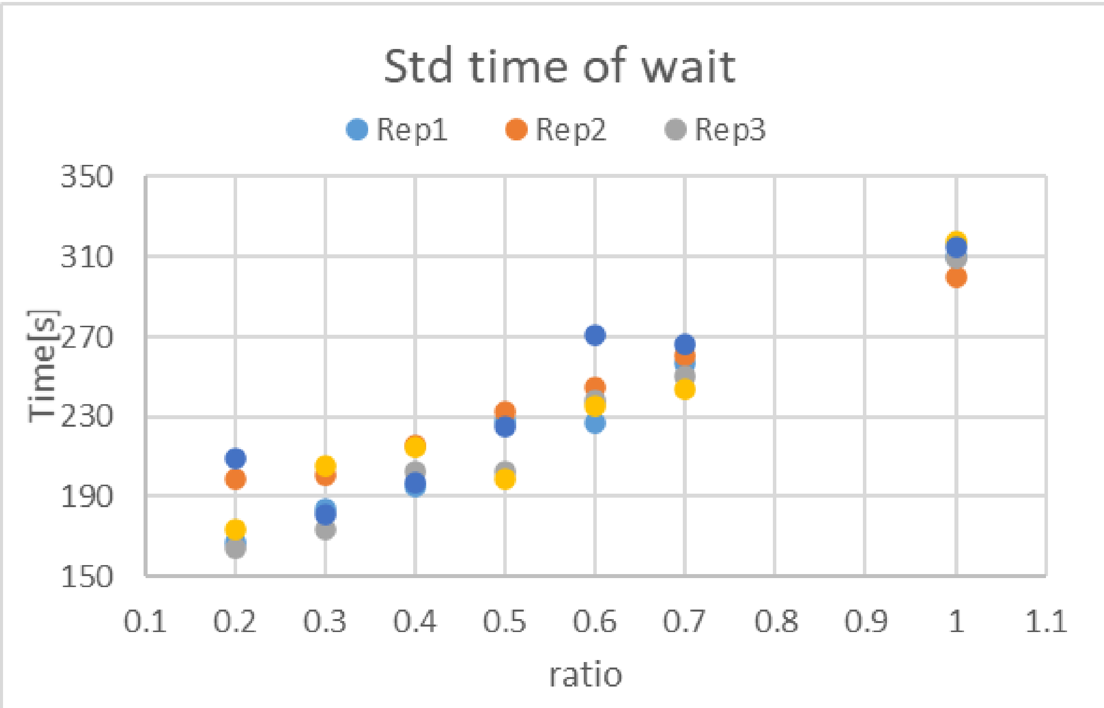

*Fig 5.1.4 Std time of wait with warehouse size 12*6*

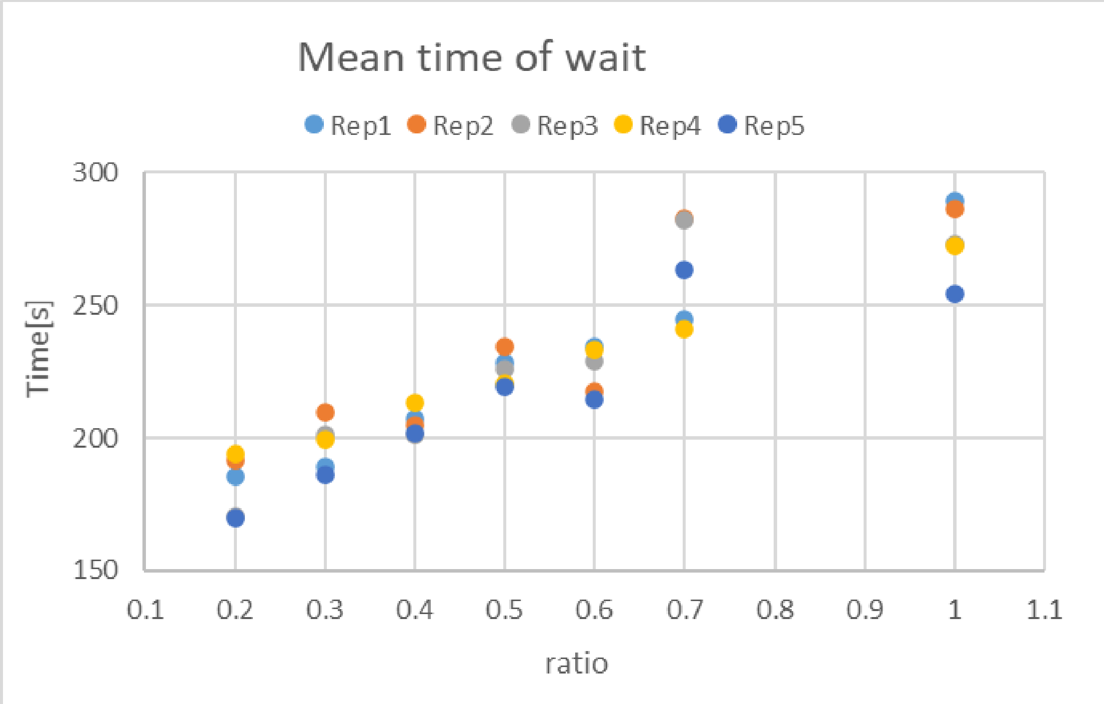

*Fig 5.1.5 Mean time of wait with warehouse size 14*6*

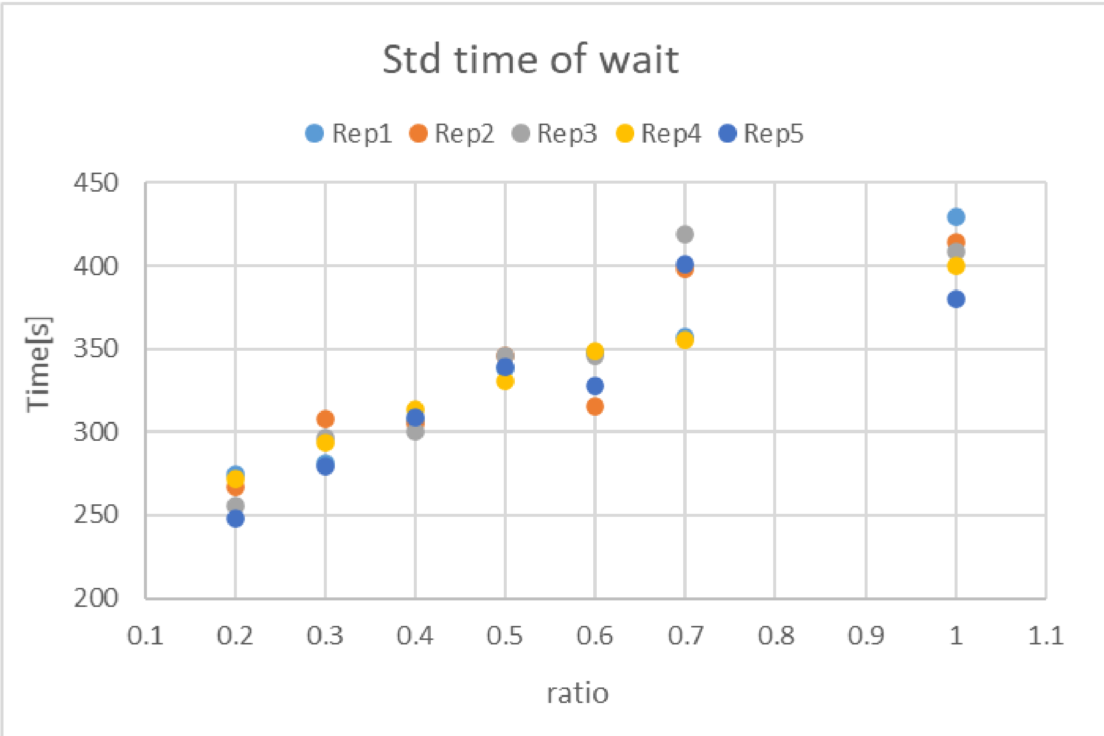

*Fig 5.1.6 Std time of wait with warehouse size 14*6*

As it shown above, we can find that the value of mean of waiting time and Std of waiting time is slightly increasing with the charge ratio increasing. Because when more batteries involving in day time swapping, the ASRS have to travel to a further position to get the batteries which cause the extra service time. Thus, the later waiting customers have to wait more time, and the effect is accumulated especially in busy time. Meanwhile, std value represents the busy time condition and that's why the std value also increasing.

However, if we consider the time various with the warehouse size change, the condition is different. We calculate a mean value for both Mean time and std time with 5 Reps, and we can plot them in Fig 5.1.7 as below:

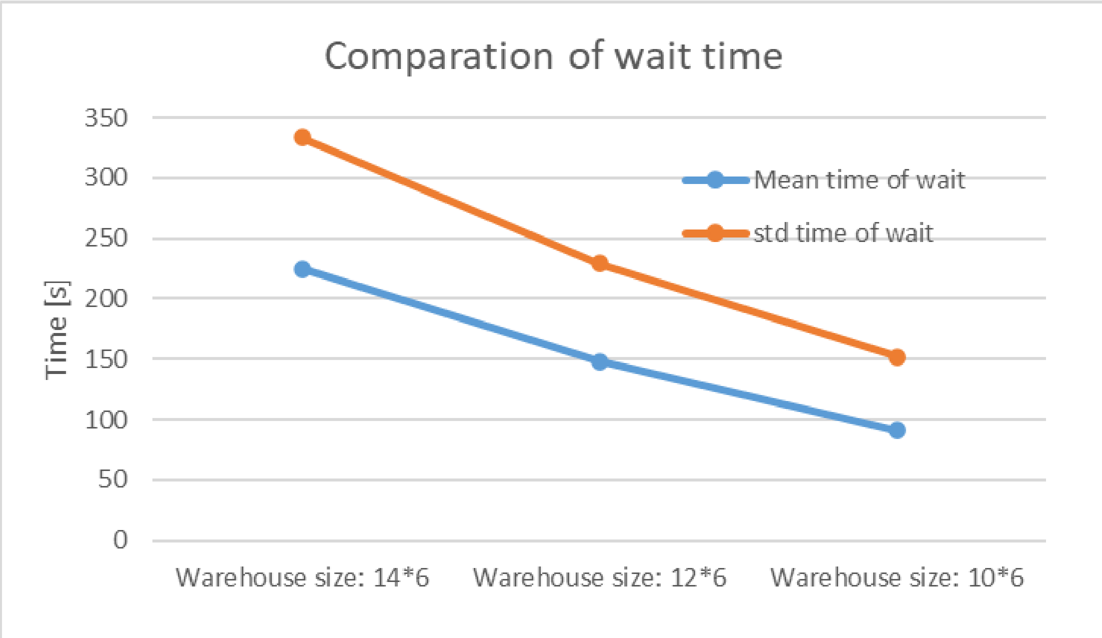

Fig 5.1.7 Comparation of waiting time according to the warehouse size

As we can see, with the warehouse size increasing, both the Mean time of Wait and Std time of Wait all increase obviously. General discuss, we could consider that the increasing of waiting time is mainly due to the ASRS. With the warehouse size increasing, the ASRS have to travel to a further position to put and catch batteries, which the extra task will cost more time and customers have to wait. For another consideration, the std value increasing is due to the same reason. The std value is mainly indicate the condition when BSS in a busy time. With mean value and std value increasing, it doesn't mean all the customers have to wait more time, instead, it represents the customers in busy time have to wait more time. After explaining the essential problem, we could say that, if we just keep the number of batteries charged in the day time constant and all these batteries put in the slots close to the bays, we may control the waiting time to have a little various.

Besides, we could consider that, generally, the waiting time within 5 mins (300 s) is "good" for customers, and within 10 mins (600 s) is "acceptable" for customers. The we can also know from the plot: all the average time could be thought as "good" performance, while considering the busy time, std value represents the possible extra time for waiting.

With 3rd condition, even in busy time, most of customer will think the service speed is good and. For 2nd condition, maybe a certain number of customers will feel "good", however, in busy time, the service could only be considered acceptable. While in 1st case, it's the worst condition but could still be considered as acceptable. Generally, all these three conditions are available, we should first consider other important data.

5.2 Service Time

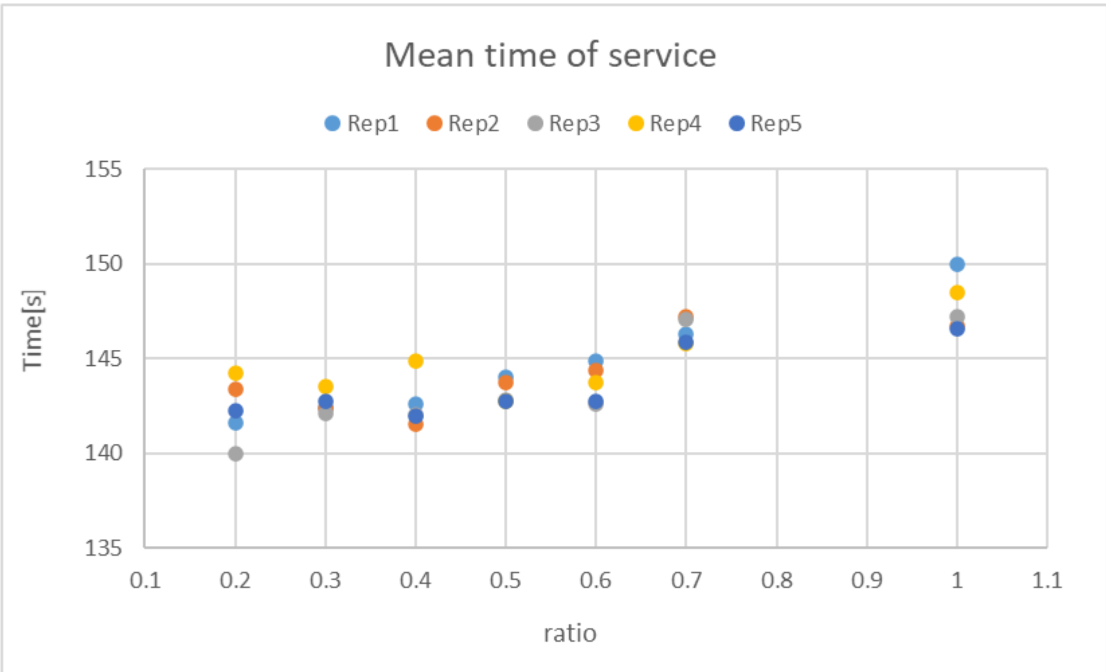

*Fig 5.2.1 Mean time of service with warehouse size 10*6*

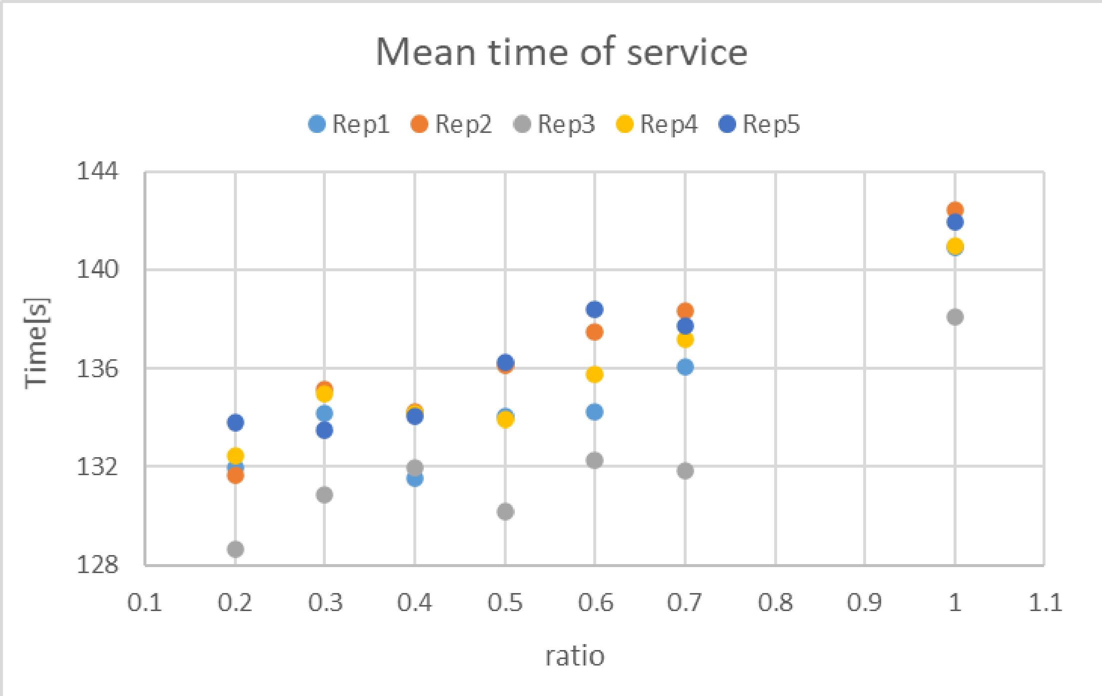

*Fig 5.2.2 Mean time of service with warehouse size 12*6*

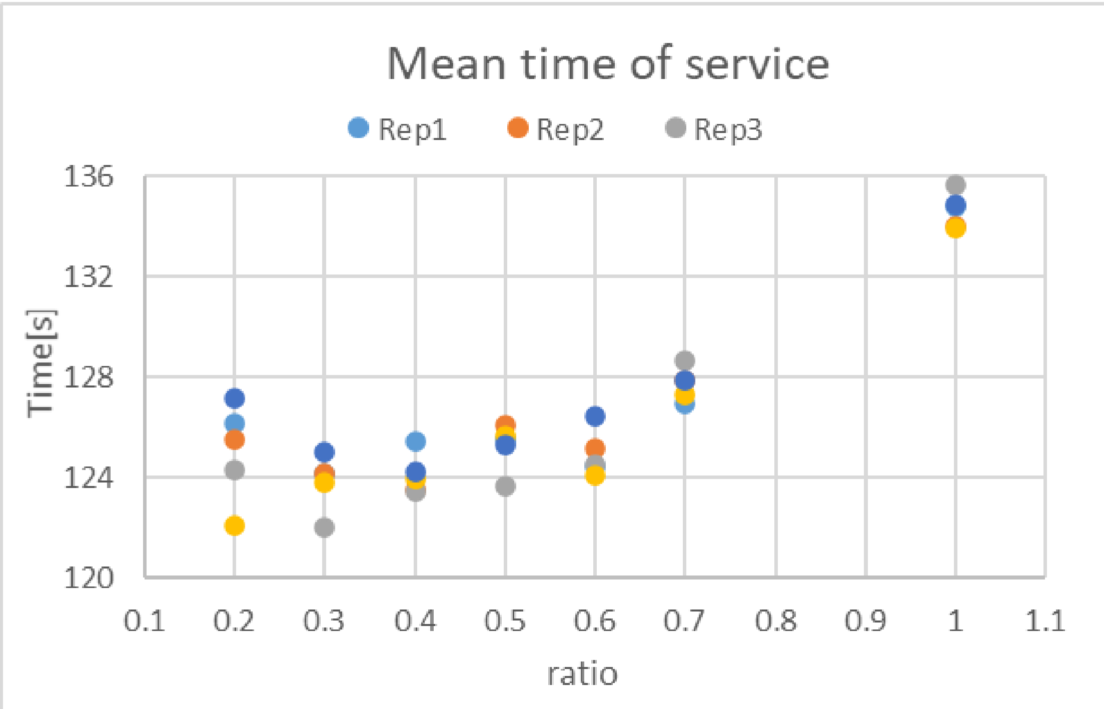

*Fig 5.2.3 Mean time of service with warehouse size 14*6*

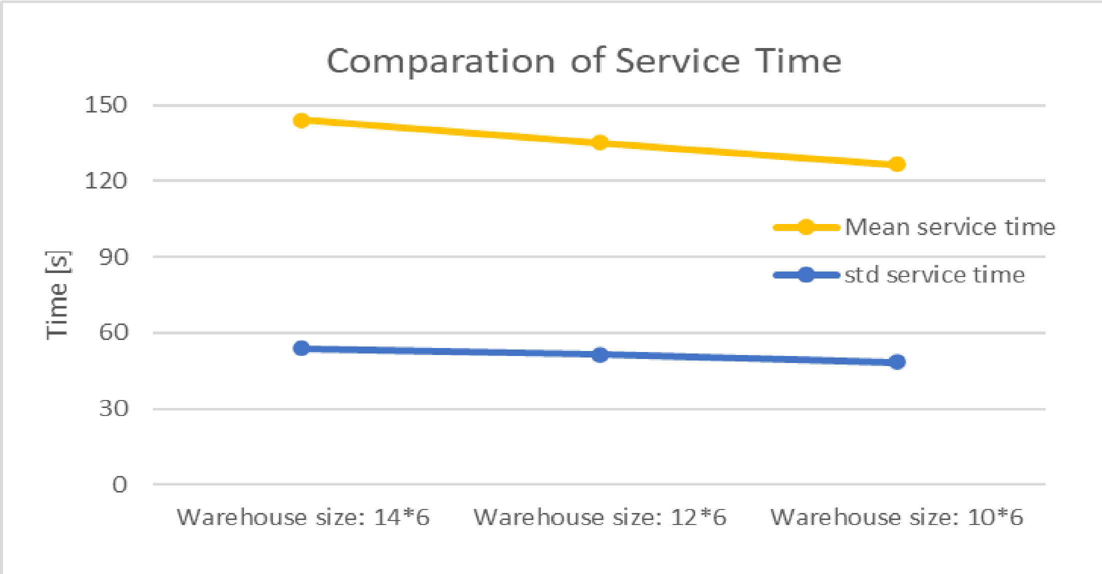

Fig 5.2.4 Comparation of service time according to the warehouse size

As it's mentioned above, with the same reason, the service time would have a very small increase due to ASRS. While the std value of service which represents the busy time have same slightly variation due to the service time is only related to the service system inner parameters like warehouse size, ASRS, AGVs, but it's not depends on the customers. Even the ratio changed, if the warehouse size keeps constant, the std value won't change. While, if warehouse size changes, the std value will have a slightly change with it.

5.3 SoC of provided batteries

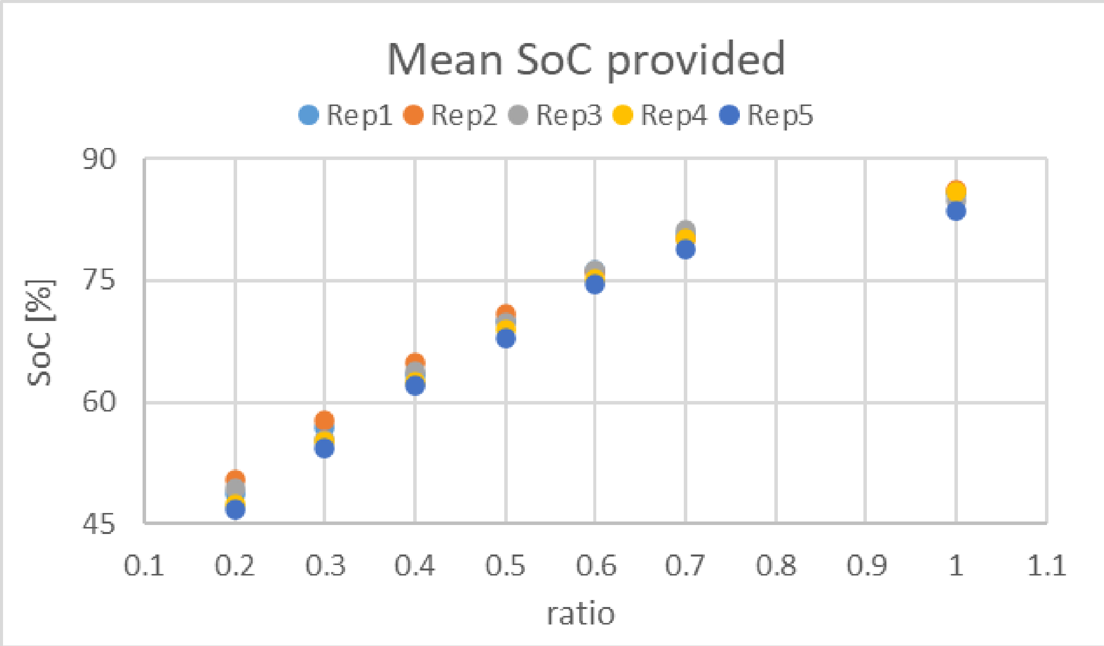

*Fig 5.3.1 Mean SoC provided with warehouse size 10*6*

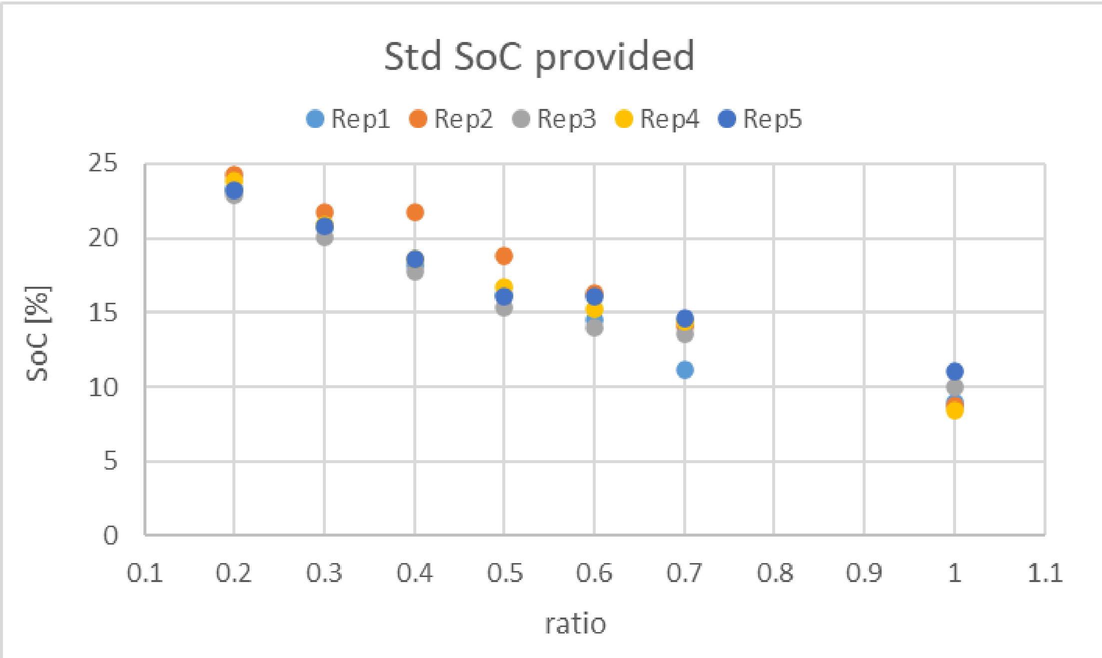

*Fig 5.3.2 Std of SoC provided with warehouse size 10*6*

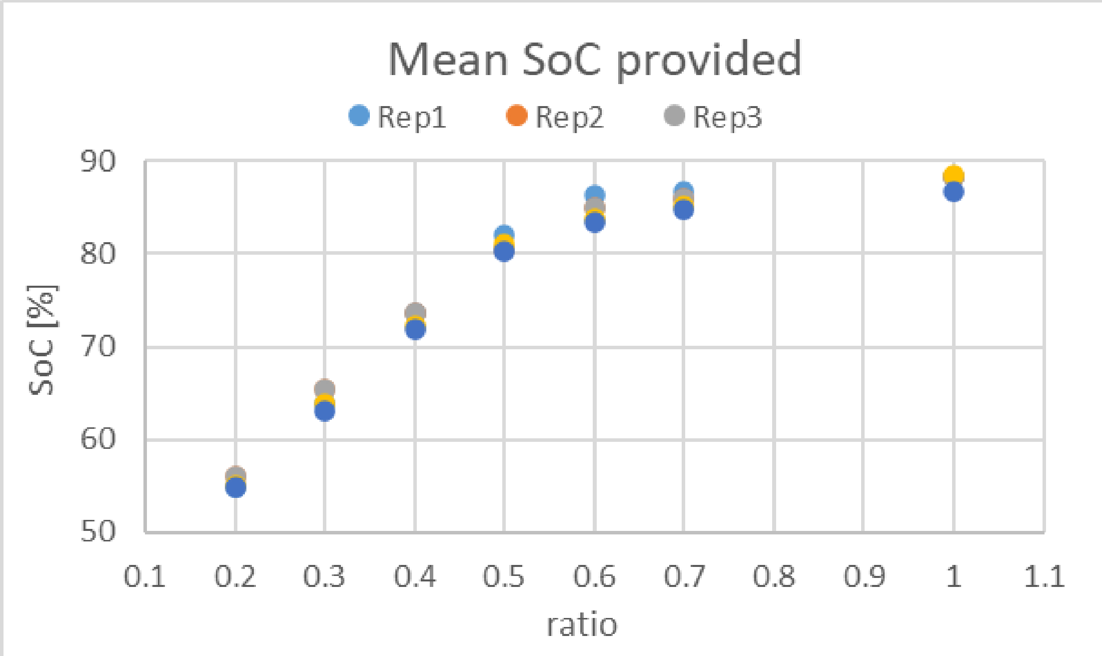

*Fig 5.3.3 Mean SoC provided with warehouse size 12*6*

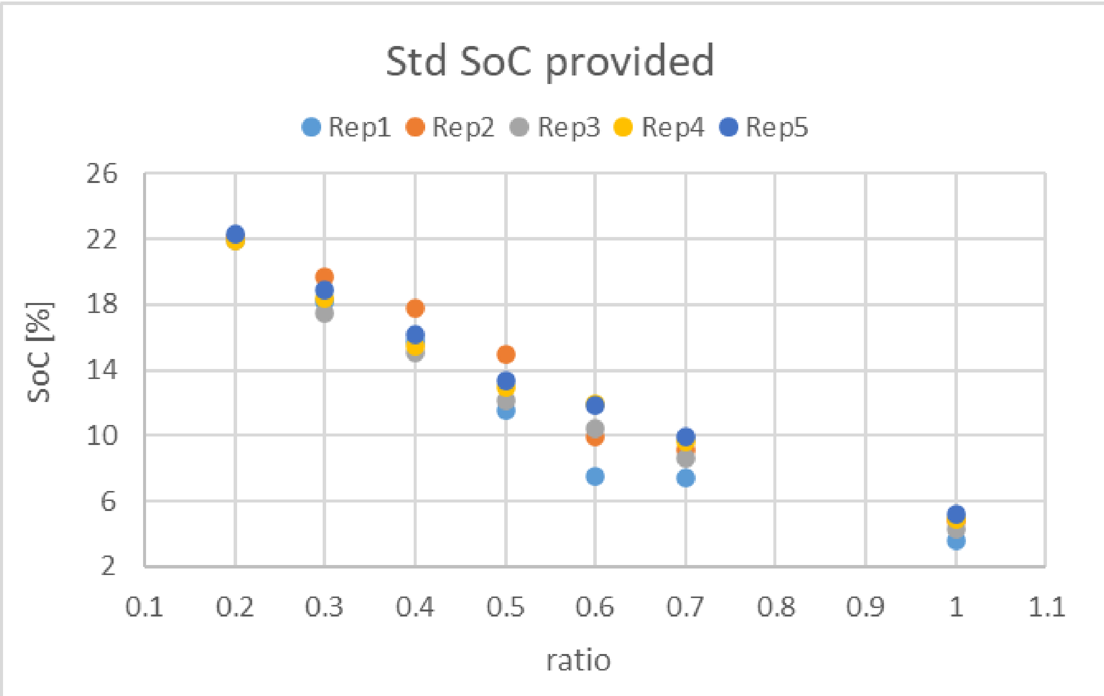

*Fig 5.3.4 Std of SoC provided with warehouse size 12*6*

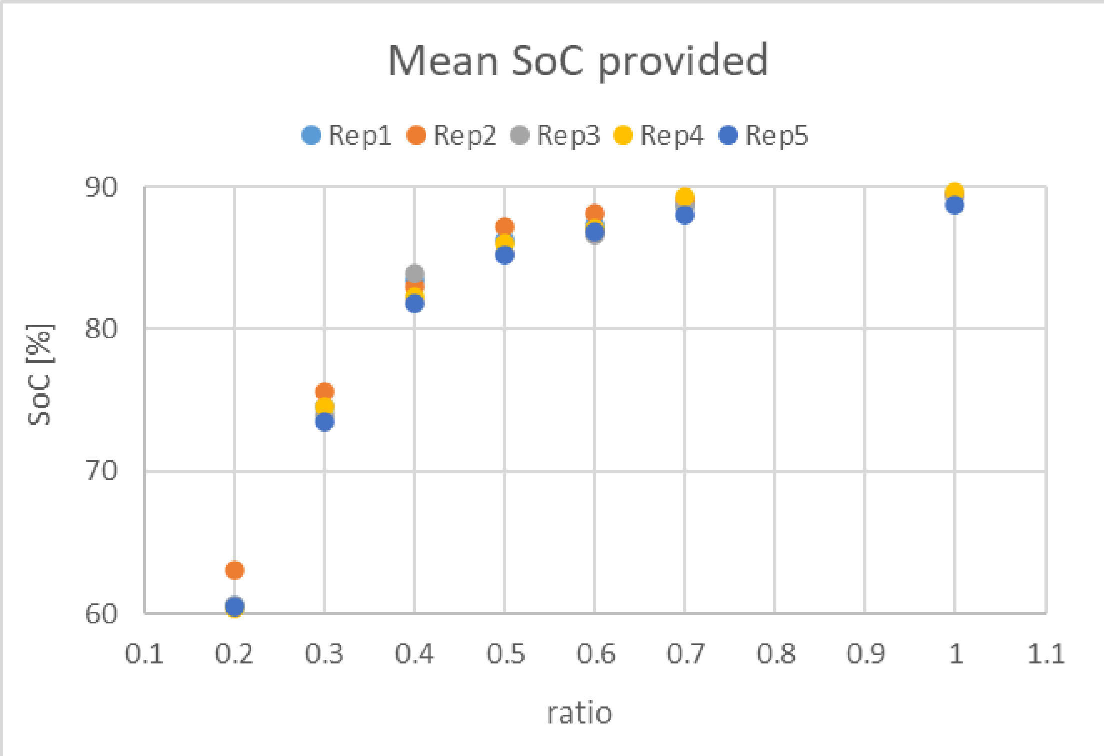

*Fig 5.3.5 Mean SoC provided with warehouse size 14*6*

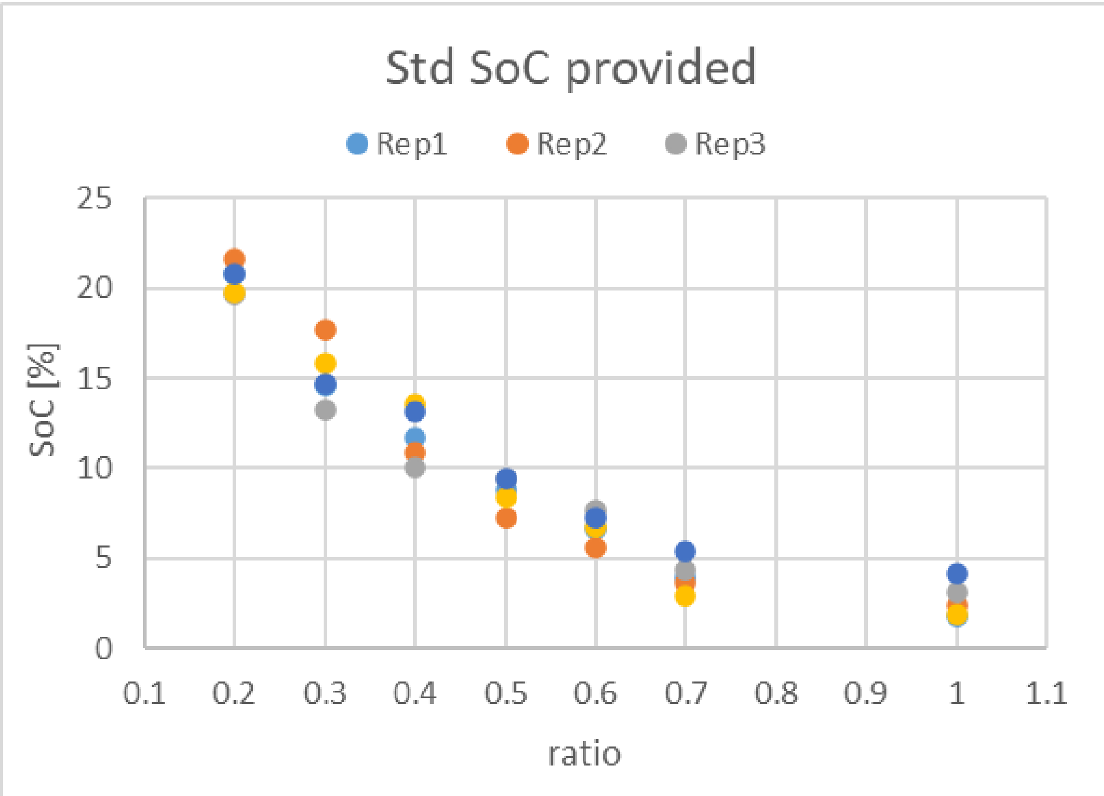

*Fig 5.3.6 Std of SoC provided with warehouse size 14*6*

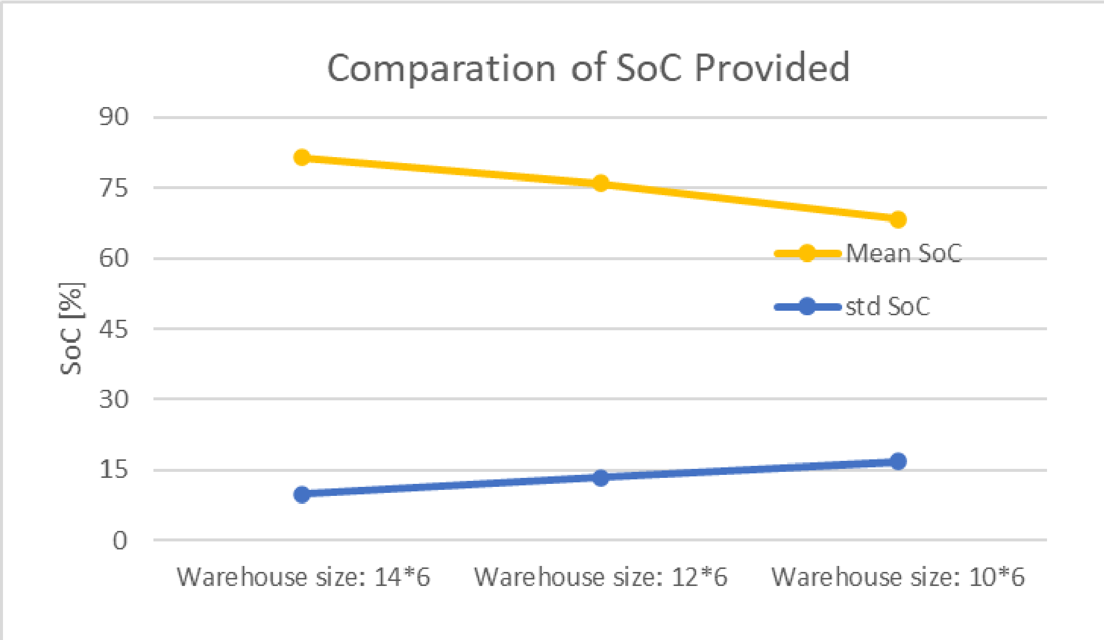

Fig 5.3.7 Comparation of SoC provided according to the warehouse size

As we can see above, with the increasing of the charge ratio, the mean value of SoC provided is increasing and the std value of SoC provided is decreasing. The reason why this condition happens is that the higher ratio represents there are more available batteries. Meanwhile, the busy time is contained in the day time, so there is no enough FBs, the not full charged batteries have to be provided in the model.

Again, the std value generally represents the busy time behaviors. More available batteries could have a better response when customers swarming to BSS.

Besides, there is another trend occurs according to the data: with the charge ratio increasing, the mean value and std value tends to "saturation" after ratio reaches about 0.6, which means keep on increasing the number of charge batteries will have small effect on SoC provided. However, whether we will set the ratio lower than 0.7 is not only determined by the SoC provided performance, we should still consider other possible factors. Meanwhile, choose ratio larger than 0.4 to make it near the saturation region is a good consideration. Because from ratio = 0.2 to ratio = 0.4, there is a big change (compare with saturation region), while from ratio = 0.4 to ratio = 0.6, the various of the mean value and std value decrease a lot and, generally, close to the max charging SoC level which is 90% mentioned above.

5.4 Energy consumption

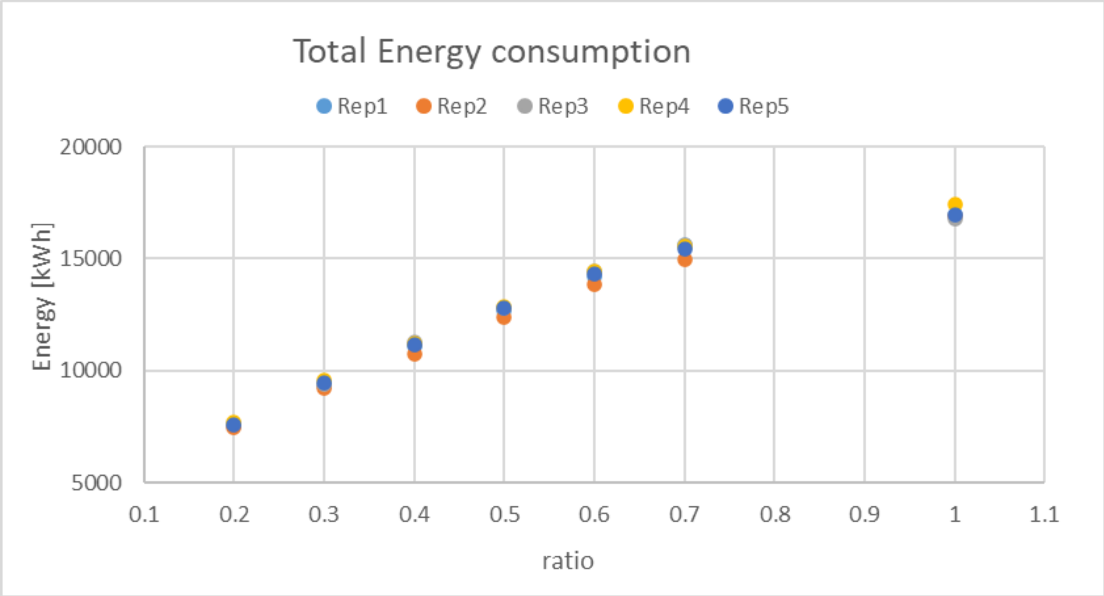

*Fig 5.4.1 Total Energy consumption with the warehouse size 10*6*

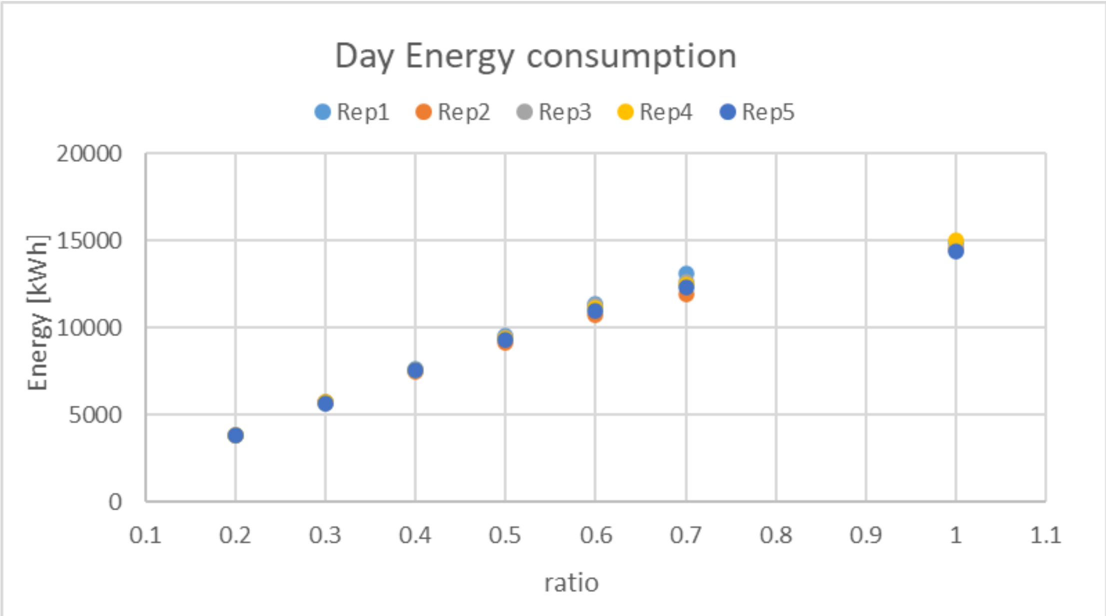

*Fig 5.4.2 Day time Energy consumption with the warehouse size 10*6*

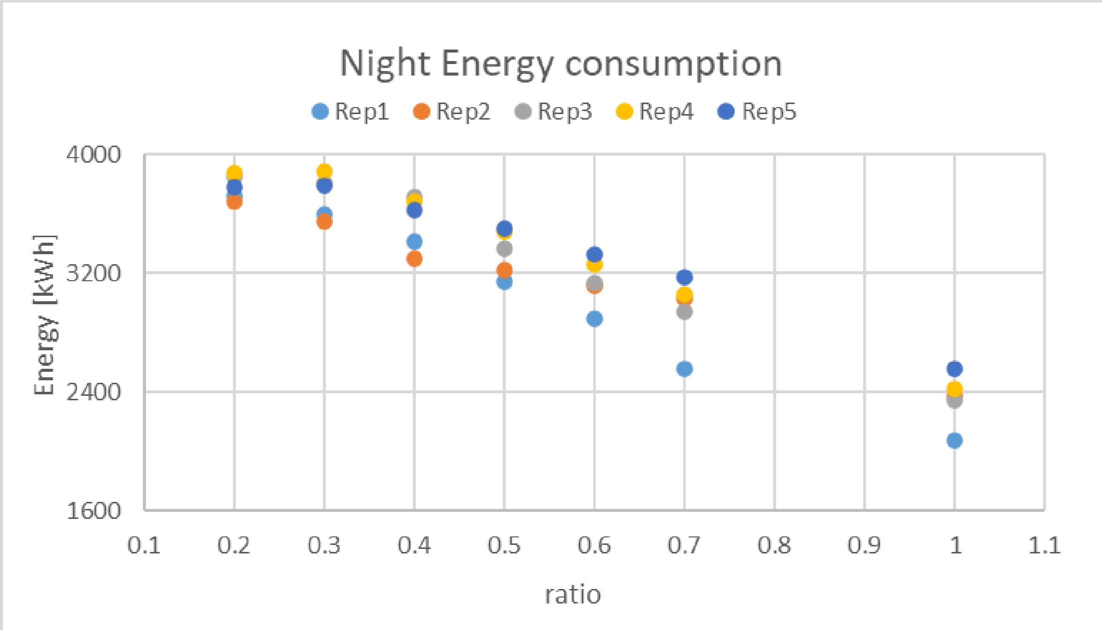

*Fig 5.4.3 Night time Energy consumption with the warehouse size 10*6*

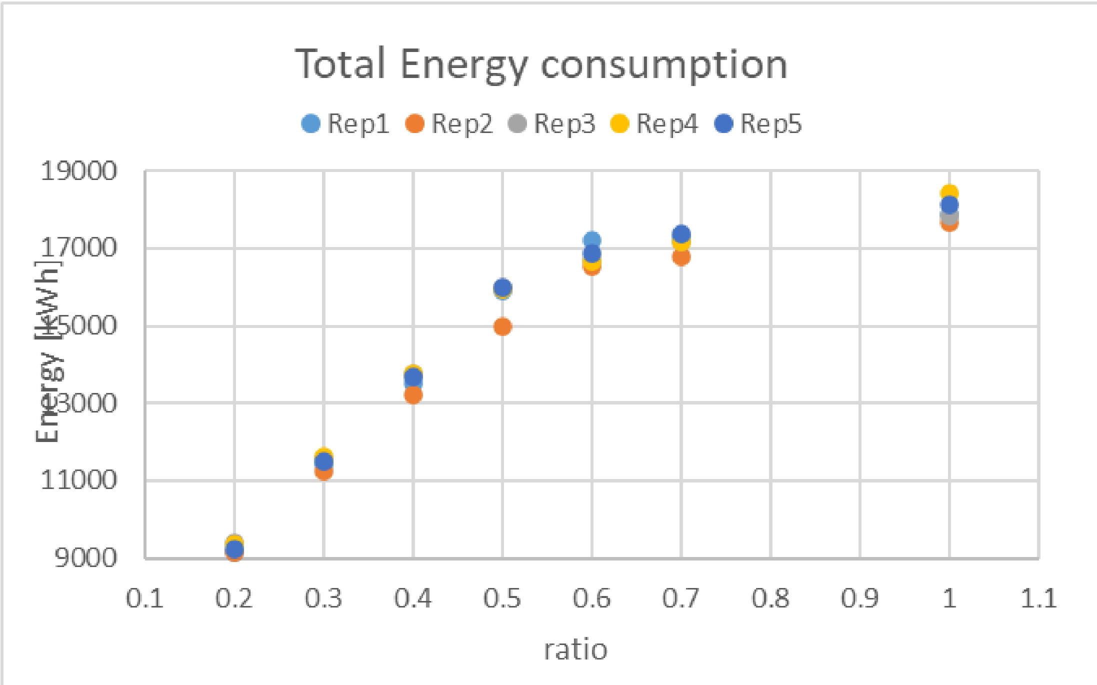

*Fig 5.4.4 Total Energy consumption with the warehouse size 12*6*

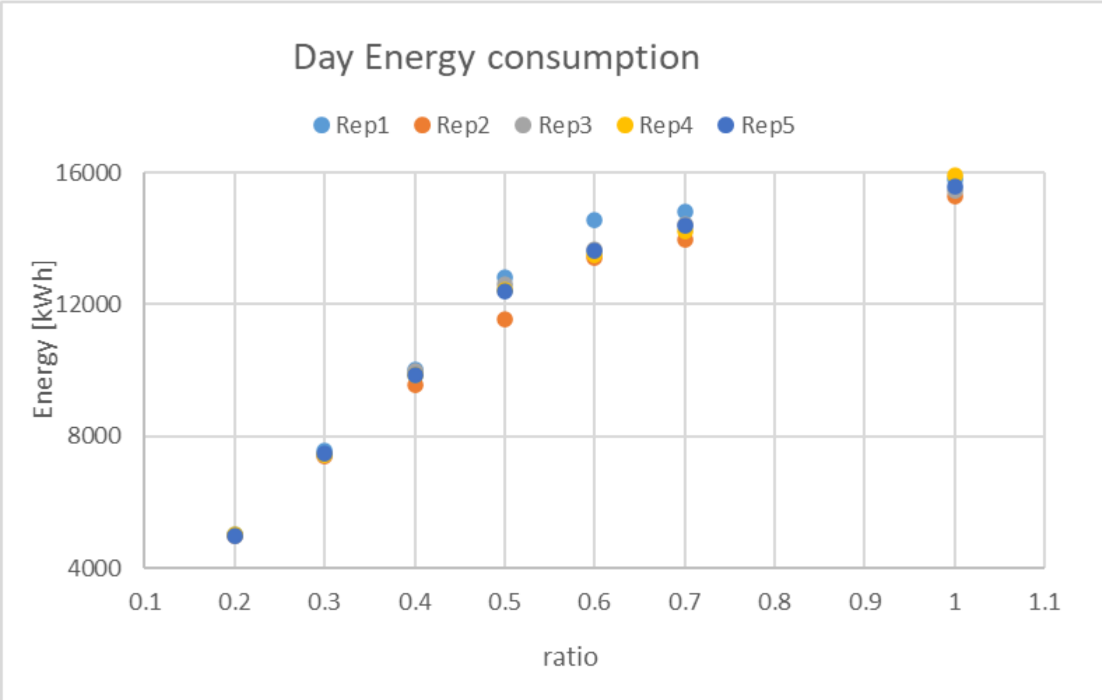

*Fig 5.4.5 Day time Energy consumption with the warehouse size 12*6*

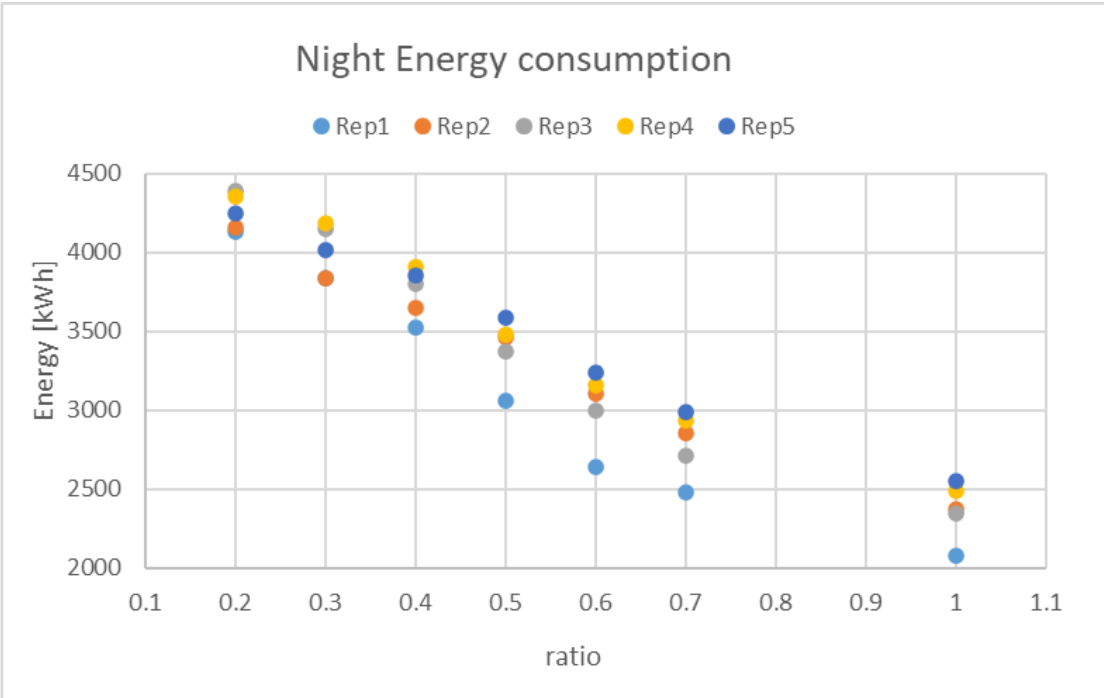

*Fig 5.4.6 Night time Energy consumption with the warehouse size 12*6*

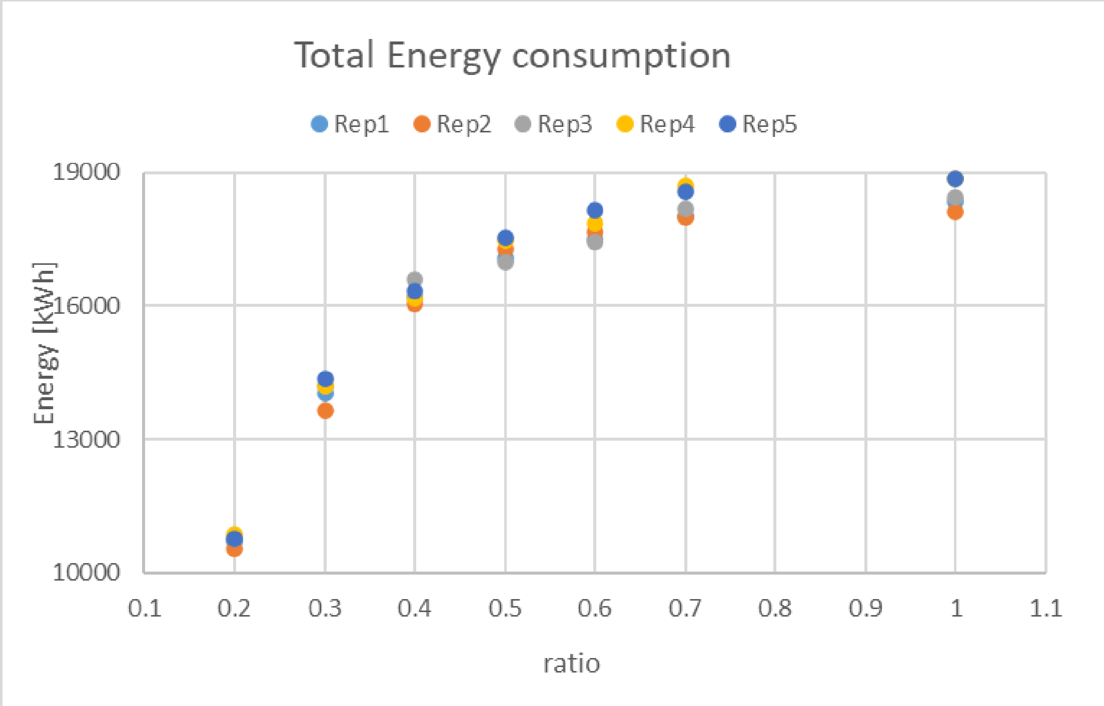

*Fig 5.4.7 Total Energy consumption with the warehouse size 14*6*

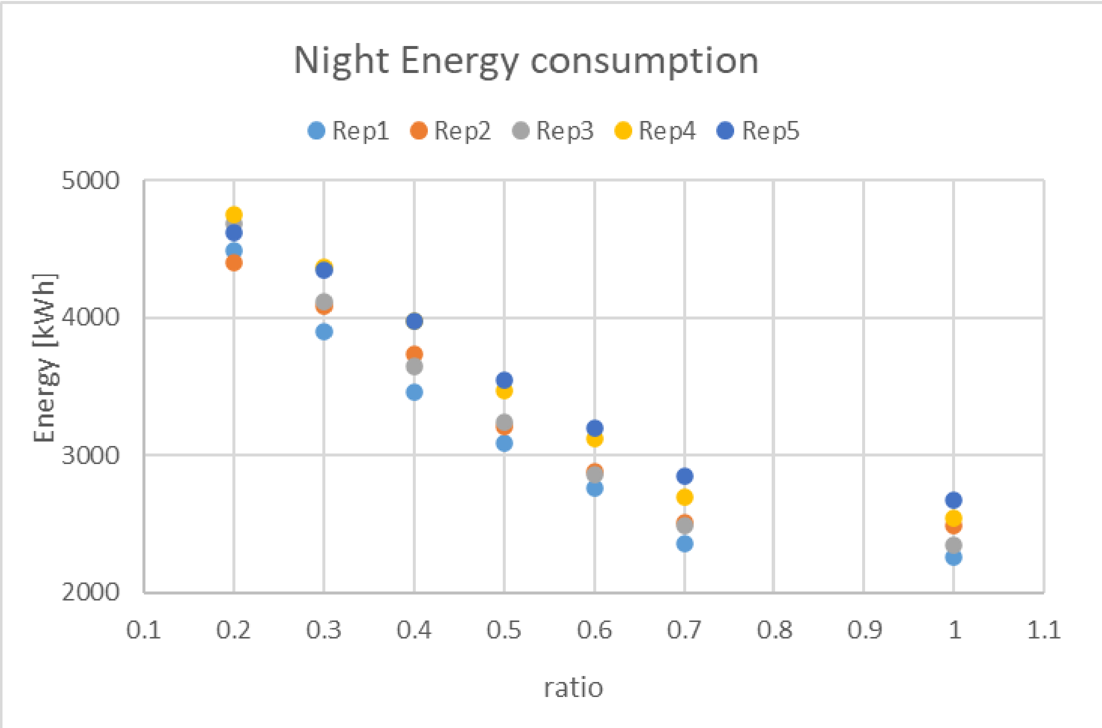

*Fig 5.4.8 Day time Energy consumption with the warehouse size 14*6*

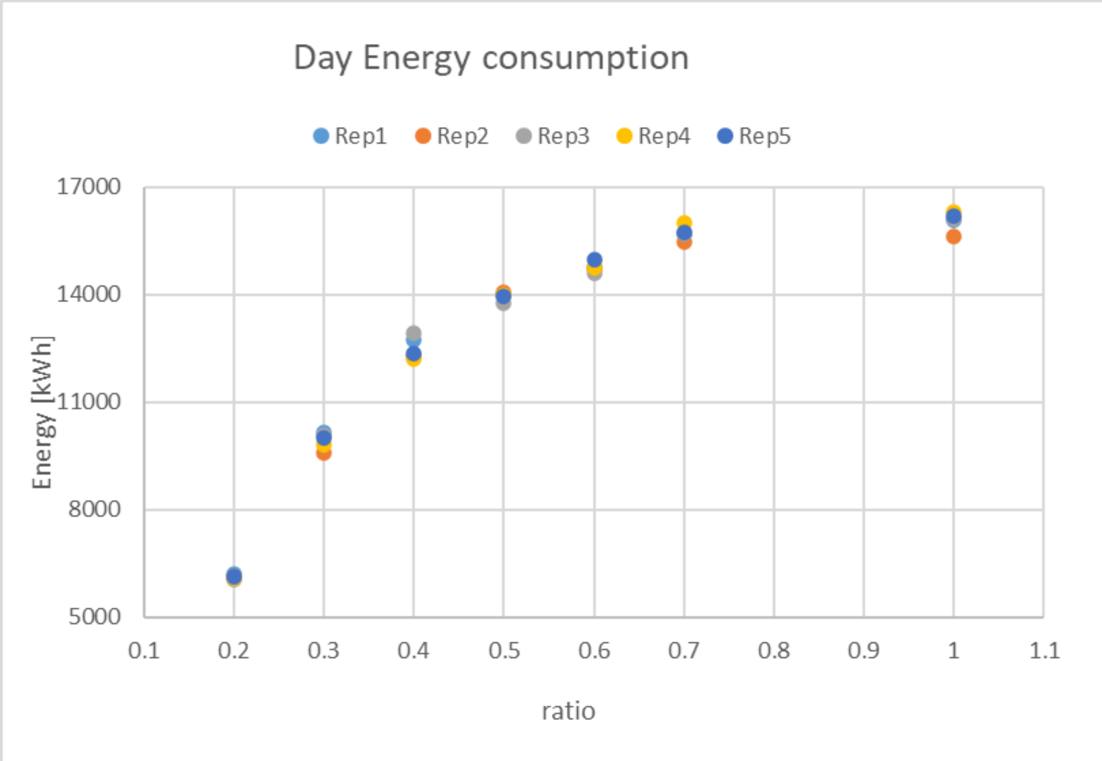

*Fig 5.4.9 Night time Energy consumption with the warehouse size 14*6*

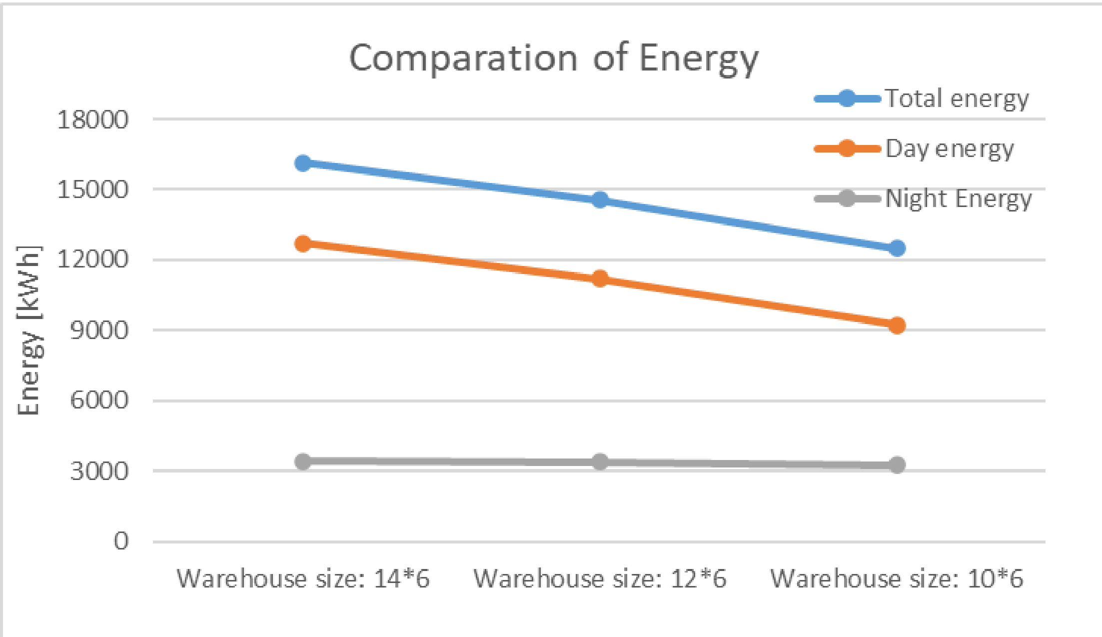

Fig 5.4.10 Comparation of energy according to the warehouse size

As it is shown above, both the total energy and day time energy consumption will increase with the larger charge ratio, while night time energy decrease. That's obviously that when the system owns more batteries charged in day time, the average SoC provided will higher as we discussed. From a general view, by accumulating the customer table per day, we could know that there are 503 customers and it's constant in the simulation. The higher the average SoC provided, the more the total energy consumption is. Meanwhile, more batteries charged in the day time, for sure, lead to higher energy consumption in day time. Different from trend of day time, the energy consumption decreasing in the night time is because there are more batteries stored in warehouse during day time should be charged at night.

And according to warehouse size view, larger warehouse also means there are more batteries charged in day time and more batteries should be charged at night, thus generally, all kinds of energy consumption increasing (even that it's slightly for night consumption).

To simply calculate the effect of delay strategy on operating cost reduction, we can calculate the electricity cost in day time and night time, and let's consider that, no delay behavior model as references, we can get the data below:

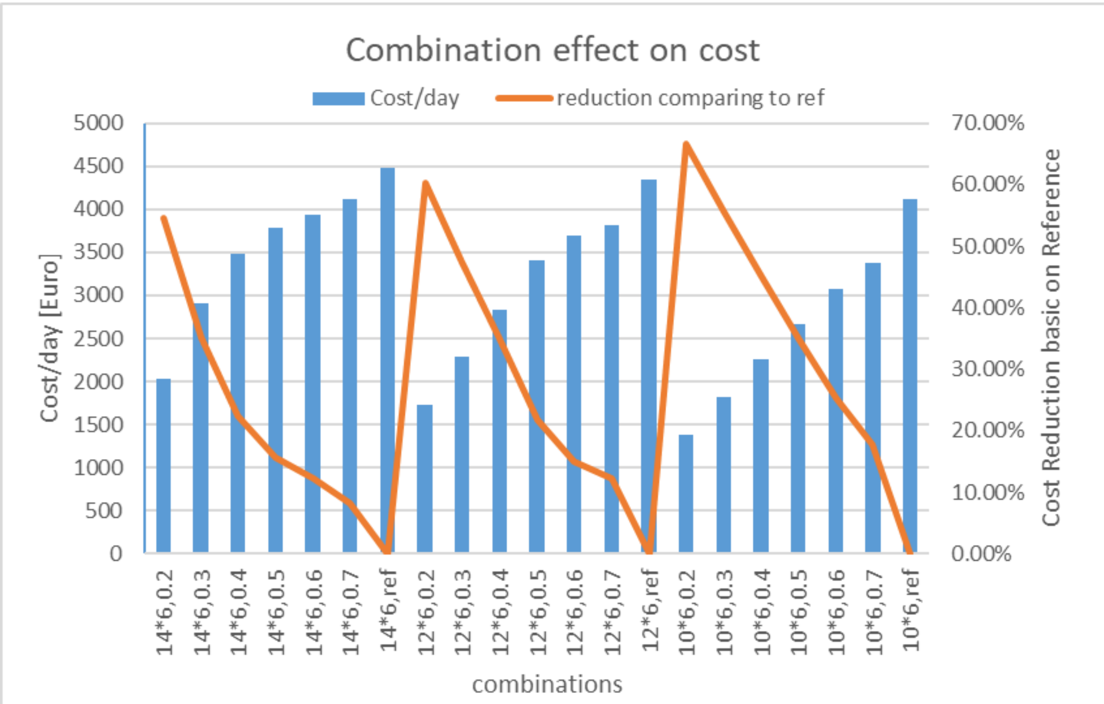

Fig 5.4.11 Combination effect on the cost (x axis: warehouse size, ratio)

Generally speaking, the high ratio will bring a big reduction on cost, and with larger warehouse size, the cost also increases. The essential reason is the number of batteries charged at day time. This is just a general calculation, but we can learn something from it.

5.5 General discussion

Now, all the important data have been shown above. Among all the data, the Cost per day and SoC provided by BSS seems to be the main factor when we design this facilitation.

Let's only consider our model. Small warehouse size or could say less batteries store will make the SoC provided far away from the customers need, we could only accept a little variation (max 5%) which means warehouse size lower than 12*6 would be impossible. For warehouse size 12*6, the ratio has to larger than 0.6 to reach the standard. For warehouse size 14*6, ratio larger than 0.5 is acceptable. Which the choice also means we can not make most of customers feel "good" due to long waiting time, but it's acceptable. Besides, the service time is not influenced much, while if we want to improve the service time and waiting time, we need to hire more ASRS and AGVs.

Then, of course, only if we have a charge ratio smaller than 1, we could have an operating cost saving. But, saving money is not our aim, instead, we want to find a best choice. So, lager ratio is not worth to be discussed, the comparation between "12*6,0.6" and "14*6, 0.5" is meaningful. They have nearly the same cost per day and SoC provided level. Even "14*6, 0.5" combination have a slightly advantage in SoC provided level (1%), however, in the "mean waiting time" and "std of waiting time", "12*6,0.6" combination wins nearly 100s in both two parameters. That's why "12*6,0.6" is better than another one. So far, in our model, we have found a best choice.

6. Conclusion

Generally speaking, we have tried 21 kinds of combination to find a best choice according to some standards. The methods are very simple, however, we could have a rapid decision by doing so. During the discussion, we also analysis the trends of each parameters when variables change. We point out the essential reason for each case and that's very useful when designing a real BSS. There are still some shortages in model:

1. Of course, there are still many shortcomings in the model. For further jobs, these factors could be also considered.
2. The warehouse size could be change also as different number of levels and bays, each slot could also store more than one battery.
3. The AGVs and ASRS are both simplified modes, in the real condition, they will have a worse performance.
4. We don't consider the customers leave during waiting and more details about customers behaviors.
5. During Energy consumption calculation and Cost calculation, the coming batteries types and SoC would have a more complex distribution.
6. The dissipation of battery and basic infrastructure cost are not considered.
7. In real condition, the electricity price could be less by negotiation like it's mentioned before.

Ultimately, whilst it is true that battery swapping solution has to face several obstacles in the private car sector because of the existence of a conservative and deep-rooted "car culture" that considers the car as something strictly personal, it can provide more benefits for urban public transport as an ancillary service for electric buses and taxis or even as a shared way and placed at the bus stands, in strategic points of prearranged routes or in the areas of vehicle storage as regards buses whose routine is relatively predictable and at taxi stands or parking areas such as parking near stations, airports, hotels or shopping centers for taxis on duty that unlike scheduled public transport do not follow fixed routes. The installation of BSSs in these locations would solve the problem of limited range for some type of electric vehicles. Whatever, the EVs are gradually affect human's transportation behaviors and it's a big adventure, there should be more good ideas be put forward.

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