POLITECNICO DI MILANO

Scuola di ingegneria industriale e dell'informazione

Master of science in Management Engineering

Exploring reverse supply chain configurations of high voltage li-ion batteries for heavy e-vehicles under different structural and operational conditions.

Master Graduation Thesis:

Nicolò Grassi. Student ID: 929315

Relator: Professor Lapko Yulia

INDEX

ABSTRACT

Climate changes are widely recognised as one of the most catastrophic events that the world is facing. Electrification of transportation is one of the most challenging proposal to fight the global warming. So far, industries have been focusing their attention on technology deployment and scaling up, focusing less on the enviromental impact that these technologies could have. However, it is important to have a profitable and green strategy to fight climate changes with the reutilization of critical products, such as the electric batteries.

The aim of this study is to find a suitable way to reintroduce in the market heavy electric batteries linked to the EVs (in particular bus and trucks) more than once enlarging their life cycle using a reverse supply chain configuration. To do that simulation has been used in order to find the most profitable solutions exploring different possible configurations. The main focus of the study is the introduction in the MILP model of the second life cycle of the battery finding the best solution to manage it according to economic and circular economy parameter. Moreover, the second life cycle of battery's study has been enlarged with the introduction of uncertainty in one of the activities performed. Results provide valuable ground for decision making regarding the development of the closed loop supply chain model of high voltage batteries showing that this solution can provide economic benefits for car manufacturers.

SOMMARIO

I cambiamenti climatici sono largamente riconosciuti come uno dei più catastrofici eventi che il mondo sta fronteggiando. L'elettrificazione dei trasporti è al momento una delle più importanti sfide per combattere il riscaldamento globale. Al momento le aziende si sono concentrate maggiormente sulla creazione di nuove tecnologie e sulla loro scalabilità, trascurando l'impatto ambientale che queste ultime potrebbero avere. Tuttavia, è importante avere una strategia green e profittevole sul lungo periodo per combattere il cambiamento climatico tramite il riutilizzo di prodotti critici, quali ad esempio le batterie elettriche.

L'obiettivo di questo studio è trovare una soluzione per reintrodurre nel mercato le batterie elettriche legate al mercato automobilistico (in particolare bus e camion) più di una volta allargando il loro ciclo vita tramite l'utilizzo di una reverse supply chain configuration. Per trovare la più profittevole e migliore soluzione si è utilizzato un modello di simulazione informatico. Il principale obiettivo di questo studio è l'introduzione del secondo ciclo vita delle batterie all'interno del MILP model guardando a quale sia la soluzione migliore per gestirlo. Inoltre, è stato condotto uno studio anche sull'impatto che l'incertezza potrebbe avere sul modello. I risultati sono una base per aiutare a prendere decisioni sul come sviluppare una strategia di closed loop supply chain per le batterie elettriche legate al mercato automobilistico; inoltre, dimostrano come questa strategia possa portare benefici economici per i produttori di automobili.

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

- RSC = Reverse supply chain
- RM = remanufacturing
- RF= Refurbishing
- RP= Repurposing
- RC= Recycling
- CH= Core Hub
- DL= Dealer
- RM/RF= Remanufacturing/refurbishing
- WH= Warehouse
- CRM= Critical raw material
- MILP= Mixed linear integral programming
- BP= Battery pack
- BM= Battery module
- SOH= State of health
- EVs= Electric vehicles
- KPI= Key performance indicator
- 1 LC= One life cycle
- 2 LC= Two life cycles

1. INTRODUCTION

In the last decades world has faced many catastrophes, most of them linked to climate changes. In the last thirty years CO2 emissions has been higher than emissions of all the years before cumulatively. This fact has led to an increase of the average temperature of 1°C and to an increasing instability of climate. Forecast about this trend are devastating. A rapid change in the culture of people and industries is needed to slow down the global warming.

For this reason, representatives from all over the world has met together in 2015 in Paris during the conference organized by the United Nations. During this meeting, an agreement between all the 195 countries belonging to the United Nations has been signed. The deal was to not increase the temperature of the world more than 2°C respect to the pre-industrialization era before 2050 (Paris agreement, 2015).

Most of the countries are trying to shift organizations' culture to reach the goal mentioned above. Electrification of transportation in substitution to the commonly used ICEV (Internal combustion engine vehicle) is necessary to slow down the global warming. In this way, it is possible to reduce consistently carbon emissions. Governments of all over the worlds are creating ad hoc laws to force this shift.

The automotive sector will be strongly affected by this transformation. This shift towards electrification of transportation will lead to an exponential increase in the future year of the demand of electric vehicles, as shown in the figure below (Nallusamy et al., 2016), forcing car manufacturers to be ready as soon as possible to reach the market.

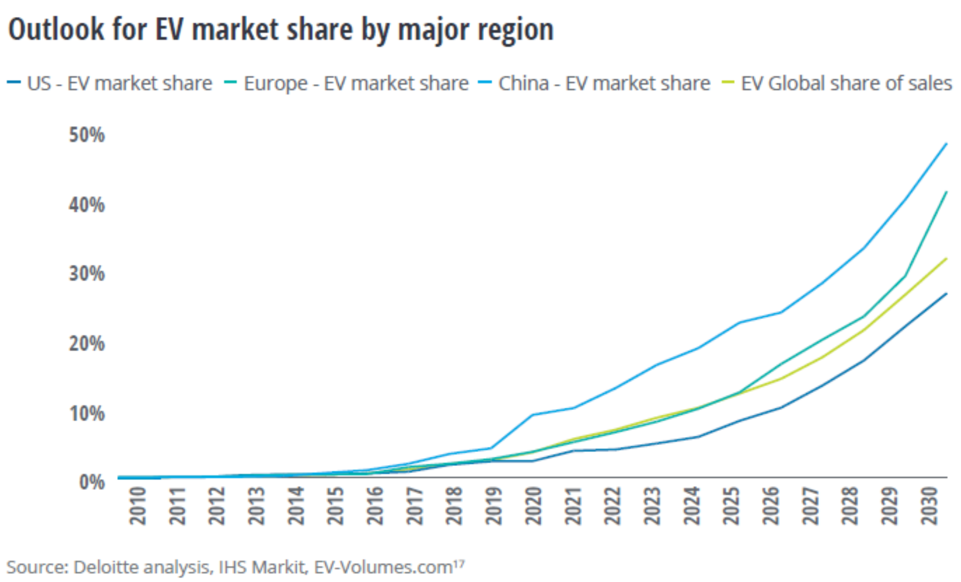


Figure 3: Outlook for EV market share by major region (Nallusamy et al., 2016)

The increasing awareness of customer about climate changes will directly affect the demand trend, in particular heavy EVs market will benefit of this fact. Many articles talk about this and a focal role in fighting climate changes will be played by the shift from private to public transportation (Logan et al., 2020). Looking only at the private sector none of the countries will be able to meet the threshold of Paris agreement in the next years due to the fact that there are also other sources of GHG emissions. Governments are moving towards this direction encouraging people using public vehicles. Heavy electric vehicles demand will benefit from what already mentioned. Academic studies demonstrate how heavy vehicles electrification creates benefits in terms of CO2 emissions if the public transportation will be exploited at all the capacity (Logan et al., 2020).

Talking in general about heavy vehicles market, bus and trucks are responsible for more than one quarters of the total C02 emission linked to the road transportation in UE. UE government is creating ad hoc law to force the electrification shift also for trucks (Regulation (EU) 2019/1242, 2019). This will lead to an increase in the future year of the heavy electric vehicles demand. Companies should be ready to adapt to this change as soon as possible.

Car manufacturer will have a leading role during the shift of electrification of transportation. As mentioned in Earl & Fell (Earl & Fell, 2019), most of them recognise this change as necessary but a lot of question points emerges.

Firstly, there are issues linked to the batteries used in electric vehicles: lithium-ion batteries show the best performances in terms of reliability and market price. However, this type of battery has a problem linked to the disposal at the end of life that affects its enviromental impact: at the moment, it is necessary to find a way to extend its life cycle to have a sustainable product with lower impact for the enviroment. Secondly, some of the battery raw materials (such as lithium) have been added in the critical raw materials list of UE, since they are distributed all over the world, but they are difficult to extract it in large quantities (Study on the EU's list of Critical Raw Materials (2020) Final Report).

To cope with these issues, it is necessary to explore the circularity of lithium-ion batteries at its full potential, finding different options for recovering batteries at the end of the first life cycle.

One of the possible ways to manage this shift towards electrification of transportation is to adopt a reverse supply chain (RSC) strategy. With the term "Reverse Supply Chain" it is intended "the series of activities required to retrieve a used product from a customer and either dispose of it or recover value" (Guide, Harrison, and Van Wassenhove 2003).

RSC could help heavy EVs manufacturers in reintroducing several times the product in the market, enlarging its lifetime (giving a second life cycle to the product). In this way, it could be possible to cope with issues mentioned above gaining advantages from these characteristics of batteries. This type of operational setup exploits the circularity of lithium-ion batteries creating new possibilities to explore for companies that permits to reduce the enviromental impact of the product.

One of the most important challenges linked to this strategy is related to the multiplicity of processes involved. They need to be managed in the most efficient and effective way both in the forward supply chain and in the reverse supply chain in order to gain advantages of this operational setup. Otherwise, there is the risk that RSC will not be sustainable from an economic point of view in the long term.

As explained above, introducing this type of operational setup for heavy EVS manufacturers is a challenge. They have to shift from a traditional supply chain approach to a new one and a period of transition is needed. If this transformation will not be pursued in the right direction risks could overcome benefits leading to undesirable effects.

The aim of this study is to examine the circularity of the transition process (reverse supply chain development) though the comparison of economic and enviromental (circularity) parameters for a heavy electric vehicle manufacturer company. Several studies have been conducted to find a profitable solution (in terms of economic and circularity viewpoint) to manage the transition towards RSC. Introduction of the second life cycle of batteries and the impact that this has in the simulation model is the focus of this thesis. Moreover, uncertainty linked to one of the most important activities have been studied to find the best configuration to manage it.

In the next chapter a deeper analysis of reverse supply chain of batteries is performed focusing on criticalities and challenges related to this operational setup. In chapter 4, simulation model is described starting from a physical point of view; in this section all modifications performed to the model during this study are explained. In chapter 5 there is an overview of all the assumptions and constraints linked to the analyses performed. In section 6 all the results found during model simulation are discussed with comparisons between different setup of scenarios. To conclude, the last two chapters are the discussions and conclusions. In the appendix (section 11.3) it is possible to find the MATLAB model.

2. REVERSE SUPPLY CHAIN OF BATTERIES

In the last years, many studies about reverse supply chain have been performed. Companies could adopt this operational setup to achieve advantages on competitors and reduce wastes. The heavy electric vehicle market could benefit from this type of solution thanks to the possibility to reintroduce several times product in the market; in this way, it could be possible for manufacturer to resell batteries gaining additional profits (Nagasawa et al., 2019) (Van Engeland et al., 2020) (Gao & Cao, 2020).

RSC is defined as the series of activities required to retrieve a used product from a customer and either dispose of it or recover value. This type of operational setup is composed by many key processes and activities to be performed. Firstly, product acquisition from the end-users is the first process followed by the pre-processing operations that are the activities performed to determine the product conditions. Then the last two key processes are the product reconditioning and the remarketing. With the term product reconditioning it is intended the set of activities that permits the reintroduction of the product in the market, while with remarketing it is intended the placement and redistribution of the reconditioned product in the market.

Due to the multiplicity of process involved RSC development is challenging for companies. To exploit all the advantages linked to this operational setup it is important to manage all the activities in the right way. In addition, RSC requires huge investments at the beginning of life and the risk is that in the short term it should be not profitable.

Focusing now on the lithium-ion batteries RSC it is important to present what are the main recovery option of this type of battery. According to the experts (Vu et al., 2020) four main options are possible for recovery:

- Remanufacturing: old battery modules are substituted with new ones and they reach the "as good as new" condition.
- Refurbishing: battery modules are reused in the same market but with lower performances (for example they have lower capacity and lower state of health (SOH)).
- Repurposing: Battery modules that do not reach technical requirements of the heavy EVs market are reintroduced in other market (such as Electric Storage System).
- Recycling: battery modules are disassembled, and raw materials are extracted.

Using RSC configuration will help companies in controlling better all these processes exploiting all the possibilities for the second life cycle of batteries.

A possible RSC setup for batteries is shown in figure 2.

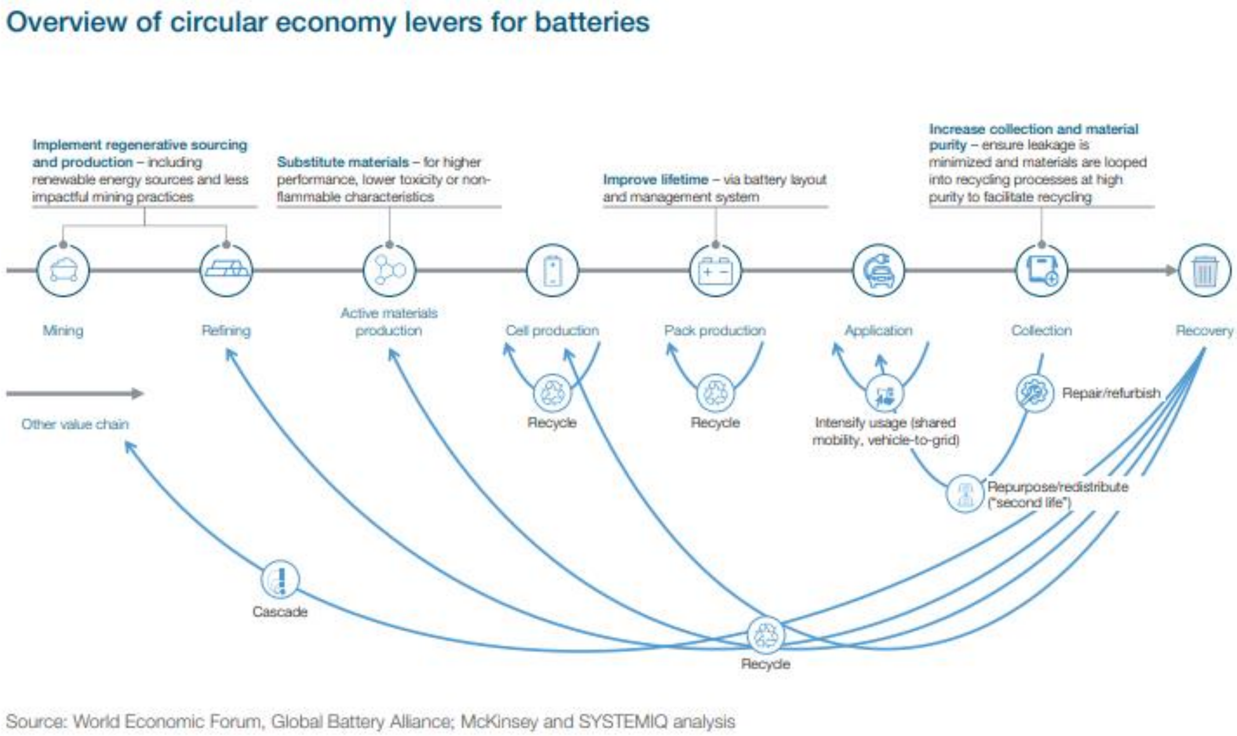


Figure 4: RSC for lithium-ion batteries overview (World Economic Forum; Global Battery Alliance, 2019a)

As it is possible to see from the image, many processes are involved in this type of setup. Customer will have a central role inside RSC since the first activity performed is the collection of batteries from the end-users. Lithium-ion batteries can be used for their fully potential using RSC, enlarging their lifecycle and reducing enviromental impact.

Reverse supply chain permits manufacturer to collect used batteries and reuse them in the most appropriate way. Thanks to this, it will be easier to extend batteries' life cycle postponing the disposal of them. Moreover, it is possible to resell the same product in the same market, or in alternative in others (in case technical constraints are not met), increasing profits, and enlarging the possible revenue streams of the company.

This operational setup could be also profitable and a feasible solution to cope with raw materials issue. In fact, thanks to this configuration it is possible to better manage batteries that must be recycled and extract from them the CRMs. This fact could lead to two main benefits: firstly, it is possible to reuse these materials to create new lithium-ion batteries reducing the overall costs; secondly if the company does not need them, they can be sold to other competitors or customers introducing another revenue stream.

One of the main criticalities linked to the second life cycle application of batteries is the benchmark with the new batteries and the possible decrease of their market price. It is important for manufacturer that second life cycle option for lithium-ion batteries are profitable in the long term otherwise it will be difficult to reach the threshold linked to the Paris agreement. RSC helps company in reducing cost of second life cycle application exploiting different solutions and eventually economies of scale (World Economic Forum; Global Battery Alliance, 2019b).

RSC development is a critical point for heavy electric vehicles manufacturer. Uncertainties about second life cycle of batteries and the sustainability of their market will be discussed in this thesis together with challenges linked to the multiplicity of process involved and to the huge initial investments needed to develop this operational setup.

3. MODEL DESCRIPTION

Exploring the transition process between a normal supply chain to a reverse supply chain is the aim of this thesis. Before going on with the mathematical model, physical model characteristics has been discussed with a European heavy vehicle manufacturer. After this discussion and a collection of the most important data, a simulation model has been created using the software MATLAB.

The decision of which software choose between all the alternatives has been done taking into consideration two main factors: simplicity of programming and ease of modifying the model. MATLAB results as the best choice to perform this type of activity.

The model has been modelled via MILP (Mixed Integer Linear Programming) an optimization approach that permits to find analytically a set of key parameters that minimizes a given KPI. In addition, it calculates economic and circularity parameters for each of the scenarios. The time of simulation has been set to twelve years.

3.1 KEY PROCESSES AND FLOWS

The physical model considers more than one recovery options for the batteries that enter in the cycle. First option is the remanufacturing one in which new batteries modules are assembled to create new battery pack; refurbishing is taken as a second option in which battery modules are reused to recreate battery packs that will be reintroduced in the heavy EVs market. The main difference between these types of batteries is linked to the SOH: remanufactured battery packs have a SOH approximately of 100% while the refurbished ones have only 80% of the initial SOH. This is achieved thanks to assembling of new battery modules (BM) for remanufactured battery packs (BP) and assembling of returned BM for refurbished BP.

Repurposing is the third option in which batteries with a SOH lower than 80% are directed to other markets (such as ESS for example). Last option is recycling in which raw materials are extracted from the battery modules to be reused in batteries or other applications.

These processes are accomplished through a set of important activities that are performed in different factories. Here is the list of all of them:

- Collection of used battery packs (BP) (1).
- Visual inspection of returned battery packs for damage (2).
- Battery pack (BP) dismantling into battery modules (BM) (3).
- Visual inspection of BM for damage (4).
- BM testing (5).
- BM sorting by state of health (SOH) (6).
- assembling of used BM (7).
- assembling of new BM (8).
- testing of assembled BP (9).
- storing/sending to dealers (or customers) (10).
- sending damaged parts and scrap to recycling (11).

The total number of different scenarios is 24 because of the different set-up allowed by the model. The differences are related to the different type of flow (flow type 1, flow type 2 and flow type 3), the different process allocation (type A or type B) and the different operational setups related to the remanufacturing/refurbishing and repurposing factories (in-house or outsourced).

The model permits the opening of only predefined factories that have been strategically selected by the automotive company.

These 11 processes are performed at 7 different typologies of factories linked together by different flow of battery packs and battery modules.

The battery cycle begins at the DEALER (DL) factory. In this factory there is the collection of used battery packs sent by customers and a first visual inspection of the battery to see if any damage is present (activities number 1 and 2). All the dealers are used by the model and locations of factories are shown below in table 1.

After this first step, battery packs are directed to the different CORE HUBS (CH). In these factories several activities could be performed depending on the type of process allocation that the scenario has (A o B):

- Battery pack (BP) dismantling into battery modules (BM) (3)
- Visual inspection of BM for damage (4)
- BM testing (5) (only in case of process allocation type A)
- BM sorting by state of health (SOH) (6) (only in case of process allocation type A)
- sending damaged parts and scrap to recycling (11).

To sum up, the main job of the core hubs is sorting battery modules to the right factories. A problem occurs if process allocation type B is set; since activities number 5 and 6 are not performed in these factories, uncertainty about the real SOH of the battery modules arise. One of the focus of this thesis is to study model reaction to the different process allocation introducing uncertainty during these stages.

The model could choose between 5 different locations for Core Hubs shown in table 1.

After the Core Hubs activities, flow of the battery modules is split into 3 different ways according to their SOH:

- If the SOH is higher than 80% (or it is supposed to be higher in case of process allocation type B) the battery modules are sent to the remanufacturing (RM) and refurbishing (RF) plants.
- If the SOH is lower than 80% (or it is supposed to be higher in case of process allocation type B) but not severely damaged the BMs are sent to the repurposing (RP) plants.
- If the BMs are severely damaged or defective, they are sent to the recycling (RC) factory.

Operations of remanufacturing and refurbishing of batteries are done in the same factory due to the similarity of them. The list of the operation that could be performed are:

- BM testing (5) (only in case of process allocation type B, it will be discussed in section 3.2)
- BM sorting by state of health (SOH) (6) (only in case of process allocation type B, it will be discussed in section 3.2)
- assembling of used BM (7)
- assembling of new BM (8)

- testing of assembled BP (9)
- storing/sending to dealers (or customers) (10)
- sending damaged parts and scrap to recycling (11).

Activities number 5 and 6 are performed in these factories only in the scenarios in which is set process allocation type 2.

The main difference linked to these types of factories is related to the battery requested for their activities. To create a remanufactured battery, new battery modules are required (SOH equal to 100%) while to produce refurbished batteries there is the necessity to reuse battery modules with a SOH higher than 80%. In this way it is possible to reintroduce these batteries in the heavy EVs market.

Possible locations for these plants are below in table 1.

Moving on to the repurposing plants, the list of activities performed is similar to the ones of remanufacturing and refurbishing. The only difference is that activities number 8 (assembling of new battery modules) is not execute: for repurposing activities only used battery modules are required. The final product of these processes will be sorted in a different market respect to the heavy EVs one. For example, one of the possible applications for these batteries is to be introduced in the Electric Storage System market.

The possible locations for repurposing factories are shown in table 1.

In the recycling factories battery modules are disassembled to save critical raw materials and reuse them for new batteries or different purposes. The model does not consider income from these factories and they are seen only as a cost. This is explained by the fact that activities performed during the recycling stages are not the focus of this study. Possible locations are shown in table 1.

Last facilities considered in the model are warehouses. These factories play an important role to fulfil the customer demand and feed the remanufacturing plants with new battery modules. Possible locations are shown in table 1 below.

Table 1:Possible locations of facilities

Location	Dealer	Core Hubs	Remanufacturing/Refurbishing	Repurposing	Warehouse	Recycling
1	Toledo	Ghent	Ghent	Ghent	Ghent	Antwerp
2	Ahun	Flen	Flen	Vasteras	Karlstad	Viviez
3	Walhain	Skovde	Skovde	Skovde	Skovde	Halmstad
4	Orebro	Cracow	Limoges	Mulheim an der Ruhr	Eindhoven	
5	Haina	Utrecht	Varsaw			
6	Menzberg		Hol			
7	Skipton		Ede			
8	Wagrain					
9	Folldal					
10	Dronten					
11	Gmina Łyszkowice					

As it is possible to see from the table above, some locations are common for several processes. The idea is to test the model to see if the best choice is a centralized or decentralized setup.

The model can choose autonomously which locations and which facilities open to maximize the given KPI. Most of the location are in the northern Europe (Sweden, Holland, Poland, north western Germany, Belgium) for mainly two reasons: the first one is that the automotive company under consideration already works in this area and the locations have been determined during the previous study to this thesis.

3.2 SCENARIO DEVELOPMENT

The RSC described in the previous section is going to be examined under different conditions such as: different flow allocation, different process allocation, in-house or outsourcing of two facilities. The main idea is to test which configuration is the best one to develop a reverse supply chain model in the heavy EVs market.

Flow type 1: This type of flow differs from the others for two main assumptions. The first one refers to the customer demand: it is supposed that demand is composed by 30% of refurbished battery packs and 70% of remanufactured battery packs. This fact leads to a greater flow between warehouses and remanufactured factories. As it is possible to see from the Figure 1 below, the remanufacturing plants require 70% of new battery modules to fulfil customer request.

The second factor that differentiate this flow from others is linked to the SOH of the battery modules. Here the assumption is that the 80% of the used battery modules that arrives at core hubs have a SOH greater than the 80%: in this way they can be used in the refurbishing factories. Only 10% of battery modules have a SOH lower than 80% and they will be sorted to the repurposing plants and 10% are directed to recycling plants due to a high damaged condition. In further section ("new logic to sort the battery modules") it will be explained the fact that only the strictly necessary batteries to fulfil customer demand are sent from the core hubs to the remanufacturing/refurbishing factories.

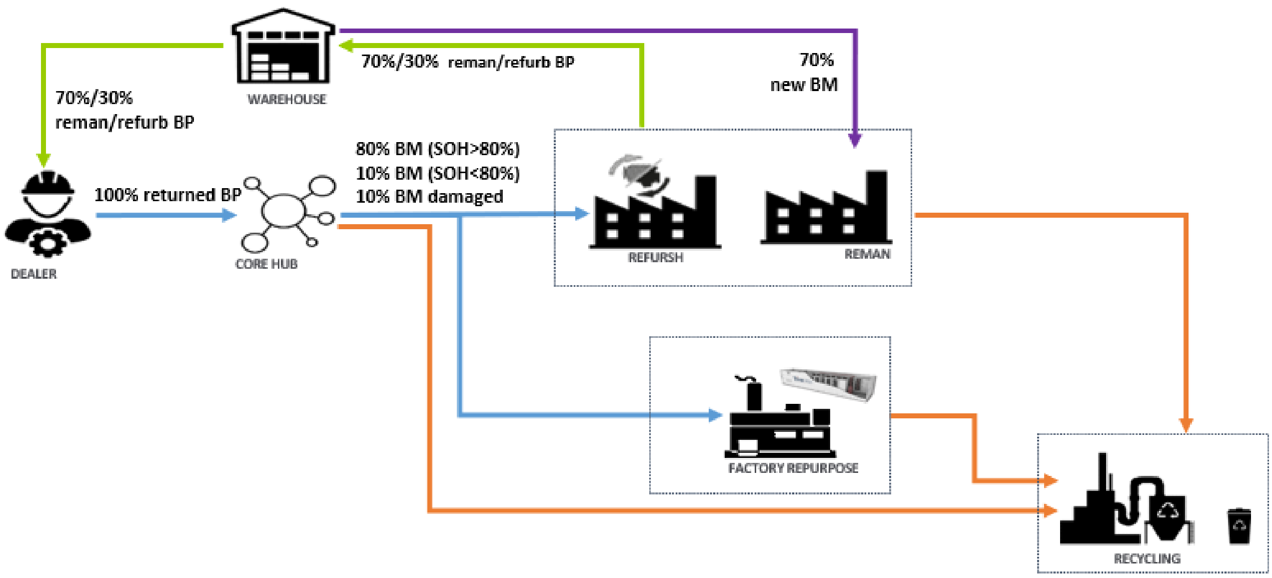
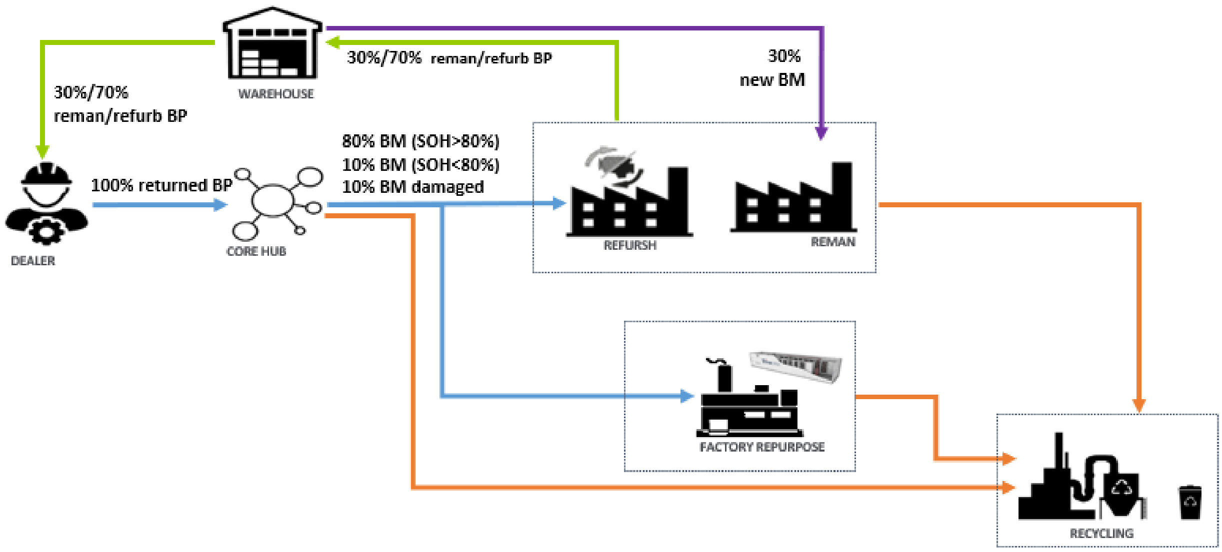


Figure 5: Flow 1 details.

Flow type 2: Assumptions linked to this flow are similar to the ones mentioned in flow 1. Regarding the SOH of the batteries the assumption is the same (80% with a SOH higher than 80%, 10% with a SOH lower than 80% and 10% sorted to the recycling factories).

The difference is related to the customer demand. In this case the assumption is that the demand is composed by 70% of refurbished battery packs and by 30% of remanufactured battery packs. The main implication of this fact is the flow between warehouses and remanufacturing plants that is lower respect to the previous one.

Figure 6: Flow 2 details.



Flow type 3: The customer demand for this type of flow is the same as the flow 2 (70% of refurbished and 30% of remanufactured).

The difference is linked to the assumption of the state of health of the batteries. In this case only the 70% of the batteries that arrives at core hubs has a SOH higher than 80% and can be used in refurbishing activities. Then 20% of them have a SOH lower than 80% (and for this reason they will be sorted to the repurposing factories) and 10% goes directly to the recycling phase.

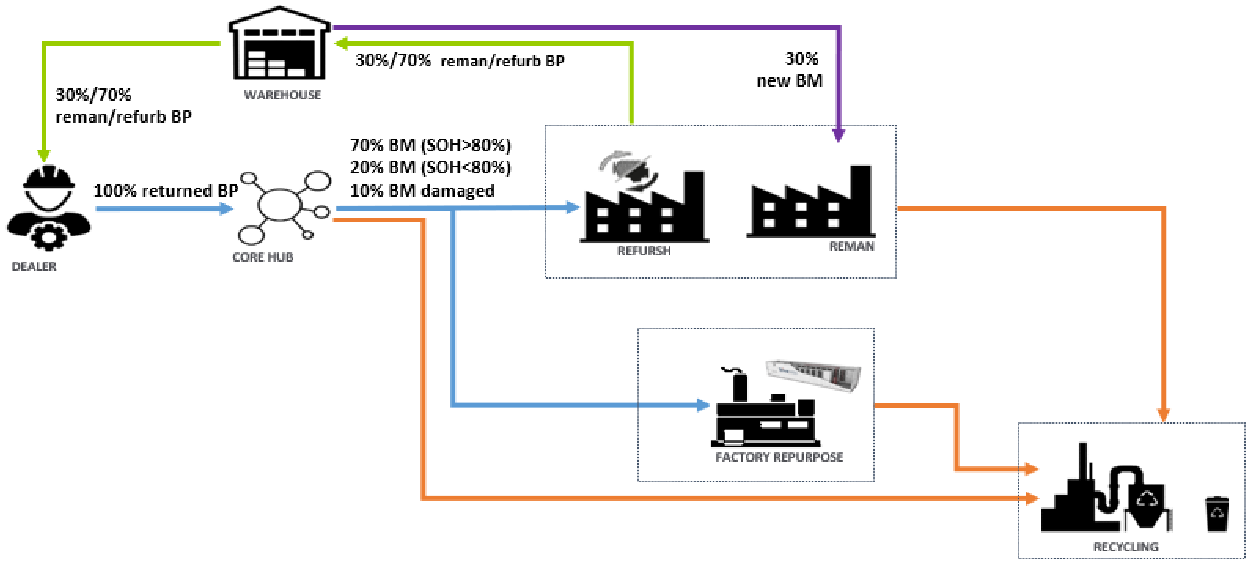


Figure 7: Flow 3 details

3.2.1 NEW LOGIC TO SORT THE BMs IN THE MODEL

The first analysis on the model has been performed changing the logic of sorting of the batteries from the core hubs. In the previous situation batteries path was linked only to their SOH creating an unnecessary flow between remanufacturing/refurbishing factories and repurposing plants.

The main idea is to send to the RM/RF factories only the strictly necessary batteries to fulfil customer demand. This means that the flow between RM/RF and RP will become equal to 0 leading to a decrease in the transportation costs. These change impacts on the different percentages of batteries that are sorted from the core hubs.

To run these types of simulation scenarios flow percentages have been changed in the way explained in table 2.

Table 2:Flow percentages between factories

	FLOW 1	FLOW 2	FLOW 3
CH_RM	0,32	0,72	0,7
CH_RP	0,58	0,18	0,2
CH_RC	0,1	0,1	0,1
CH_RC_BP	0,7	0,3	0,3
CH_RC_BM	0,3	0,7	0,7
RM_WH	0,7	0,3	0,3
RF_WH	0,3	0,7	0,7
RM_RF_RC	0,02	0,02	0,02
RM_RF_RP	0	0	0
RP_RC	0,05	0,05	0,05
WH_RM	0,7	0,3	0,32

The first thing to notice is how the flow called GAMMA (RM_RF_RP) is not present anymore. Moreover, it is easy to see how this theorical changes affects the flow between core hubs and repurposing increasing the percentage of batteries involved.

The idea of this tests is to see if GAMMA negatively affect the transportation costs in the as-is situation and to detect if any changes in the best scenario (both in terms of KPIs and configuration of the model) happens. Below are reported the new maps with the changes highlighted:

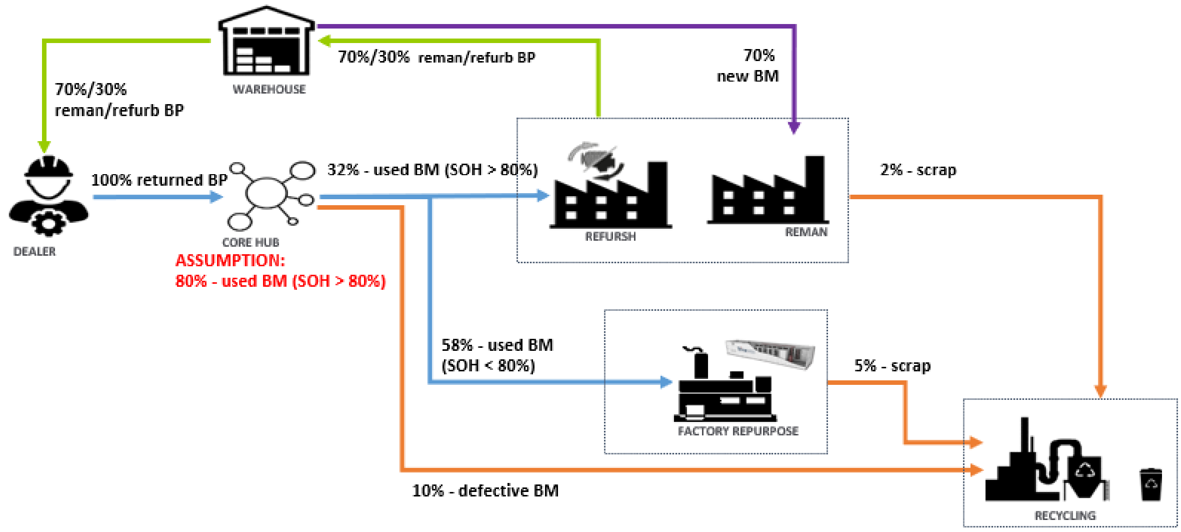


Figure 8:Flow 1 percentages using the new logic

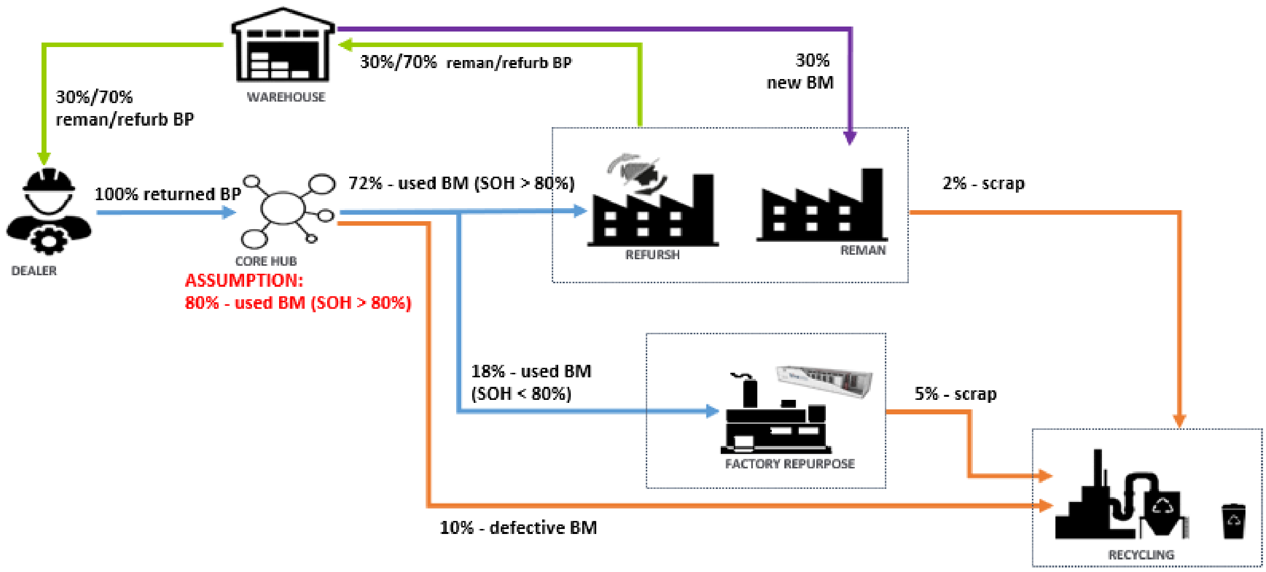


Figure 9:Flow 2 percentages using the new logic

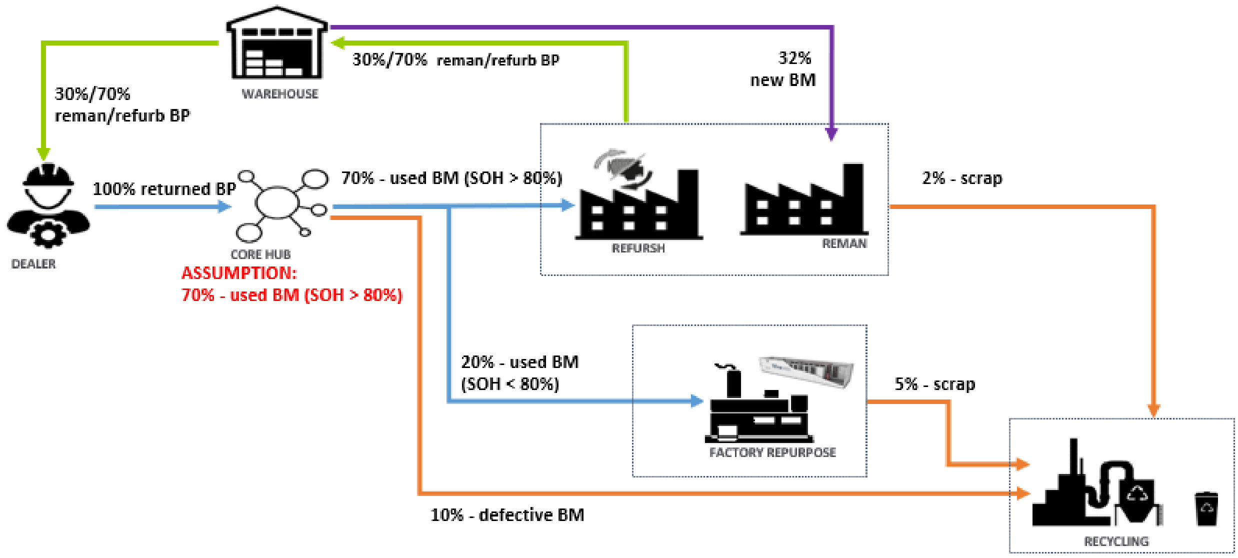


Figure 10: Flow 3 percentages using the new logic

3.2.2 INTRODUCTION OF THE SECOND LIFE CYCLE OF BATTERIES

The second analysis conducted is linked to the introduction of the second life cycle of batteries inside the model. Firstly, it will be done for scenarios characterised by process allocation type A and in a second time for scenarios with process allocation type B.

Second life cycle of batteries in EVs field has a critical importance to create a profitable and sustainable market environment. Before introducing it, a critical assumption is done: the model can absorb all the increase of the demand linked to the second life cycle (both for remanufacturing/refurbishing batteries and also for repurposing batteries).

To begin with, the first fact to take into consideration is the lifetime of batteries. Starting from the batteries that have been remanufactured at the first life cycle, we can assume a lifetime equal to 6/7 years (Zhang et al., 2014).

Remanufactured batteries are characterised by the fact that all the battery modules inside them are substituted with new ones. It is possible to state that these batteries will reach the "as good as new" condition and their lifetime can be approximated as the new battery lifetime. Taking into consideration that the lifetime of an EVs batteries range from 5 to 10 years we assume a lifetime of 7 (the average) for both remanufactured and new batteries that came back inside the system.

Regarding refurbished batteries other type of consideration should be done. These batteries are different from the previous one: BPs are disassembled and reassembled with the used BMs that have a SOH higher than 80%. This fact leads to the assumption that refurbished batteries will have a SOH<100% when they will be sold to customers. Due to this the lifetime of them is lower respect the new and the remanufactured ones. Researches have been conducted to determinate the lifetime of this batteries and it is possible to assume an approximate life span of 4 years.

After having considered all the first life cycle implication, let us move on the assumption of the second one. Refurbished batteries that will come back at the dealer starting from year 4 (for RF batteries) will be redirected to the repurposing factories. This decision has been taken after having considered the difficulties in reintroducing them another time market. In fact, due to the lower capacity of the batteries they will not meet the technical requirement for the heavy EVs market. Although some of them can be also reintroduced in the EVs cycle, most of them will not fit the market, leading to the decision to use all of them in repurposing activities.

For the RM batteries that come back in the system after the first life cycle situation is different. The idea is that they can be reused in the RF plants to reduce the amount of new battery modules needed to satisfy customer demand. The assumption is that the RM batteries behave exactly as the new batteries (due to the "as good as new" condition). It is possible to state that flow of the second life cycle for remanufactured batteries will the same as the first one.

To introduce the second life cycle of batteries this path has been followed:

1. Analysis of the initial rb/demand matrix.
2. RF batteries created/used at year x have been reintroduced in the demand at year x+3. So, for example, RF batteries of year 1 have been reintroduced at year 4.
3. RM batteries created/used at year x have been reintroduced in the demand at year x+7. So, for example, RF batteries of year 1 have been reintroduced at year 8.

Due to the different customer demand between the 3 type of flows two different matrixes have been created. They are shown in the appendix 1.

For flow type 1 the customer demand is thus divided: 30% of RF batteries and 70% of remanufactured. On the contrary, for flow type 2 and 3 demand is composed by 70% of RF batteries and 30% of remanufactured. This fact leads to different amount of batteries that re-enter in the model starting from year 4.

The implementation on the model of the second life cycle of batteries implies different percentages of flows starting from CH.

The first assumption regards the recycling percentage related to the second life cycle batteries. For simplicity, this percentage has been taken constant (10%) for all the flows considered. This means that in every year for every scenario the percentage of batteries that goes from CH to RC is equal to 10% (CH_RC=0,1).

For the first 3 year the percentages linked to the flows remains the same as in the paragraph above ("new logic to sort battery modules") due to the fact that in this period none of the batteries will reach the second life cycle. From year 4 to year 7 we have different rb between flow type 1, 2 and 3, linked to the fact that the amount of RF batteries that begin the second life cycle in this period is different for the two types of flows. For flow type number 1 the RF batteries amount for only the 30% of the total demand while for flow type 2 and 3 they amount for the 70%.

<u>Flow type 1</u>: The main assumption for flow type 1 is that the 80% of batteries that reach dealers have a SOH higher than 80%. This means that 80% of the batteries can be used in refurbishing activities. Customer demand for refurbishing batteries amount for only the 30% of the total one.

By the introduction of second life cycle, we want to explore also the new logic to sort the batteries. The main idea is that the flow between CHs and RM/RF plants will be the minimum one to satisfy the customer demand, as already explained in the previous paragraph. In this way it is possible to avoid the extra transportation cost linked to the flow between RM/RF factories and RP ones (the flow called GAMMA).

After this consideration, you can find the new setup for the model with the new percentages caused by the introduction of the second life cycle:

For all the years of simulation situation is the same of the figure 2. It is possible to see that flow between RM/RF and RP is not present. This is explained by the fact that also considering the introduction of the second life cycle for RM and RF batteries, these parameters will not be affected: in fact, the 32% of the total batteries will always be sent to the RM/RF plants every year while the remaining part (including batteries at the second life cycle) will be sorted to the RP plants. Every year the model is able to satisfy the RF demand only using batteries that come back at dealer plants.

Flow type 2: Regarding flow type number two the situation is different. The customer demand is composed by the 30% of remanufactured batteries and by the 70% of refurbished one. Due to this fact flow percentages differs respect flow 1.

The idea also in this case is to send from the CH to the RM/RF factories only the strictly necessary batteries to satisfy customer demand. The main assumption for flow type 2 is that the 80% of the batteries that came back in the model have a SOH>80%. This means that these batteries can be used in the RF factories satisfy the customer demand.

First thing to notice is that the flow percentages change year by year. The reason of this fact is that the amount of batteries that came back in the model increase exponentially from year 4 (year in which RF batteries start to come back in the cycle) to year 12. The model is not able to satisfy the demand only with the utilization of used batteries. To cope with this, acquisition of new BM is required.

To explain better the logic, I have introduced some variables explained in the table below:

Table 3:Volume variables

V(n)	Volume of the batteries at the first life cycle in year n
V(n-3)	Volume of the RF batteries that come back in the model 3 years after the first life cycle
V(n-7)	Volume of the RM batteries that come back in the model 6 years after the first life cycle. Of these batteries only the 90% can be used in the RF factories due to the assumption of the 10% of damaged batteries that come back in the system

For the first 4 years of simulation all the flow percentage are the same of the figure 3.

The calculation of the percentages for the year after is performed in this way:

- From year 4 to year 6 the fact to be verified is that amount of batteries that come to the Core Hubs after the first life cycle is enough to satisfy the customer demand of RF batteries of that specific year. The logic used to verify is: if 72% * (V(n) + V(n-3)) < 80% * V(n), then CH_RM_RF = 72% * (V(n)+V(n-3)). As you can see from the table 11 below this constraint is verified till year 5; after that year we are not able to satisfy the RF batteries demand only with the utilization of batteries that come to the CH at the end of the first life cycle and there is the need to increase the amount of new battery modules to cope with the demand (WH_RM parameter increases).

- From year 7 to the end of the period under consideration the calculation to be verified is a little bit different. In fact, from this year also the RM batteries used in the second life cycle start to come back in the model. This leads to an increase of the demand (rb) with difficulties in satisfy that with only batteries at the end of the first lifecycle. The logic used to verify if the model can satisfy the demand without any additional new battery modules is:

Supply of BM with SOH > 80%" = 80% *[V(n) + V(n-7)]

Demand = 72% * [V(n) + V(n-7) + V(n-3)]

When Supply >= Demand , then CH_RM = Demand and there is no need for new BM. ➔ 72%

In this case there is no need for new BM.

When Supply < Demand, then CH_RM = the proportion of the flow that corresponds to 80% *[V(n) + V(n-7)]

In this case, there will be need for new BM.

Figure 11: Explanation of the calculation performed for determine flow percentages

- An example for the calculation of year 8 flow's percentages follows.

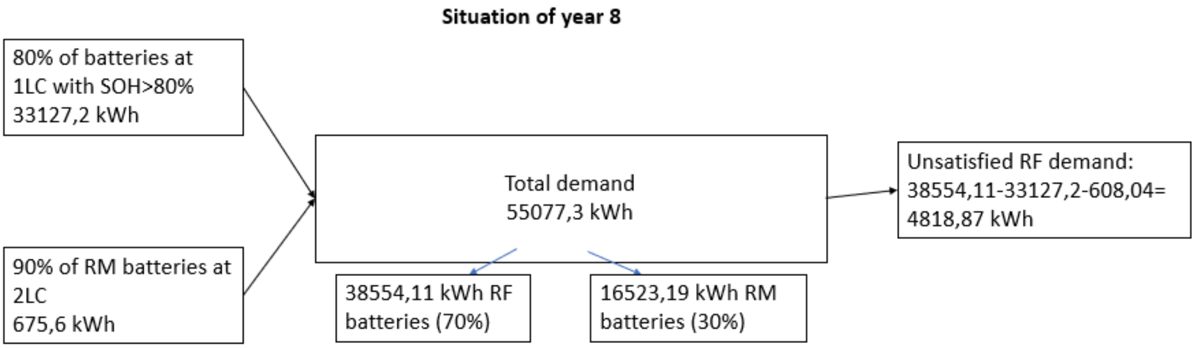


Figure 12: Example of calculation of percentages of flow for year 8

In this case the model does not have the necessary kWh to satisfy the RF batteries demand. Then the percentage of the flow between CH and RM/RF factories is lower than 72%. To calculate it we proceed in this way:

CH_RM=(80%*V(n)+90%*V(n-7))/(V(n)+(V(n-7) + V(n-3)).

In this case the result is 0,6133.

After this consideration you can see the results (of the changes of flow percentages) in the table 4 below.

Table 4: Flow 2 percentages

	YEAR											
	1	2	3	4	5	6	7	8	9	10	11	12
CH_RM	0,72	0,72	0,72	0,72	0,72	0,6989	0,6744	0,6133	0,6401	0,5946	0,7034	0,72
CH_RP	0,18	0,18	0,18	0,18	0,18	0,2011	0,2256	0,2867	0,2599	0,3054	0,1966	0,18
CH_RC	0,10	0,10	0,10	0,10	0,10	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,10
RM_RF_RP	0,00	0,00	0,00	0,00	0,00	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,00
WH_RM	0,30	0,30	0,30	0,30	0,30	0,3211	0,3456	0,4067	0,3799	0,4254	0,3166	0,30

<u>Flow type 3</u>: The situation for flow type 3 is similar to the one of flow 2. The customer demand is split into 70% of refurbished batteries and 30% of remanufactured ones. The main difference is that flow 2 assumes that only the 70% of the batteries that enter the model for the first time has a SOH higher than 80%.

The first implication is related to the fact that since year one we are not able to fully satisfy the demand of refurbished batteries. A higher flow between warehouses and remanufacturing factories is needed (WH_RM). This parameter as you can see below in the table 12 change yearly after year 4.

The logic followed for calculating the percentages is equal to the one of flow type 2. The only change is linked to the 70% of batteries with a SOH higher than 80% instead of the 80%. Results of calculations are shown below.

Table 5: Flow 3 percentages

	YEAR											
	1	2	3	4	5	6	7	8	9	10	11	12
CH_RM	0,7000	0,7000	0,7000	0,6943	0,6449	0,6116	0,5902	0,5380	0,5621	0,5236	0,6182	0,6455
CH_RP	0,2000	0,2000	0,2000	0,2057	0,2551	0,2884	0,3098	0,3620	0,3379	0,3764	0,2818	0,2545
CH_RC	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000
RM_RF_RP	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
WH_RM	0,3200	0,3200	0,3200	0,3257	0,3751	0,4084	0,4298	0,4820	0,4579	0,4964	0,4018	0,3745

<u>Process allocation type</u>: Differences between the process types are linked to the activities performed in the core hubs. If process type A is set activities number 3, 4, 5, 6, 11 are performed inside these factories.

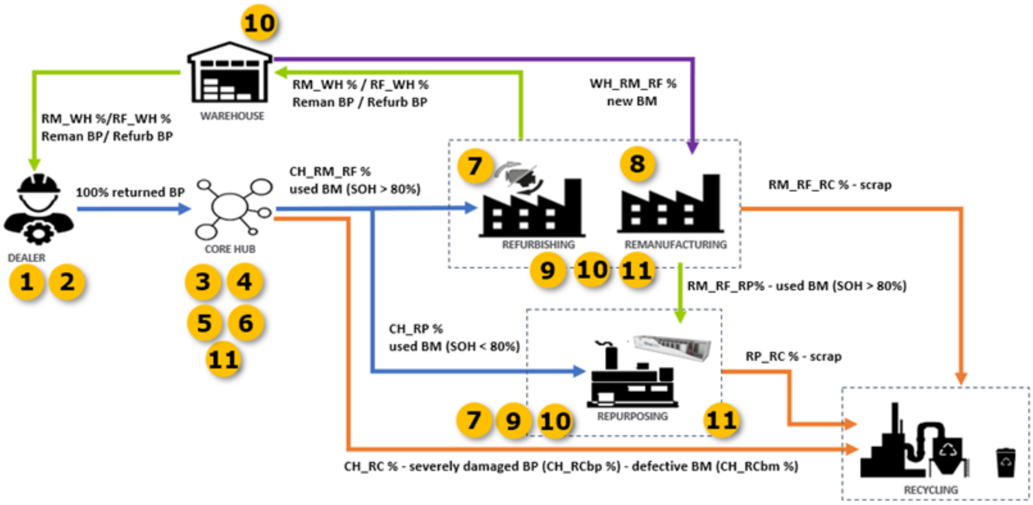


Figure 13: Process allocation type A

The main consequence is that the SOH of the batteries will be detected before the sorting phase. This leads to the fact that the model will not have any reverse flow linked to a possible mistake during sorting phase.

In case process allocation type B is set activities number 5 and 6 are not performed inside core hubs but they are performed in the RM/RF and RP factories. This fact leads to possible issues during the sorting phase at core hubs level, due to a possible mistake in the assessment of the SOH of battery modules.

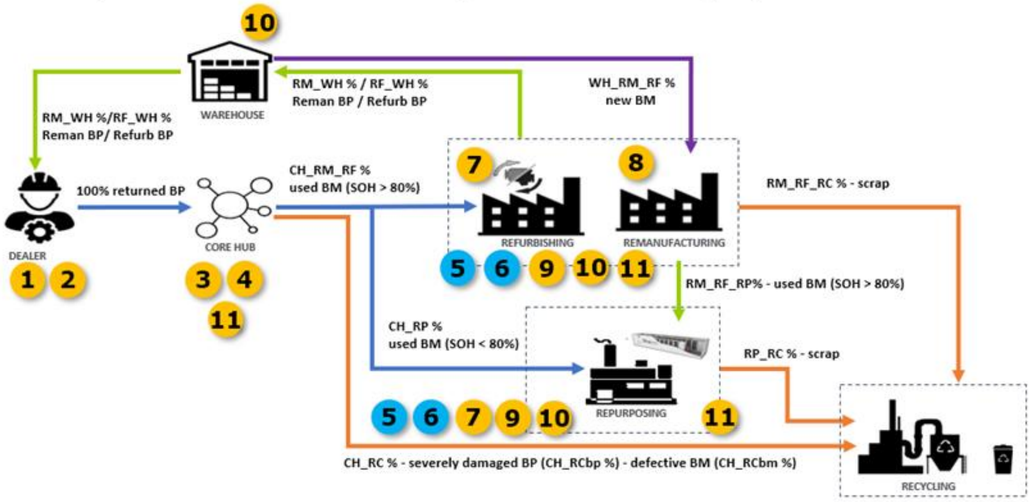


Figure 14: Process allocation type B

3.2.3 LOGIC OF THE INTRODUCTION OF UNCERTAINTY IN THE MODEL

The introduction of uncertainty inside the model has been done to detect how the model react to unexpected changes and to see the main differences (in terms of economic and circularity indicators) between process allocation type A and B. The idea is to introduce a factor that determines uncertainty in the phase of visual inspection at CHs for process allocation type B. In fact, in this type of process activities of inspection and testing of the battery modules are performed only in the remanufacturing/refurbishing and repurposing factories. This will lead to possible mistakes during the sorting phase due to a wrong detection of the real SOH of batteries.

Uncertainty at core hubs stages leads to these consequences:

1- Due to a wrong visual inspection some batteries that could be sorted to RP factories (so with SOH<80%) will be sent to the RM/RF plants.
2- The exact opposite will happen for batteries with a SOH>80% that will be sorted to the RP factories instead of the RM/RF plants.

It is important to study all the related effects that this uncertainty will create to find the best way to manage it. As it is possible to see from the image below the percentage related to the BMs' flows will change.

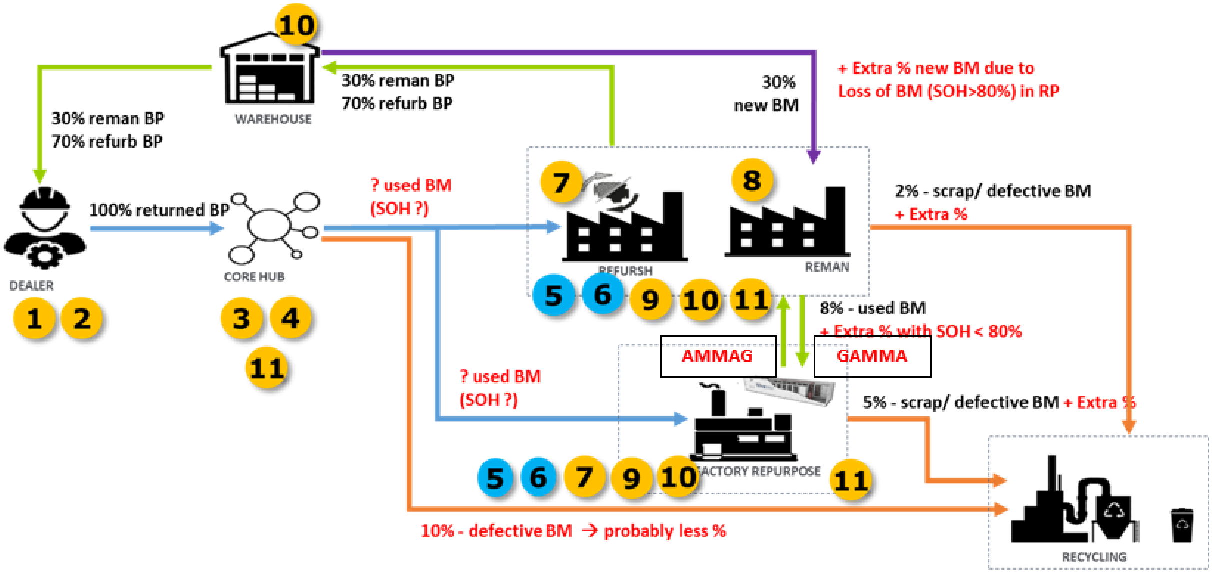


Figure 15: Uncertainty effects on the model

The first difference is related to the BMs that the CH factories sorted in the cycle process. Due to a wrong visual inspection some batteries will be sent wrongly to the RP factories instead of being sent to the RM or RF factories. To cope with this fact one main modification in the model has been carried.

New flow inside the model called AMMAG (the reverse of GAMMA that is a flow already present in the model) has been created. It indicates the amount of BM sent from the RP factories to the RF plants with a SOH higher than 80%. So, in this case all the BMs suitable for the refurbishing activities will be used. However, this fact leads to extra cost faced by the model linked to the transportation of these batteries from repurposing to remanufacturing and refurbishing plants.

Two different types of mistake are considered regarding the sorting process at core hubs level:

1- BMs with a SOH higher than 80 % sent to the RP plants. This is called "false negative" mistake.
2- BMs with a SOH lower than 80 % sent to the RM/RF plants. This is called "false positive" mistake.

Another important assumption regards the management of the second life cycle batteries. Regarding the refurbished batteries it is possible to assume that no mistake will be faced because they will be directly sorted to the repurposing factories. On the other hand, the remanufactured batteries are considered as new batteries and the assumption is that they will have the same behaviour of the one that come back at the first life cycle.

The most important thing to set is the percentage related to a mistake in the visual inspection phase.

This process will be performed by operators without any type of supervisor and engineer that organize the actions. An important feature to consider is the fact that batteries are equipped with a battery management system (BMS) that helps to detect the SOH during all the life cycle.

The idea is to test how the model react to a 20% of possibility of mistake for each battery inside the system. In this way we can see how the model reacts to this type of change.

The assumptions are:

- 16% of batteries will be sorted as SOH<80% (wrongly – false negative) and thus sent to RP → increase CH→RP; as a result there will be AMMAG (to meet the demand)
- 4% of batteries will be sorted as SOH>80% (wrongly - false positive) and thus sent to RM/RF → GAMMA will be present.

The logic for numbers/proportion is that false positive false should be less than false negative, the objective of the study is to limit false positive mistakes. It is safer to assign false negative when there is uncertainty about the state of the battery. The operator will assign a SOH >80% to a BM only if they are almost sure about it.

The main idea is to test the introduction of uncertainty only for flow type 2 that has shown the overall better performances. Firstly, simulation will be done considering only batteries with one life cycle and without any increasing on the demand. Secondly, uncertainty will be tested introducing also the second life cycle of batteries and using the same assumptions done for batteries at the first life cycle.

In the next paragraph the main changes to the physical model are explained with the calculation of all the new flow percentages.

<u>Flow 2 one life cycle uncertainty</u>: Starting from the fact that demand is kept equal to the initial one in this simulation the flows for the 12 years have not significant changes in terms of percentages. Here below are underline all the interesting parameters that affect the model:

- CH_RM=0,7 (this percentage is composed by 0,66 are battery modules with SOH higher than 80%, and 0,04 caused to the false positive mistake)
- CH_RP=0,2 (this flow is composed by 0,06 of BMs with SOH lower than 80%, and 0,14 BMs with a SOH higher than 80%, called false negative)
- CH_RC=0,1 (this parameter is kept constant during all the simulations)
- RM_RF_RC=0,02
- RM_RF_RP=0,04 (this flow, also called GAMMA in the model, is the flow caused by the false positive mistake done at the core hubs stages)
- RP_RM_RF= 0,06 (to satisfy the RF demand, the other 8% can be directly used for repurposing because they are not necessary at RM/RF factories. This flow is called AMMAG)
- RP_RC= 0,05
- WH_RM= 0,3

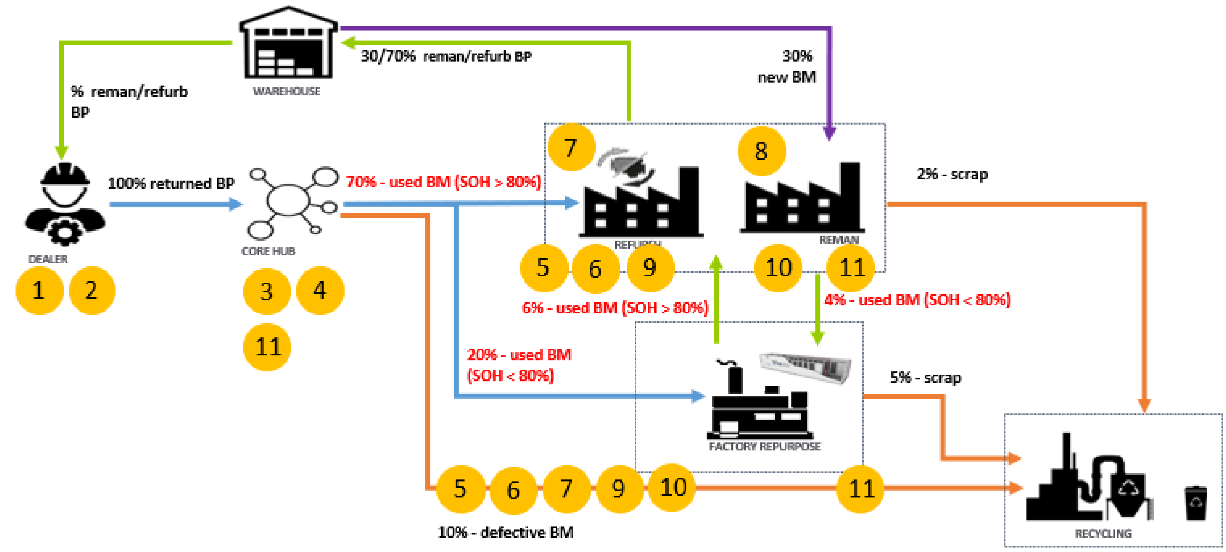


Figure 16: flow 2 one life cycle with uncertainty percentages

<u>Flow 2 two life cycle with uncertainty</u>: In this case the demand is the same reported in table 13. The second life cycle of batteries will lead to different flow percentages during the simulation period. For the first 3 years the percentages do not change.

Starting from year 4 the percentages are calculated taking using the same assumption and logic explained in the paragraph above (introduction of the second life cycle batteries). These percentages are calculated as a portion of the total demand of that specific year. Results are shown in the table:

Table 6: Flow 2 percentages with second life cycle of batteries

	YEAR											
	1	2	3	4	5	6	7	8	9	10	11	12
CH_RM	0,6000	0,6000	0,6000	0,5951	0,5528	0,5242	0,5058	0,4645	0,4825	0,4513	0,5322	0,5513
CH_RP	0,3000	0,3000	0,3000	0,3049	0,3472	0,3758	0,3942	0,4355	0,4175	0,4487	0,3678	0,3487
CH_RC	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000	0,1000
RM_RF_RP	0,0400	0,0400	0,0400	0,0397	0,0369	0,0349	0,0337	0,0310	0,0322	0,0301	0,0355	0,0368
RP_RM_RF	0,1600	0,1600	0,1600	0,1587	0,1474	0,1398	0,1349	0,1239	0,1287	0,1204	0,1419	0,1470
WH_RM	0,3000	0,3000	0,3000	0,3059	0,3566	0,3910	0,4131	0,4626	0,4410	0,4784	0,3814	0,3585

The first difference is linked to the WH_RM parameter. The increase of the demand linked to the second life cycle implies that the model is not able to satisfy all the demand of refurbished batteries. Due to this, new battery modules are bought and sorted to the remanufacturing factories. This parameter shows an interesting trend: from year 4 (year in which refurbished batteries starts the second life cycle) to year 10 it increases gradually, while for the last two years it decreases rapidly. This fact can be explained by the increasing number of remanufactured batteries that comes back in the model starting from year 7 that reach a peak in the last two simulation years.

Another important observation is linked to the flow related to the mistake performed at Core Hubs (RM_RF_RP also called GAMMA, and RP_RM_RF also called AMMAG). These flows show the opposite trend of the WH_RM parameter. The impact of mistakes decreases respect to the total demand from year 4 to year 10 and increases in the last two years.

The main differences of the flows are shown in the two figures above (figure 15 and 16). The first one is related to the situation at year 10 while the second one is linked to the situation at year 12.

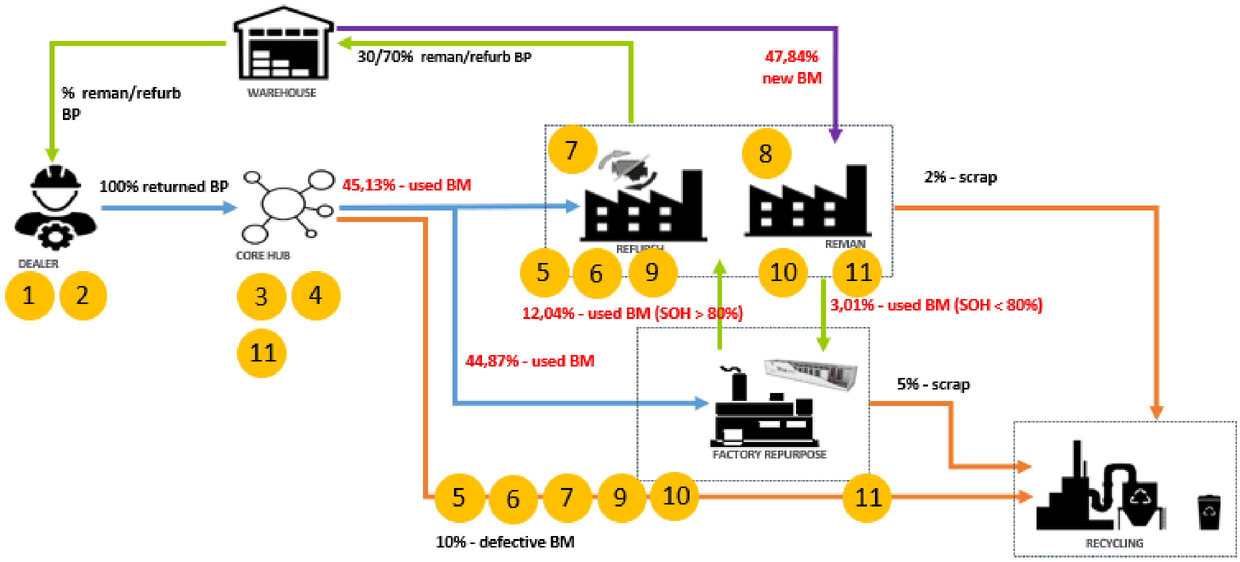


Figure 17: Flow 2 year 10 percentages with uncertainty and second life cycle of batteries

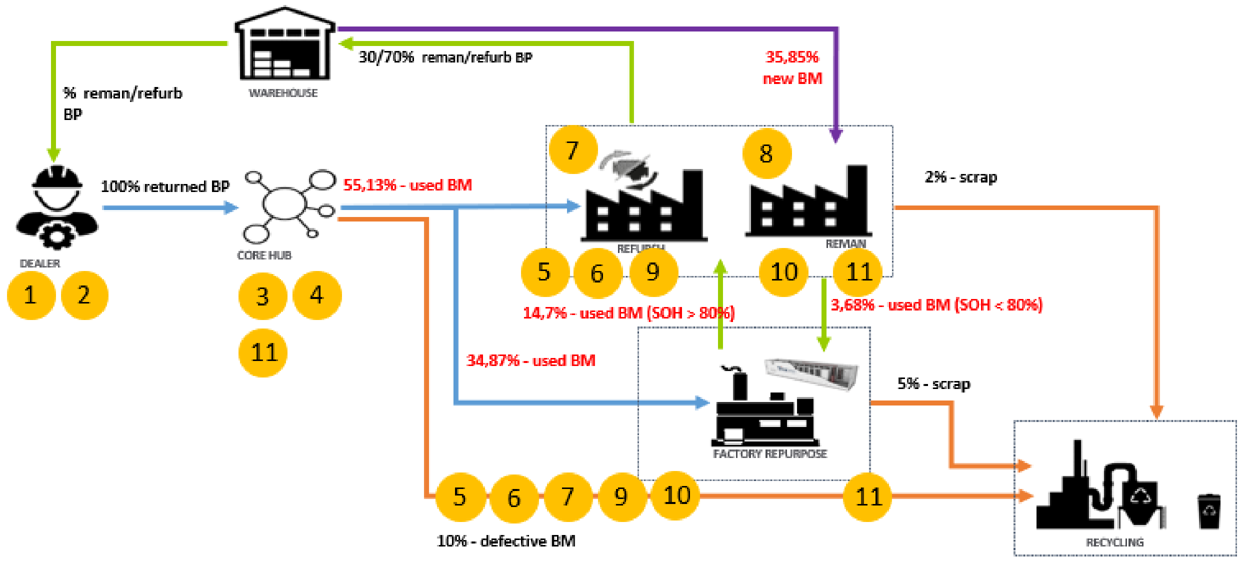


Figure 18: Flow 2 year 12 percentages with uncertainty and second life cycle of batteries

<u>Outsourcing or In-house strategy</u>: Last difference between scenarios is related to the strategy for RM/RF and RP plants. The main idea is to test which combination of outsourcing or in-house strategy is more sustainable from an economic point of view.

Four possible combinations are presents:

1. Activities of remanufacturing/refurbishing and repurposing are performed in-house.
2. Activities of remanufacturing/refurbishing are performed in-house, while repurposing processes are outsourced to third parties.

3. Activities of remanufacturing/refurbishing are outsourced to third parties, while repurposing processes are performed in-house.
4. Both activities of remanufacturing/refurbishing and repurposing are outsourced to third parties.

3.3 SUMMARY

The model tests overall 24 different scenarios, each of them with different set up and different strategy. Simulation is done for 3 different type of flows (flow 1, flow 2 and flow 3), for two different types of process/operation allocation (A or B) and for two different strategy of outsourcing for remanufacturing/refurbishing factories and for repurposing plants (outsourced or in-house).

Table 7: Scenario considered by the model.

scenario nr	FL	OP	RM_RF_OUT	RP_OUT
1	1	A	In-House rm/rf	In-House Rp
2	2	A	In-House rm/rf	In-House Rp
3	3	A	In-House rm/rf	In-House Rp
4	1	B	In-House rm/rf	In-House Rp
5	2	B	In-House rm/rf	In-House Rp
6	3	B	In-House rm/rf	In-House Rp
7	1	A	OutSourced rm/rf	In-House Rp
8	2	A	OutSourced rm/rf	In-House Rp
9	3	A	OutSourced rm/rf	In-House Rp
10	1	B	OutSourced rm/rf	In-House Rp
11	2	B	OutSourced rm/rf	In-House Rp
12	3	B	OutSourced rm/rf	In-House Rp
13	1	A	In-House rm/rf	OutSourced Rp
14	2	A	In-House rm/rf	OutSourced Rp
15	3	A	In-House rm/rf	OutSourced Rp
16	1	B	In-House rm/rf	OutSourced Rp
17	2	B	In-House rm/rf	OutSourced Rp
18	3	B	In-House rm/rf	OutSourced Rp
19	1	A	OutSourced rm/rf	OutSourced Rp
20	2	A	OutSourced rm/rf	OutSourced Rp
21	3	A	OutSourced rm/rf	OutSourced Rp
22	1	B	OutSourced rm/rf	OutSourced Rp
23	2	B	OutSourced rm/rf	OutSourced Rp
24	3	B	OutSourced rm/rf	OutSourced Rp

Scenarios highlighted in grey will not be considered in this thesis. This is linked to the fact that they have already been discussed in the previous study.

3.4 EXPLANATION OF THE PARAMETER TO DETERMINE THE BEST SCENARIO

Before looking at the results it is important to introduce parameters used inside the analysis to determine the best scenario.

Analysis has been performed taking two different viewpoints: the first one is related to the economic performance, while the second one takes into consideration parameters linked to the circularity.

Starting from the economic point of view, the two main parameters adopted are the Net Present Value (also called NPV) and the Pay Back Time (PBT). From an economic perspective, the best scenario is the one that shows the best performances in terms of higher NPV and lower PBT.

From a circularity point of view, two parameters have been taken into consideration. The first parameter introduced refers to the percentage of batteries reintroduced in the model. The formulation is quite simple: it takes into consideration all the old batteries used to satisfy the customer demand in terms of refurbished batteries and repurposed batteries, over the total demand of the year.

The second one is a mix between the percentage of batteries reintroduced in the market and the SOH of them. The calculation of this parameter is performed in this way:

(% of batteries used in the RF activities * 80% of SOH + % of batteries used in the RP activities * 50% of SOH) * (Demand of that year) [kWh]

Thanks to these two indicators it is possible to have an idea of how the model works in terms of circularity and have a better vision of the implications of the second life cycle.

For both these two indicators analysis will be performed taking into consideration customer demand at year 12.

4. MATHEMATICAL MODEL

After the introduction to the logic of the model in this paragraph are listed the main assumptions and parameters that rule simulation choices. Here is the list of the main assumptions of the model.

- Different battery types are considered cumulatively in terms of overall volumes, with average values assigned.
- Flows of battery packs and modules are assigned by the routing coefficients.
- Time is represented as discrete: the model evolves along 12-time steps (one-time step = one year), each associated with a set of parameters and depending on the previous steps.
- Processing times are considered negligible in the model (compared to the length of a time step).
- Operations taking place at dealers are not considered as differential.
- Cost parameters are considered constant during the whole simulation.
- Establishing costs are linear functions of the established capacity; expansion costs are linear functions of the expanded capacity; fixed costs are a linear function of the established capacity; variable processing costs are linear functions of the quantity of batteries processed.
- The maximum floor expansion space is supposed to be 150 m^2 for the existing plants and 1500 m^2 for the new ones.
- 100% of returned BP should be substituted with either remanufactured or refurbished BP (depending on customer demand).
- There is no demand constrains from repurposing process: all BM with SOH < 80% and BM not used in refurbishment are send for repurposing and sold to customers.
- The selling price of the remanufactured, refurbished and repurposed batteries are calculated as the product between the associated Health Factor and price of a new battery.
- The Health factor associated to remanufactured batteries is higher than the one associated to refurbished batteries, that is respectively higher than the Health Factor of repurposed batteries.
- The process flow for remanufacturing, refurbishing and repurposing activities is the same except for the assembling step: remanufacturing employs only new battery modules, while refurbishment and repurposing use mainly returned battery modules.
- The repurposed battery packs employ new boxes, wirings, cooling system and electrical/electronic systems.
- The cost of a new battery module has been considered as the 70% of the new battery pack cost expressed in Eur/KWh.
- The costs of outsourced remanufactured/repurposed batteries are calculated adding the profit margin of a third-party company to the corresponding costs of in-house operations.

- Transportation costs are calculated considering a fixed trip cost coefficient, depending on the average truck load (number of loaded batteries), and a variable trip cost coefficient, depending on the travelled distance.
- No stock is considered in the model.
- Remanufacturing, refurbishment and repurposing processes have both cost and revenue components, while recycling is composed only of cost components.
- Investments for new facilities include all relevant cost items (e.g. battery test equipment, internal transportation equipment, storing equipment etc.) depending on the process they perform.
- Three core hubs are considered as already open (Gent, Flen and Skövde) and so no establishing costs are considered at these core hub locations.
- The costs of outsourced remanufacturing, refurbishing and repurposing activities are only made of the variable component.
- Capacity of the facilities refers to the maximum cumulative processing capacity of a single time step.
- Life cycle of remanufactured batteries is estimated to be of 7 years.
- Life cycle of refurbished batteries is estimated of 4 years.
- The last assumption is related to the one life cycle demand. It is shown in the sections 11.1.

Constraints

- All the facilities have a maximum reachable capacity both in case of in-house or outsourcing set up.
- All the flows between the nodes must be balanced, batteries that come inside the facilities are the same that come out from the facilities.
- A facility that is open at time t, it cannot be closed in the following time periods. The same is true for recovery facilities that operate in-house. Location of outsourced operations can be changed through time.
- Production/handling capacity at time t+1 is equal to the production/handling capacity at time t plus the corresponding production/handling capacity expansion occurred at time t.
- It is assumed that the expansion done at time t is made effective in the same year and it can be exploited in the same year.
- The cumulative capacity expansion over all the time periods should be lower than the maximum capacity expansion allowed.
- Three core hubs are considered as already existing at year 1 by the model (Gent, Flen, Skovde).

- If a plant/core hub/warehouse is closed at time t, then its established and expanded production/handling capacity at time t has to be zero.

After having introduced main assumptions and constraints of the model, the list of parameters that are considered during the simulation are listed below. It is also present the list of indexes linked to the factories.

Indices and sets

i Index for dealers (DL)

j Index for core hubs (CH)

k Index for remanufacturing/refurbishing plants (RM_RF)

p Index for warehouses (WH)

l Index for recycling plants (RC)

m Index for repurposing plants (RP)

t Index for time periods

Model parameters

Battery related parameters

BMsize: battery module size (kWh/module)

BM_BP: number of modules per battery pack

BPsize: battery pack size (kWh/battery pack)

BP_w: battery pack weight (kg/kWh)

BPtruck: mean equivalent battery pack transported per truck

rb_{it}: returned battery packs at dealer i at time t in KWh

Emission related parameters

Co2 : equivalent CO2 emission (grams CO2/ km/ton)

Ton: mean transported tons per truck (ton/truck)

Capacity data

CHin: initial production capacity of existing core hubs (KWh/year)

Max_exp_CH: maximum cumulative expansion at the existing core hubs (KWh)

Max_exp: maximum cumulative expansion for new facilities (KWh)

Revenues and Cost parameters

BPprice: price of a new battery pack (Eur/KWh)

BMcost: cost of a new battery module (Eur/KWh)

HF_RM: health factor associated to a remanufactured battery pack (%)

HF_RF: health factor associated to a refurbished battery pack (%)

HF_RP: health factor associated to a repurposed battery pack (%)

RMpr: remanufactured battery pack selling price (Eur/Kwh)

RFpr: refurbished battery pack selling price (Eur/Kwh)

RPpr: repurposed battery pack selling price (Eur/Kwh)

CHestab_cost: establishing costs of a core hub (Eur) –function of the established capacity.

WHestab _cost: establishing costs of a warehouse (Eur) –function of the established capacity.

RM_RFestab_cost: establishing costs of a remanufacturing/refurbishing plant (Eur) –function of the established capacity.

RPestab_cost: establishing costs of a repurposing plant (Eur) –function of the established capacity.

CHexp_cost: expansion costs of a core hub (Eur) –function of the expanded capacity

WHexp_cost: expansion costs of a warehouse (Eur) –function of the expanded capacity

RM_RFexp_cost: expansion costs of a remanufacturing/refurbishing plant (Eur) –function of the expanded capacity

RPexp_cost: expansion costs of a repurposing plant (Eur) –function of the expanded capacity

CHfix: fixed costs of a core hub (Eur/year) –function of the established capacity

WHfix: fixed costs of a warehouse (Eur/year) –function of the established capacity

RM_RFfix: fixed costs of a remanufacturing/refurbishing plant (Eur /year) –function of the established capacity

RPfix: fixed costs of a repurposing plant (Eur/year) –function of the established capacity

CHvar: variable production costs of a core hub (Eur/KWh/year) –function of the quantity of processed batteries

WHvar: variable storage costs of a warehouse (Eur/KWh/year) - function of the quantity of processed batteries

RM_RFvar: variable production costs of a remanufacturing/refurbishing plant (Eur/KWh/year) - function of the quantity of processed batteries

RPvar: variable production costs of a repurposing plant (Eur/KWh/year) - function of the quantity of processed batteries

RMout: outsourcing costs for remanufactured battery packs (Eur/KWh) - function of the quantity of processed batteries and of outsourced company profit margin

RFout: outsourcing costs for refurbished battery packs (Eur/KWh) - function of the quantity of processed batteries and of outsourced company profit margin

RPout: outsourcing costs for repurposed battery packs (Eur/KWh) - function of the quantity of processed batteries and of outsourced company profit margin

Tfix: fixed transportation costs (Eur/truck)

Tvar: variable transportation costs (Eur/km/truck)

Tbp_l: transportation fees of recycling provider l for severely damaged battery packs (Eur/kg)

Tbm_l: transportation fees of recycling provider l for defective battery modules (Eur/kg)

Rbp_l: recycling costs of recycling provider l for severely damaged battery packs (Eur/kg)

Rbm_l: recycling costs of recycling provider l for defective battery modules (Eur/kg)

Warranty: percentage of warranty costs over the sales (%)

Margin: outsourced company profit margin (%)

r: interest rate of the investment

BIG: big number

Distances between plants

$DL\_CH\_dist_{ij}$: distance between dealer i and core hub j (km)

$CH\_RC\_dist_{jl}$: distance between core hub j and recycling plant l (km)

$CH\_RM\_RF\_dist_{jk}$: distance between core hub j and remanufacturing/refurbishing plant k (km)

$CH\_RP\_dist_{jm}$: distance between core hub j and repurposing plant m (km)

$RM\_WH\_dist_{kp}$: distance between remanufacturing/refurbishing plant k and warehouse p (km)

$RM\_RF\_RC\_dist_{kl}$: distance between remanufacturing/refurbishing plant k and recycling plant l (km)

$RM\_RF\_RP\_dist_{km}$: distance between remanufacturing/refurbishing plant k and repurposing plant m (km)

$RP\_RC\_dist_{ml}$: distance between repurposing plant m and recycling plant l (km)

$WH\_DL\_dist_{pi}$: distance between warehouse p and dealer i (km)

$WH\_RM\_RF\_dist_{pk}$: distance between warehouse p and remanufacturing/refurbishing plant k (km)

$RP\_RM\_RF\_dist_{km}$: distance between repurposing plant m and remanufacturing/refurbishing plant k (km). This parameter has been added in the model in the uncertainty analysis in order to calculate the transportation cost linked to the reverse flow of batteries (paragraph: introduction of uncertainty in the model)

Flow coefficients

CH_RM_RF: percentage of battery modules processed at CH and sent to RM_RF

CH_RP: percentage of battery modules processed at CH and sent to RP

CH_RC: percentage of battery modules processed at CH and sent to RC

CH_RCbp: percentage of severely damaged battery packs processed at CH and sent to RC

CH_RCbm: percentage of defective battery modules processed at CH and sent to RC

RM_WH: percentage of remanufactured battery packs at RM_RF sent to WH

RF_WH: percentage of refurbished battery packs at RM_RF sent to WH

RM_RF_RC: percentage of battery modules sent from RM_RF to RC

RM_RF_RP: percentage of battery modules sent from RM_RF to RP

RP_RM_RF: percentage of battery modules sent from RP to RM_RF. This coefficient has been added in the model during the study on uncertainty (paragraph: introduction of uncertainty in the model)

WH_RM_RF: percentage of new battery modules sent from WH to RM_RF

RP_RC: percentage of battery modules sent from RP to RC

RM_RFcoeff : 1 if remanufacturing/refurbishing activities are outsourced, 0 otherwise

RPcoeff : 1 if repurposing activities are outsourced, 0 otherwise

RF_rec : percentage of returned battery modules that are used for refurbishment at remanufacturing/refurbishing plants

RP_rec : percentage of returned battery modules that are used for repurposing at repurposing plants

Decision variables

CH_{jt}: 1 if core hub j is open at time t, 0 otherwise.

RM_RF_{kt}: 1 if remanufacturing/refurbishing plant k is open at time t, 0 otherwise.

RP_{mt}: 1 if repurposing plant m is open at time t, 0 otherwise.

WH_{pt}: 1 if warehouse p is open at time t, 0 otherwise.

$CHcap_{jt}$: maximum production capacity of core hub j at time t (KWh/year)

RM_RFcap_{kt}: maximum production capacity of remanufacturing/refurbishment plant k at time t (KWh/year)

$RPcap_{mt}$: maximum production capacity of repurposing plant m at time t (KWh/year)

$WHcap_{pt}$: maximum handling capacity at warehouse p at time t (KWh/year)

$CHexp_{jt}$: production capacity expansion of core hub j at time t (KWh/year)

RM_RFexp_{kt}: production capacity expansion of remanufacturing/refurbishment plant k at time t (KWh/year)

$RPexp_{mt}$: production capacity expansion of repurposing plant m at time t (KWh/year)

$WHexp_{pt}$: handling capacity expansion at warehouse p at time t (KWh/year)

x_{ijt}: battery packs in KWh transported from dealer i to core hub j at time t. In the MATLAB model is called X.

z_{jkt}: battery modules in KWh transported from core hub j to remanufacturing/refurbishing plant k at time t. In the MATLAB model is called Z.

θ_{jlt}: battery modules/packs in KWh transported from core hub j to recycling plant l at time t. In the MATLAB model is called THETA.

y_{jmt}: battery modules in KWh transported from core hub j to repurposing plant m at time t. In the MATLAB model is called Y.

Ω_{kpt}: battery packs in KWh transported from remanufacturing/refurbishing plant k to warehouse p at time t. In the MATLAB model is called OMEGA.

w_{klt}: battery modules in KWh transported from remanufacturing/refurbishing plant k to recycling plant l at time t. In the MATLAB model is called W.

β_{pit}: battery packs in KWh transported from warehouse p to dealer i at time t. In the MATLAB model is called BETA.

α_{pkt}: battery modules in KWh transported from warehouse p to remanufacturing/refurbishing plant k at time t. In the MATLAB model is called ALFA.

α_RF_{pkt}: battery modules in KWh needed for refurbishing operations transported from warehouse p to remanufacturing/refurbishing plant k at time t. In the MATLAB model is called ALFA_RM.

α_RM_{pkt}: battery modules in KWh needed for remanufacturing operations transported from warehouse p to remanufacturing/refurbishing plant k at time t. In the MATLAB model is called ALFA_RM.

δ_{mlt}: battery modules in KWh transported from repurposing plant m to recycling plant l at time t. In the MATLAB model is called DELTA.

γ_{kmt}: battery modules in KWh transported from remanufacturing/refurbishing plant k repurposing plant m at time t. In the MATLAB model is called GAMMA.

I_{mt}: battery packs in KWh transported from repurposing plant m to customers at time t. In the MATLAB model is called IOTA.

AMMAG_{mkt}: battery modules in KWh transported from repurposing plant m remanufacturing/refurbishing plant k at time t. In the MATLAB model is called AMMAG. This parameter has been introduced in the model during the study of uncertainty for process allocation type B (paragraph: introduction of uncertainty in the model).

Objective function and related formula

These assumptions led to a mathematical formulation of the model objective. The main objective is the maximization of the NPV during the 12 years life cycle. Here is the objective function of the model:

Maximize $NPV = \sum_t \frac{Rev_t - TC_t - Rcpc_t - EstC_t - FixC_t - ExpC_t - VarC_t - OutC_t}{(1+r)^t}$

The NPV at time t will be equal to the sum of the revenues at time t, minus the transportation costs at time t, minus the recycling costs at time t, minus the establishing costs at time t, minus the fixed costs at time t, minus the expansion costs at time t, minus the variable costs at time t, minus the outsourcing costs (if presents) at time t, everything divided by the discount rate.

Below it is possible to find all the other formulas linked to the revenues and costs faced by the model divided per categories.

$\boldsymbol{Rev_t - revenues\ at\ time\ t}$

$$Rev_t = \sum_m I_{mt} \cdot RPpr + \sum_k \sum_p \Omega_{kpt} \cdot RF\_WH \cdot RFpr + \sum_k \sum_p \Omega_{kpt} \cdot RM\_WH \cdot RMpr$$

$$with\ RPpr = HF\_RP \cdot BPprice, \qquad RFpr = HF\_RF \cdot BPprice, \qquad RMpr = HF\_RM \cdot BPprice;$$

Revenues at time t will be equal to the sum of the sold repurposed batteries revenues times their price, plus the sum of the sold refurbished batteries revenues times their price, plus the sum of the sold remanufactured batteries revenues times their price.

$\boldsymbol{TC_t - trasportation\ costs\ at\ time\ t}$

$$TC_t = VTC_t + FTC_t + RCTC_t$$

Transportation costs at time t are the sum of variable transportation costs of time t, plus fixed transportation costs at time t plus transportation costs towards recycling centers at time t.

$VTC_t - variable\ trasportation\ costs\ at\ time\ t$

$$VTC_t = \frac{Tvar}{BPtruck \cdot BPsize} \left(\sum_i \sum_j x_{ijt} \cdot DL\_CH\_dist_{ij} + \sum_p \sum_i \beta_{pit} \cdot WH\_DL\_dist_{pi} + \sum_k \sum_p \Omega_{kpt} \cdot RM\_RF\_WH\_dist_{kp} + \sum_p \sum_k \alpha_{pkt} \cdot WH\_RM\_RF\_dist_{pk} + \sum_j \sum_k z_{jkt} \cdot CH\_RM\_RF\_dist_{jk} + \sum_j \sum_m y_{jmt} \cdot CH\_RP\_dist_{jm} + \sum_j \sum_l \theta_{jlt} \cdot CH\_RC\_dist_{jl} + \sum_k \sum_l w_{klt} \cdot RM\_RF\_RC\_dist_{kl} + \sum_k \sum_m \sigma_{kmt} \cdot RM\_RF\_RP\_dist_{km} + \sum_m \sum_l \delta_{mlt} \cdot RP_{RC_{dist}ml} + \sum_m \sum_k \mathrm{AMMAG}_{mkt} \cdot RP\_RM\_RF\_dist_{km} \right)$$

Variable transportation costs at time t are the sum of all the flows of batteries between facilities at time t, times the distances between facilities, times a coefficient linked to the road trip.

In this case the factor with AMMAG is used only for the analysis performed during the study of uncertainty. Otherwise, the last factor of the expression is not considered, because is equal to zero.

$FTC_t - fixed\ trasportation\ costs\ at\ time\ t$

$$FTC_t = \frac{Tfix}{BPtruck \cdot BPsize} \left(\sum_i \sum_j x_{ijt} + \sum_p \sum_i \beta_{pit} + \sum_k \sum_p \Omega_{kpt} + \sum_p \sum_k \alpha_{pkt} + \sum_j \sum_k z_{pkt} + \sum_j \sum_m y_{pkt} + \sum_j \sum_l \theta_{jlt} + \sum_k \sum_l w_{klt} + \sum_k \sum_m \sigma_{kmt} + \sum_m \sum_l \delta_{mlt} + \sum_m \sum_k \mathrm{AMMAG}_{mkt} \right)$$

Fixed transportation costs at time t are the sum of all the flows between facilities of the model times a fixed coefficient.

In this case the factor with AMMAG is used only for the analysis performed during the study of uncertainty. Otherwise, the last factor of the expression is not considered, because is equal to zero.

$RCTC_t - trasportation\ costs\ towards\ recycling\ centers\ at\ time\ t$

$$RCTC_t = BP\_w \cdot \left(+ \sum_j \sum_l \theta_{jlt} \cdot Tbp_l \cdot CH\_RCbp + \sum_j \sum_l \theta_{jlt} \cdot Tbm_l \cdot CH\_RCbm + \sum_k \sum_l w_{klt} \cdot Tbm_l + \sum_m \sum_l \delta_{mlt} \cdot Tbm_l \right)$$

$\boldsymbol{RCPC_t - recycling\ processing\ costs\ at\ time\ t}$

$$RCPC_t = BP\_w \cdot \left(\sum_j \sum_l \theta_{jlt} \cdot Rbp_l \cdot CH\_RCbp + \sum_j \sum_l \theta_{jlt} \cdot Rbm_l \cdot CH\_RCbm + \sum_k \sum_l w_{klt} \cdot Rbm_l + \sum_m \sum_l \delta_{mlt} \cdot Rbm_l \right)$$

$\boldsymbol{EstC_t - establishing\ costs\ at\ time\ t}$; $t_{est}\ is\ the\ year\ in\ which\ the\ plant\ is\ established.$

$$EstC_t = \sum_j CH\_estab\_cost(CHcap_{j,t_{est}}) + (1 - RM\_RFcoeff) \sum_k RM\_RF\_estab\_cost(RM\_RFcap_{k,t_{est}}) + (1 - RPcoeff) \sum_m RP\_estab\_cost(RPcap_{m,t_{est}}) + \sum_p WH\_estab\_cost(WHcap_{p,t_{est}})$$

Establishing costs at time t took into consideration all the facilities opened at time t times the capacity. In case of outsourced facilities this cost is not considered.

$\boldsymbol{ExpC_t - expansion\ costs\ at\ time\ t}$

$ExpC_t = \sum_j CH\_exp\_cost(CHexp_{jt}) + (1 - RM\_RFcoeff) \sum_k RM\_RF\_exp\_cost(RM\_RFexp_{kt}) + (1 - RPcoeff) \sum_m RP\_exp\_cost(RPexp_{mt}) + \sum_p WH\_exp\_cost(WHexp_{pt})$

Expansion costs at time t considers all the facilities expanded at time t times the coefficient linked to the expansion costs. If the facilities is outsourced this cost is not considered.

$\boldsymbol{FixC_t - fixed\ costs\ at\ time\ t}$

$FixC_t = \sum_j CHfix(CHcap_{jt}) + (1 - RM\_RFcoeff) \sum_k RM\_RFfix(RM\_RFcap_{kt}) + (1 - RPcoeff) \sum_m RPfix(RPcap_{mt}) + \sum_p WHfix(WHcap_{pt})$

Fixed costs at time t considers all the fixed costs linked to the facilities owned by the company with a proportional factor linked to the capacity of them. Outsourced costs are not considered.

$\boldsymbol{VarC_t - variable\ costs\ at\ time\ t}$

$VarC_t = \sum_j CHvar(\sum_i X_{ijt}) + (1 - RM\_RFcoeff) \sum_k RM\_RFvar\left(\sum_p \Omega_{kpt}\right) + (1 - RPcoeff) \sum_m RPfix(I_{mt}) + \sum_p WHvar\left(\sum_i \beta_{pit}\right) + (warranty \cdot RM\_WH \cdot RMpr) \sum_p \sum_i \beta_{pit} + (warranty \cdot RF\_WH \cdot RFpr) \sum_p \sum_i \beta_{pit} + (warranty \cdot RPpr) \sum_m I_{mt}$

Variable costs at time t considers all the variable costs linked to the facilities owned by the company with a proportional factor linked to the capacity of them. Outsourced costs are not considered.

$\boldsymbol{OutC_t - outsourcing\ costs\ at\ time\ t}$

$OutC_t = RM\_RFcoeff \cdot RMout \cdot RM\_WH \cdot \sum_p \sum_i \beta_{pit} + RM\_RFcoeff \cdot RFout \cdot RF\_WH \cdot \sum_p \sum_i \beta_{pit} + RPcoeff \cdot RPout \sum_m I_{mt}$

Outsourcing costs at time t considers all the costs linked to outsourced facilities. These costs are calculated taking into consideration a fixed coefficient.

$\boldsymbol{Percentage\ of\ batteries\ reintroduced\ in\ the\ market\ at\ time\ t}$

$$\text{Percentage of batteries reintroduced in the market } (\boldsymbol{t}) = \frac{(\text{\% of refurbished battery sold } (\boldsymbol{t}) + \%\ of\ repurposed\ batteries\ sold\ (\boldsymbol{t}))}{\boldsymbol{TotalDemand\ (t)}}$$

$\boldsymbol{kWh\ of\ batteries\ reintroduced\ in\ the\ market\ at\ time\ t}$

$$\text{kWh of batteries reintroduced in the market at time t} = \text{sum of kWh of refurbished batteries sold (t)} * \text{SOH of refurbished batteries (80\%)} + \text{sum of kWh of repurposed batteries sold (t)} * \text{SOH of repurposed batteries (50\%)}$$

5. RESULTS ANALYSIS

5.1 OVERVIEW OF THE TEST CONDUCTED

The aim of the thesis is to examine the circularity of the transition process (RSC development) through the comparison of economic and environmental (circularity) parameters. To perform this objective several analyses have been performed.

The first analysis has been conducted on scenarios characterised by process allocation type A using a new logic to sort the batteries. In this way, it was possible to screening the scenarios and to select the interesting ones. The same analysis has been conducted introducing the second life cycle on the same scenarios and a comparison between one life cycle and two life cycle of batteries has been performed.

Thanks to this analysis it has been possible to select the best scenario that will be compared with the best one characterised by operation type B.

After that, several tests to detect how the model reacts to the introduction of uncertainty has been conducted. Only 4 scenarios have been tested: the ones characterised by flow type 2 (that shows overall the best results in the previous analysis) and process allocation type B. Firstly, the test has been conducted taking into consideration only one life cycle of batteries and, in a second time, introducing also second life cycle. Moreover, a comparison analysis of these two configurations has been performed.

To conclude the study, a last comparison between the best scenario characterised by process allocation type A and the best scenario characterised by process allocation type B has been conducted both for one life cycle and for the second life cycle.

Table 9: Overview of the analyses performed

Considered scenarios	Type of analysis
FL 1-2-3 / OP-A / In-house & Outsourcing (12 scenarios) 1st LC	NPV vs PBT, configurations Examination of the changes through time for the best scenario(s)
FL 1-2-3 / OP-A / In-house & Outsourcing (12 scenarios) 1st LC + 2nd LC	NPV vs PBT, configurations Examination of the changes through time for the best scenario(s)
FL 1-2-3 / OP-A / In-house & Outsourcing	Comparison: one vs two LC (NPV,PBT, configurations of the best scenarios)
FL 1-2-3 / OP-B / In-house & Outsourcing (4 scenarios) 1st LC	NPV vs PBT, configurations with uncertainty Examination of the changes through time for the best scenario(s)
FL 2 / OP-B / In-house & Outsourcing (4 scenarios) 1st LC + 2nd LC	NPV vs PBT, configurations with uncertainty Examination of the changes through time for the best scenario(s)
FL 2 / OP-B / In-house & Outsourcing (4 scenarios)	Comparison: one vs two LC (NPV,PBT, configurations of the best scenarios)
FL 2 / OP-A vs OP-B 1st LC	Comparison: OP-A vs OP-B Examine the impact of uncertainty (error) on NPV, PBT, configurations of best scenarios
FL 2 / OP-A vs OP-B 1st LC+ 2nd LC	Comparison: OP-A vs OP-B Examine the impact of uncertainty (error) on NPV, PBT, configurations of best scenarios

5.2 SINGLE LIFE CYCLE ANALYSIS: FLOW 1,2,3 PROCESS ALLOCATION TYPE A

The first analysis performed is about the single life cycle. It takes into consideration only process allocation type A. Scenario characterised by process allocation type B will be considered in further analysis with the introduction of uncertainty.

All the possible scenarios have been tested with the logic explained in the section "new logic to sort the battery modules" (the Core Hubs send to the remanufactured and refurbished plants the strictly necessary battery to satisfy the customer demand).

Results and configuration of scenarios are shown below.

Table 10: Scenarios configuration for one life cycle process allocation type A

scenario n	CH (n=5)	RM/RF (n=7)	RP (n=4)	WH (n=4)
1	4(1,2,3,5)	3(1,3,7)	2(1,3)	4
2	5	3(1,2,3)	1(3)	3(1,2,3)
3	4(1,2,3,5)	3(2,3,7)	1(3)	3(2,3,4)
7	4(1,2,3,5)	3(1,3,7)	2(1,3)	4
8	4(1,2,3,5)	4(1,2,3,7)	1(3)	3(2,3,4)
9	4(1,2,3,5)	4(1,2,3,7)	1(3)	3(2,3,4)
13	4(1,2,3,5)	3(1,2,3)	3(1,2,3)	3(1,2,3)
14	4(1,2,3,5)	3(1,3,7)	3(1,2,3)	3(2,3,4)
15	4(1,2,3,5)	3(1,2,3)	3(1,2,3)	3(1,2,3)
19	5	3(1,3,7)	4	4
20	5	4(1,2,3,7)	4	4
21	5	4(1,2,3,7)	4	4

Table 11: Economic parameters of scenarios, one life cycle process allocation type A

scenario nr	FL	OP	RM_RF_OUT	RP_OUT	PBT	NPV
1	1	A	In-House rm/rf	In-House Rp	12	€ 2.738.291
2	2	A	In-House rm/rf	In-House Rp	11	€ 20.417.106
3	3	A	In-House rm/rf	In-House Rp	11	€ 19.689.185
7	1	A	OutSourced rm/rf	In-House Rp	12	€ 2.757.525
8	2	A	OutSourced rm/rf	In-House Rp	11	€ 21.246.966
9	3	A	OutSourced rm/rf	In-House Rp	11	€ 19.582.697
13	1	A	In-House rm/rf	OutSourced Rp	12	€ 3.870.518
14	2	A	In-House rm/rf	OutSourced Rp	10	€ 23.491.388
15	3	A	In-House rm/rf	OutSourced Rp	10	€ 22.610.269
19	1	A	OutSourced rm/rf	OutSourced Rp	12	€ 988.502
20	2	A	OutSourced rm/rf	OutSourced Rp	10	€ 23.419.535
21	3	A	OutSourced rm/rf	OutSourced Rp	10	€ 22.730.986

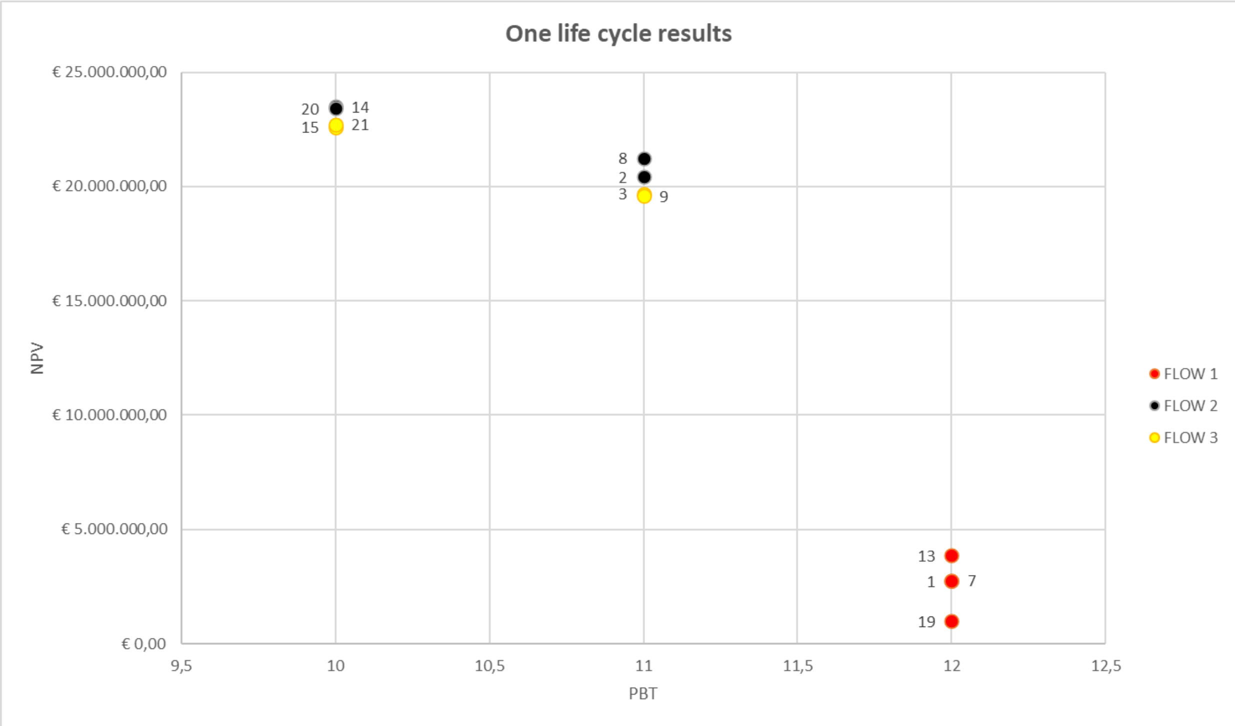


Figure 17: NPV vs PBT graph of scenarios characterised by process allocation type A and one life cycle.

The first step of the analysis is conducted under an economic perspective. Scenarios characterised by flow type 1 appear to be weaker respect the others. For all of them the PBT is at the final year of simulation with low NPV: the maximum value is 3.8 million €.

Going deeper into this analysis it is possible to see how scenario 1 and scenario 7 are very similar in terms of economic parameters and position themselves in the middle from an economic viewpoint. The configuration of these scenario is different: scenario 1 is characterised by in-house facilities of remanufacturing/refurbishing and repurposing, while scenario 7 have remanufacturing/refurbishing plants outsourced.

Based also on the different possibilities that the model considers (open or not a factory i.e.) it is possible to notice how these two scenarios have an identical layout, both from a numerical standpoint and a geographical perspective. We can assume that in this case the outsourcing strategy of remanufacturing and refurbishing activities is not a critical differentiating factory.

Looking at the other two scenarios (number 13 and 19) that are the best and the worst from an economic standpoint for flow type 1, different considerations can be done. Both are characterised by an outsourcing strategy regarding the repurposing factories; for scenario 13 we have an in-house strategy for remanufacturing and refurbishing activities, while for scenario 17 we have a totally outsourced configuration.

In this case the economic differences between the scenario are caused by this strategy. It is possible to assume that in case of an outsourcing configuration of repurposing factory characterised by flow type 1 it is better to pursue an in-house strategy for the remanufacturing and repurposing activities.

Taking into consideration scenarios characterised by flow type 2 and 3 an interesting analysis can be performed.

If we coupled the scenarios with the same strategy in terms of outsourcing or in-house strategy characterised by different flow type it is evident how flow type 2 shows better results.

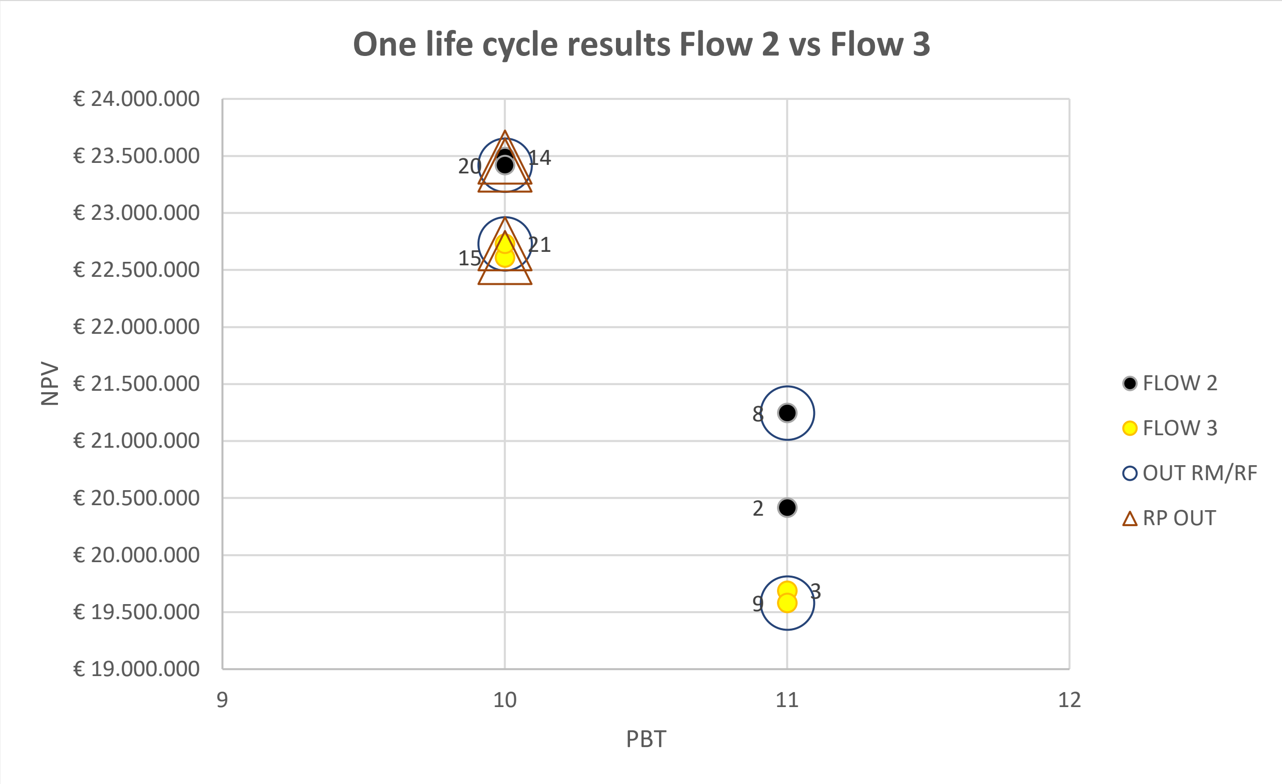


Figure 18: Flow type 2 and 3 overview

Table 12: Flow type 2 and 3 results

scenario n	FL	OP	RM_RF_OUT	RP_OUT	PBT	NPV	NPV differences
2	2	A	In-House rm/rf	In-House Rp	11	€ 20.417.105,73	3,57%
3	3	A	In-House rm/rf	In-House Rp	11	€ 19.689.184,53	
8	2	A	OutSourced rm/rf	In-House Rp	11	€ 21.246.965,58	7,83%
9	3	A	OutSourced rm/rf	In-House Rp	11	€ 19.582.697,46	
14	2	A	In-House rm/rf	OutSourced Rp	10	€ 23.491.387,52	3,75%
15	3	A	In-House rm/rf	OutSourced Rp	10	€ 22.610.269,39	
20	2	A	OutSourced rm/rf	OutSourced Rp	10	€ 23.419.535,16	2,94%
21	3	A	OutSourced rm/rf	OutSourced Rp	10	€ 22.730.986,44	

The average distance between scenarios characterised by flow type 2 and scenarios with flow type 3 is 4,52%.

Looking now at the table above it is possible to state that scenarios characterised by an outsourcing strategy for repurposing activities outperformed the others from an economic standpoint. The PBT is 10 years instead of 11 and the NPV increase of more than 2.5 million €.

Taking into consideration the possible different strategy of remanufacturing and refurbishing it is interesting to notice that also this time this configuration is not a differential economic factor. In fact, fixed the repurposing strategy, all the scenario characterised by different layout of remanufacturing and refurbishing activities are very close in terms of economic parameters. This statement can be highlighted looking for example at scenario 2 and scenario 8 or scenario 3 and scenario 9: the economic parameters are similar, PBT remains always the same while NPV is slightly different.

The best scenario under an economic perspective is scenario number 14 followed by 20, 21 and 15.

From a circular economy point of view the scenarios can be considered only by the type of flow. In fact, all the scenarios with the same flow type have the same indicators performances.

Table 13:Circularity indicators results

Circularity indicators	Flow 1 Year 12	Flow 2 Year 12	Flow 3 Year 12
Percentage of batteries reintroduced in the market	83%	83%	83%
Amount of kWh of batteries reintroduced in the market	202743,9	250920,6	248511,8

Looking at the table with the results of the indicator it is easy to understand how flow type 2 shows overall better performances respect the other two types. This is easy to explain by the fact that flow type 2 is the one with the most refurbished batteries reintroduced in the market. Flow type 2 shows a high gap respect flow type one in terms of kWh (almost 20%) while it is very similar with flow type 3 (less than 1% of difference).

Focusing now on the best scenario (scenario 14 from an economic point of view) it is interesting to see the physical changes of the model through the years of simulation. In the next images a European map will be shown with all the facilities opened by the model at year 1, 10 and 12.

Figure 19: Scenario 14 year 1

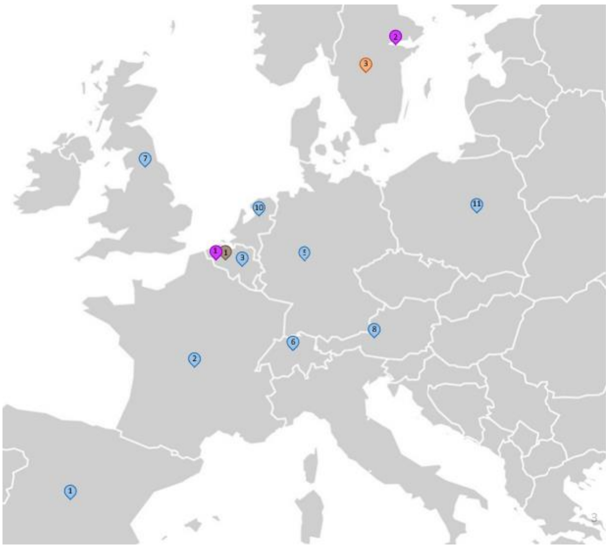


Figure 20: Scenario 14 year 10

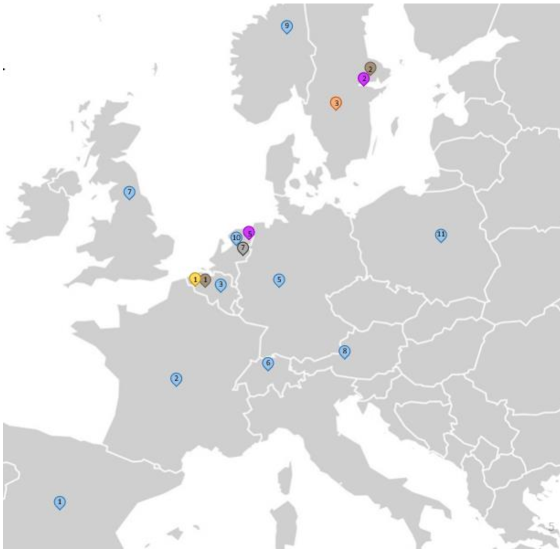


Figure 21: Scenario 14 year 12

As it is possible to see from the maps, the model tries to centralize most of the facilities in two main areas (Sweden, Holland, and Belgium). The facilities created during the year of simulation are always close to already opened facilities, minimizing costs of transportation.

To sum up all the consideration done in this analysis, we can affirm that flow types 2 and 3 are always preferable respect to flow type 1. From the table it is also possible to conclude that flow 2 has a better performance than flow 3 for the same operational configurations. For this reason, next analyses on process allocation type B will be performed taking into consideration only scenarios characterised by flow type 2.

5.3 SECOND LIFE CYCLE ANALYSIS FOR PROCESS ALLOCATION TYPE A

The introduction of the second life cycle of batteries has an important impact over the parameters. The analysis below is performed on the scenarios characterised by operation type A as done in the previous paragraph.

Table 14: Second life cycle results for scenarios with process allocation type A

scenario nr	FL	OP	RM_RF_OUT	RP_OUT	PBT	NPV
1	1	A	In-House rm/rf	In-House Rp	12	€ 5.397.497,42
2	2	A	In-House rm/rf	In-House Rp	11	€ 25.215.622,78
3	3	A	In-House rm/rf	In-House Rp	11	€ 18.447.189,01
7	1	A	OutSourced rm/rf	In-House Rp	12	€ 4.739.768,94
8	2	A	OutSourced rm/rf	In-House Rp	10	€ 25.529.956,08
9	3	A	OutSourced rm/rf	In-House Rp	11	€ 16.815.232,23
13	1	A	In-House rm/rf	OutSourced Rp	12	€ 5.458.064,15
14	2	A	In-House rm/rf	OutSourced Rp	11	€ 27.722.595,86
15	3	A	In-House rm/rf	OutSourced Rp	11	€ 20.310.241,11
19	1	A	OutSourced rm/rf	OutSourced Rp	12	€ 1.526.229,96
20	2	A	OutSourced rm/rf	OutSourced Rp	10	€ 26.965.148,14
21	3	A	OutSourced rm/rf	OutSourced Rp	10	€ 19.896.071,62

Table 15: Second life cycle configurations for scenarios with process allocation type A

scenario n	CH (n=5)	RM/RF (n=7)	RP (n=4)	WH (n=4)
1	5	3(1,2,3)	2(1,3)	4
2	5	3(1,2,3)	2(3,4)	3(1,2,3)
3	5	3(1,2,3)	2(1,3)	3(1,2,3)
7	4(1,2,3,5)	3(1,3,7)	2(1,3)	4
8	5	4(1,2,3,7)	1(3)	4
9	5	4(1,2,3,7)	2(1,3)	4
13	4(1,2,3,5)	3(1,2,3)	3(1,2,3)	4
14	5	3(1,2,3)	4	3(1,2,3)
15	5	3(2,3,7)	4	3(2,3,4)
19	5	3(1,3,7)	4	4
20	5	5(1,2,3,4,7)	4	4
21	5	4(1,2,3,7)	4	4

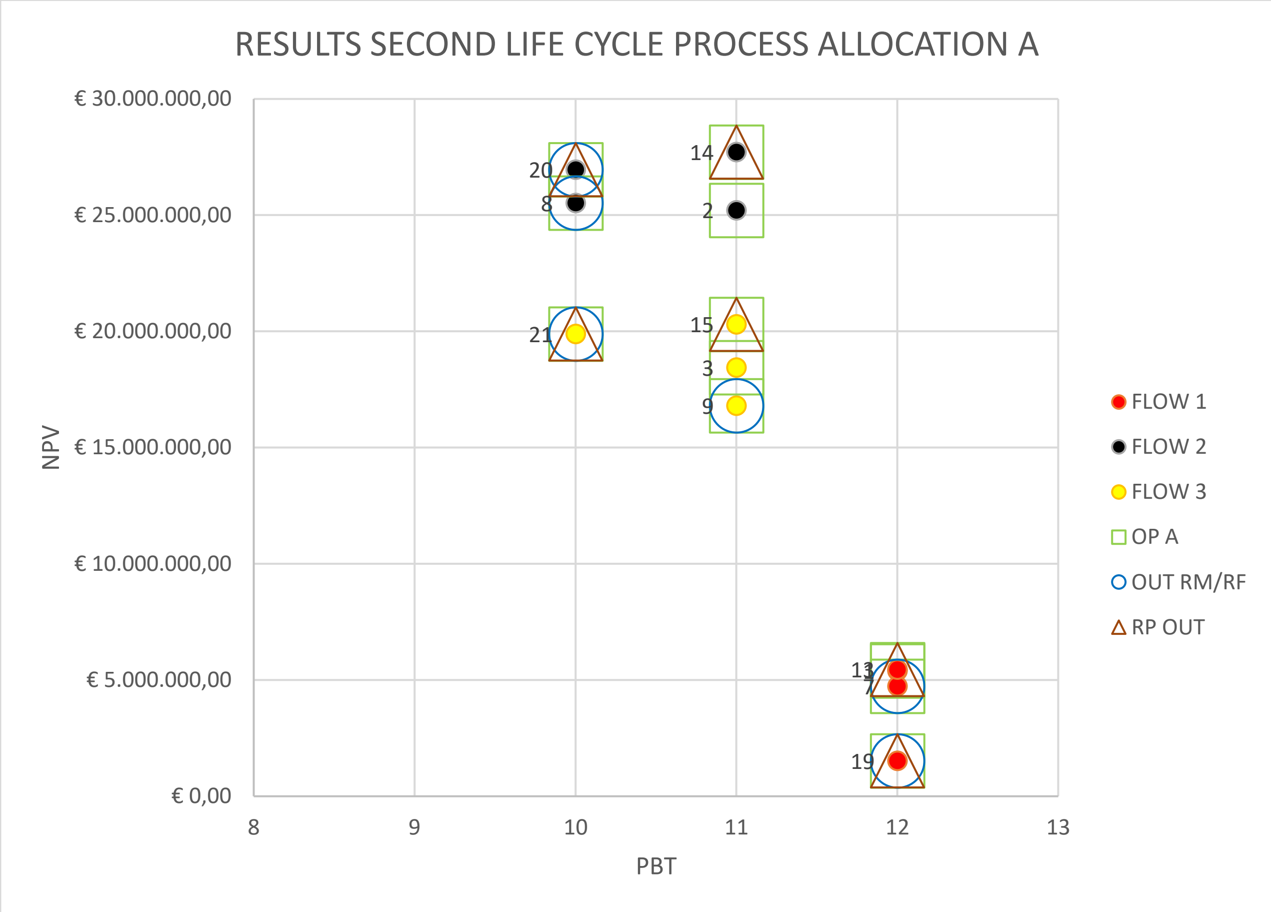


Figure 22: NPV vs PBT for second life cycle scenarios with process allocation type A

As it is possible to notice, the introduction of the second life cycle for the refurbished and remanufactured batteries creates economic benefits. Looking at the figure 12 it is easy to understand how flow type 2 shows another time the best economic results. In fact, all the best scenarios in terms of NPV are characterised by this type of flow.

Looking only at PBT indicators, we can state that scenario 20 and 21 shows the better results together with scenario 8. The peculiarity of scenario 20 and 21 is the fact that they have the same configuration (total outsourcing of the RM/RF and RP plants) except for the flow type. Another important consideration is the fact that both scenario 8 and scenario 20 characterised by outsourcing of RM/RF activities has the best PBT. This will lead to the consideration that independently from the strategy of repurposing activities the strategy of outsourcing remanufacturing and refurbishing one will lead to a shorter payback time.

However, this strategy seems to be better in the first ten year, but it is outpaced in the long term by the in-house strategy of RM/RF activities in terms of NPV. In fact, Due to the increasing demand linked to the second life cycle of batteries an in-house strategy seems to be better, to have more visibility on the cycle of the products and to exploit the scale effect in all the factories.

Scenario 14 exceed the other by more than one million euro at year 12 but it is possible to state that this difference will increase if we take into consideration a longer simulation time. This assumption is explained by the fact that the demand will continue to increase exponentially after year 12 and the advantages mentioned before will lead to a more profitable and sustainable solution.

Focusing now on the different configurations of the model it is clear how the best solution regarding core hubs is to open all the 5 possible locations. In fact, all the scenario with a PBT lower or equal to 11 and a NPV higher than 15 million euro shows this peculiarity.

The same consideration can be done for the warehouses: all the warehouses are opened at year 12 for the best scenarios and it is possible to state that this solution is the most profitable according to the model logic.

Regarding remanufacturing and repurposing factories, it is possible to point out that location number 5 (Varsaw) and 6 (Hol) are never opened also with the increase of the demand linked to the second life cycle of batteries. Location number 4 (Limoges) is used in only one case (scenario 20) where the remanufacturing and repurposing activities are outsourced.

Looking at repurposing factories the situation is different: in case of an outsourcing logic the model chooses every time to use all the possible 4 locations, while in case of an in-house strategy he tries to minimize the number of factories. The only factory that is open in all the cases is the one in Skovde (location 3) in which also the RM/RF activities are present: this leads to the conclusion that in case of in-house strategy a centralized solution is the best one.

Focusing on the circularity parameters the results are shown in the table:

Table 16: Circularity parameters results

Circularity indicators	Flow 1 Year 12	Flow 2 Year 12	Flow 3 Year 12
Percentage of batteries reintroduced in the market	83%	83%	83%
Amount of kWh of batteries reintroduced in the market	217101,8	276999	267094

The indicators are taken 12 in order to see better the impact of the second life cycle. Looking at the overall performances flow type 2 shows another time the best ones.

The introduction of the second life cycle seems to have positive results in terms of kWh of batteries reintroduced in the market for all the flows.

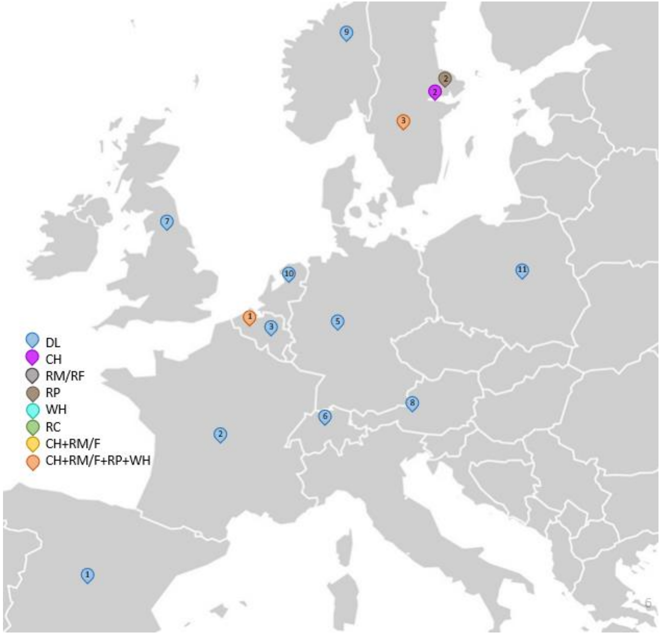


Figure 23: Scenario 14 second life cycle year 10

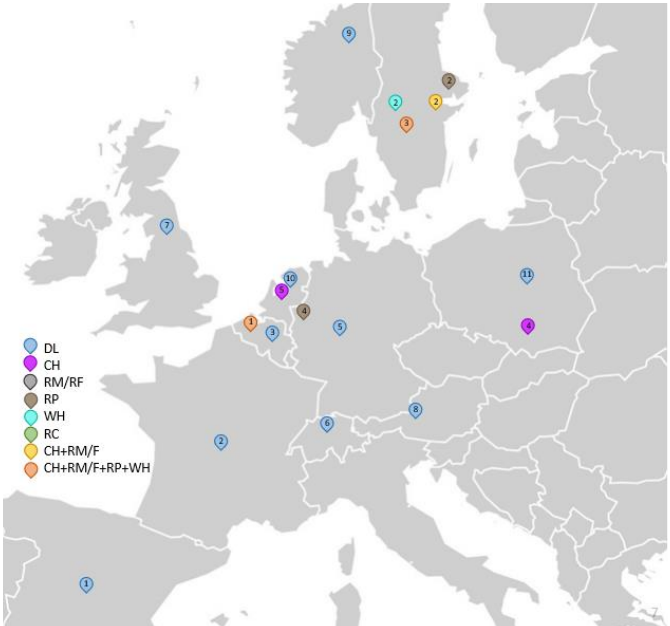


Figure 24: Scenario 14 second life cycle year 12

It is interesting to focusing on how the introduction of the second life cycle influences the configuration of the model. As you can see from the figure 22 and 23, the model prefers always to open facilities close one to each other. The only exception is linked to the core hub number 4 (Cracow). This fact is linked to the increase of the demand that leads to an impossibility to manage it with only 4 core hubs; the only way to cope with it is to open the last available location for core hub in Cracow.

5.4 COMPARISON BETWEEN ONE LIFE CYCLE AND TWO LIFE CYCLES FOR PROCESS ALLOCATION A

It is interesting now to see the effect of the introduction of the second life cycle in the model. The comparison will be done on the twelve-scenario characterised by operation type A to see what the main differences are.

Table 17: Comparison between one life cycle and two life cycle with process allocation type A

	ONE LIFE CYCLE		TWO LIFE CYCLE	
scenario nr	**PBT**	**NPV**	**PBT**	**NPV**
1	12	€ 2.738.291,19	12	€ 5.397.497,42
2	11	€ 20.417.105,73	11	€ 25.215.622,78
3	11	€ 19.689.184,53	11	€ 18.447.189,01
7	12	€ 2.757.525,32	12	€ 4.739.768,94
8	11	€ 21.246.965,58	10	€ 25.529.956,08
9	11	€ 19.582.697,46	11	€ 16.815.232,23
13	12	€ 3.870.518,04	12	€ 5.458.064,15
14	10	€ 23.491.387,52	11	€ 27.722.595,86
15	10	€ 22.610.269,39	11	€ 20.310.241,11
19	12	€ 988.501,86	12	€ 1.526.229,96
20	10	€ 23.419.535,16	10	€ 26.965.148,14
21	10	€ 22.730.986,44	10	€ 19.896.071,62

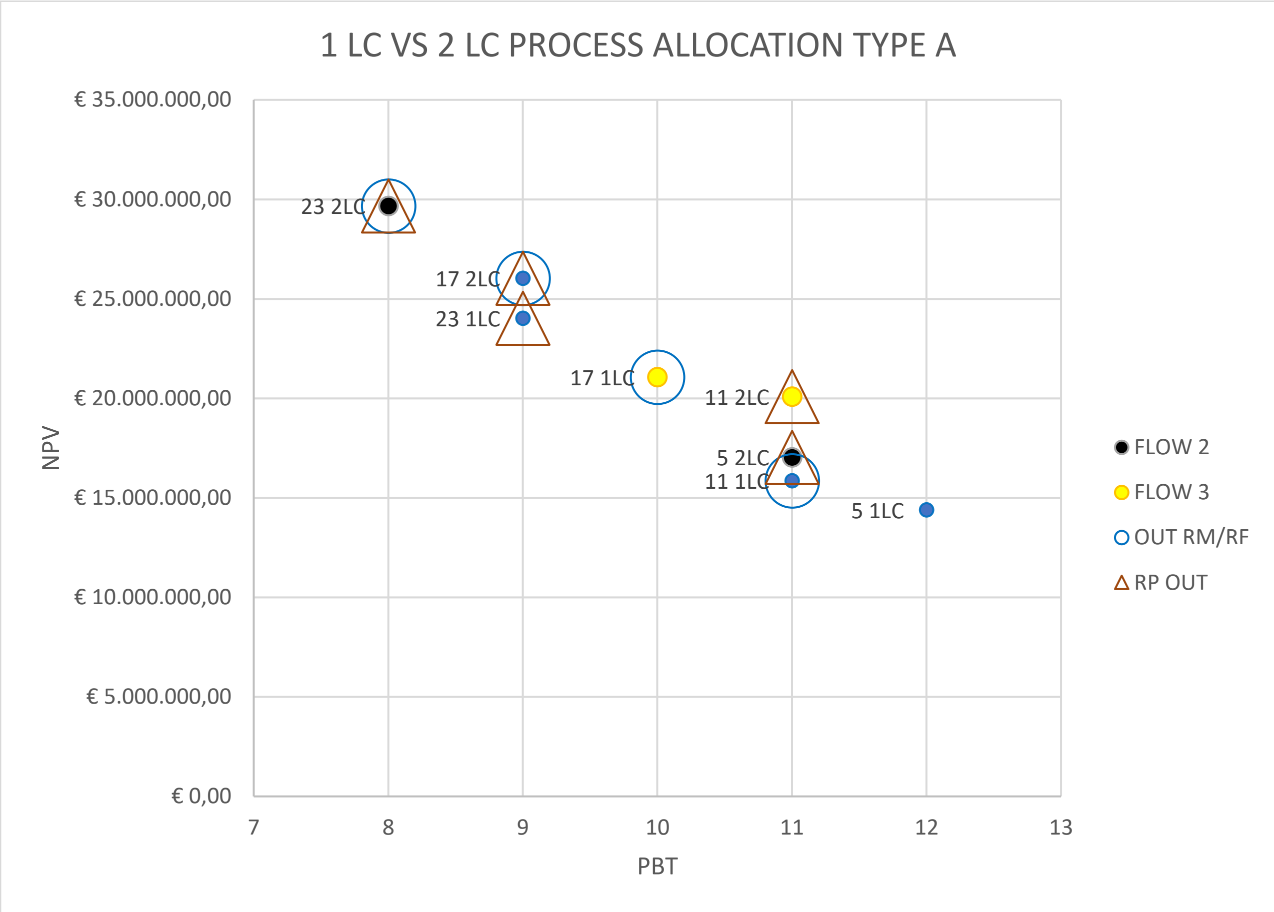


Figure 25: Best 4 scenarios comparison 1LC vs 2 LC

Considering the economic aspect, it is obvious that an extra life for batteries will create benefits in terms of NPV for almost all the scenarios (except for scenario 3, 9, 15 and 21 in which we have the opposite situation). Analysing deeper this situation NPV increase for scenarios characterised by flow type 1 and 2 while decrease for scenario characterised by flow type 3. This is linked to the fact that in case of flow type 3 the amount of new battery modules bought by the model to satisfy the customer demand increases linearly. In fact, looking at the trend of parameter WH_RM in table 12, the amount of battery modules necessary to feed the demand increases. This fact leads to extra costs that impacts directly on the NPV.

Regarding PBT the situation is different, the introduction of the second life cycle seems not to have a big impact for most of the scenario and the PBT remain the same.

By introducing the second life cycle the difference between flow type 2 and flow type 3 become more evident (particularly looking at the NPV indicator) leading to the conclusion that flow type 2 is the preferable one. Looking at the NPV the best scenarios are the number 14 followed by number 20, 11 and 8. All these scenarios are characterised by flow type 2.

To choose the best one company can focus on two possibilities. If the most important driver is re-enter in the initial investment the total outsourcing solution is the best one (scenario 20) in case of second life cycle. Otherwise, if the NPV is the focus parameter scenario 14 is the best option to pursue.

Table 18: different configurations of scenarios one life cycle vs two life cycle process allocation type B

	ONE LIFE CYCLE				TWO LIFE CYCLE			
scenario nr	**CH (n=5)**	**RM/RF (n=7)**	**RP (n=4)**	**WH (n=4)**	**CH (n=5)**	**RM/RF (n=7)**	**RP (n=4)**	**WH (n=4)**
1	4(1,2,3,5)	3(1,3,7)	2(1,3)	4	5	3(1,2,3)	2(1,3)	4
2	5	3(1,2,3)	1(3)	3(1,2,3)	5	3(1,2,3)	2(3,4)	3(1,2,3)
3	4(1,2,3,5)	3(2,3,7)	1(3)	3(2,3,4)	5	3(1,2,3)	2(1,3)	3(1,2,3)
7	4(1,2,3,5)	3(1,3,7)	2(1,3)	4	4(1,2,3,5)	3(1,3,7)	2(1,3)	4
8	4(1,2,3,5)	4(1,2,3,7)	1(3)	3(2,3,4)	5	4(1,2,3,7)	1(3)	4
9	4(1,2,3,5)	4(1,2,3,7)	1(3)	3(2,3,4)	5	4(1,2,3,7)	2(1,3)	4
13	4(1,2,3,5)	3(1,2,3)	3(1,2,3)	3(1,2,3)	4(1,2,3,5)	3(1,2,3)	3(1,2,3)	4
14	4(1,2,3,5)	3(1,3,7)	3(1,2,3)	3(2,3,4)	5	3(1,2,3)	4	3(1,2,3)
15	4(1,2,3,5)	3(1,2,3)	3(1,2,3)	3(1,2,3)	5	3(2,3,7)	4	3(2,3,4)
19	5	3(1,3,7)	4	4	5	3(1,3,7)	4	4
20	5	4(1,2,3,7)	4	4	5	5(1,2,3,4,7)	4	4
21	5	4(1,2,3,7)	4	4	5	4(1,2,3,7)	4	4

Looking at the configurations for the two simulations we can notice that the model works in a similar way. In fact, all the factories that have been opened in case of only one life cycle of the batteries are opened also in the other case. The most important different is the fact that the model decides to open more factories in case of 2 life cycle: this is linked to the fact that we have an important increase of the demand and the model needs additional capacity to manage batteries.

Introducing the second life cycle has an important impact also on the circularity parameters. From an enviromental point of view the re-use of the battery modules leads to a lower CO2 emission per unit considering all the useful life. The first parameter introduced is not relevant to understand the impact that the second life cycle could have since it remains the same. The second indicator performances are shown in the table below.

Table 19: Comparison between circularity parameter of one life cycle and two life cycle

	One life cycle			**Two life cycle**		
Circularity indicators	**Flow 1 Year 12**	**Flow 2 Year 12**	**Flow 3 Year 12**	**Flow 1 Year 12**	**Flow 2 Year 12**	**Flow 3 Year 12**
Amount of kWh of batteries reintroduced in the market	202743,9	250921	248512	217102	276999,1	267093,6

As it is possible to notice the introduction of the second life cycle creates benefits in terms of kWh reintroduced in the market for all the flows. It is possible to notice how flow types 2 and 3 have more benefits (in terms of kWh) respect flow type 1 linked to the introduction second life cycle.

To sum up, it can be state that flow type 2 shows the overall best performances followed by number 3. The introduction of the second life cycle is a profitable choice for the company focusing on circularity indicators.

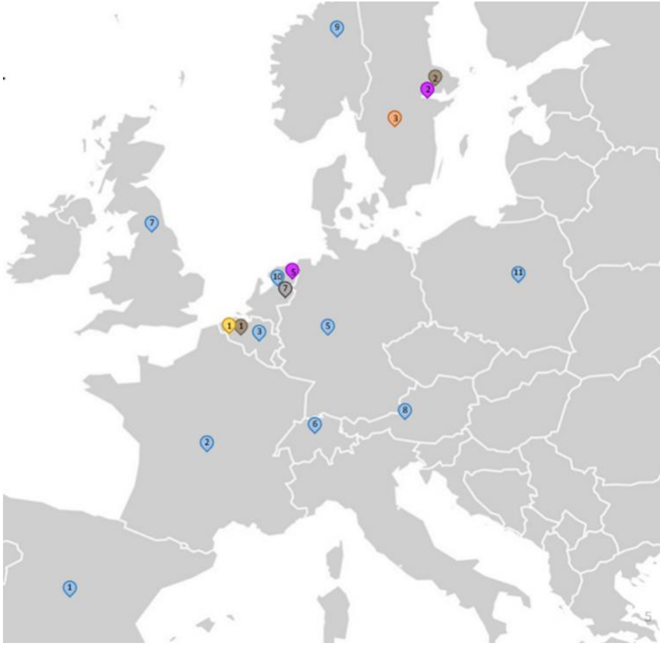


Figure 26: Scenario 14 year 12 One life cycle

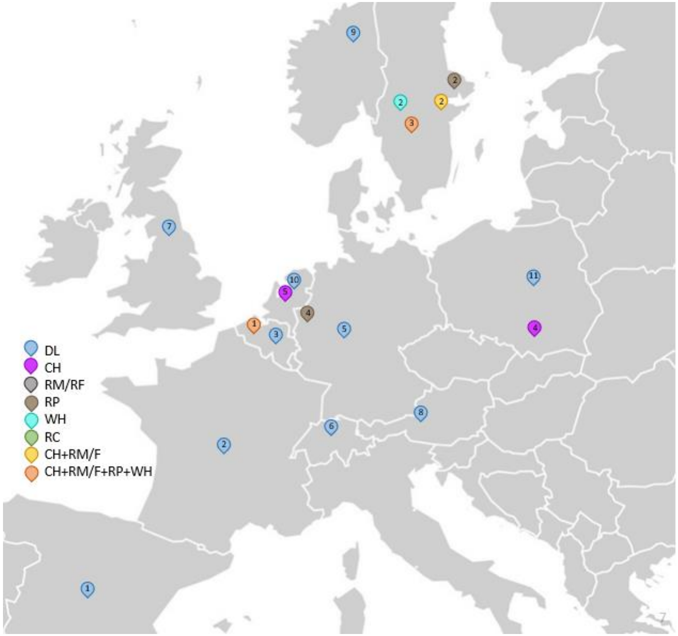


Figure 197: Scenario 14 year 12 Second life cycle

Looking at the different configuration of the best scenario with first and second life cycle some considerations can be made. First of all, it is interesting to see how the model tries to centralize when possible, in both of the cases. The facilities open in case of only one life cycle are opened also in case of second life cycle. The only difference is linked to those plants necessary to cope with the increase of the demand as the core hub in Cracow and the additional remanufacturing factory and warehouse opened in Sweden.

5.5 CONSIDERATION OF ONE LIFE CYCLE WITH UNCERTAINTY PROCESS ALLOCATION B FOR FLOW TYPE 2

After the first analyses conducted, it is now interesting to analyse how flow type 2 behaves with the introduction of uncertainty. The decision to test only scenarios characterised by flow type 2 has been taken because it is the one that shows the best performances both in terms of economic parameter and circularity ones. As already explained before, the introduction of uncertainty is done only for scenarios characterised by operation type B due to the fact that the testing and inspection of the battery modules (activities number 5 and 6) will be performed in the remanufacturing/refurbishing and repurposing factories instead inside the core hubs.

Results and configurations of scenarios with only one life cycle are shown below in table 19 and 20.

Table 20: Economic parameters of scenarios characterised by process allocation type B and one life cycle

scenario nr	FL	OP	RM_RF_OUT	RP_OUT	PBT	NPV
5	2	B	In-House rm/rf	In-House Rp	12	€ 14.396.575,15
11	2	B	OutSourced rm/rf	In-House Rp	11	€ 15.858.290,82
17	2	B	In-House rm/rf	OutSourced Rp	10	€ 21.075.043,24
23	2	B	OutSourced rm/rf	OutSourced Rp	9	€ 24.035.109,22

Table 21: Configurations of scenarios characterised by process allocation type B and one life cycle

scenario n	CH (n=5)	RM/RF (n=7)	RP (n=4)	WH (n=4)
5	4(1,2,3,5)	3(2,3,7)	2(1,3)	3(2,3,4)
11	4(1,2,3,5)	4(1,2,3,7)	2(1,3)	3(2,3,4)
17	4(1,2,3,5)	3(1,2,3)	4	4
23	4(1,2,3,5)	4(1,2,3,7)	3(1,3,4)	3(2,3,4)

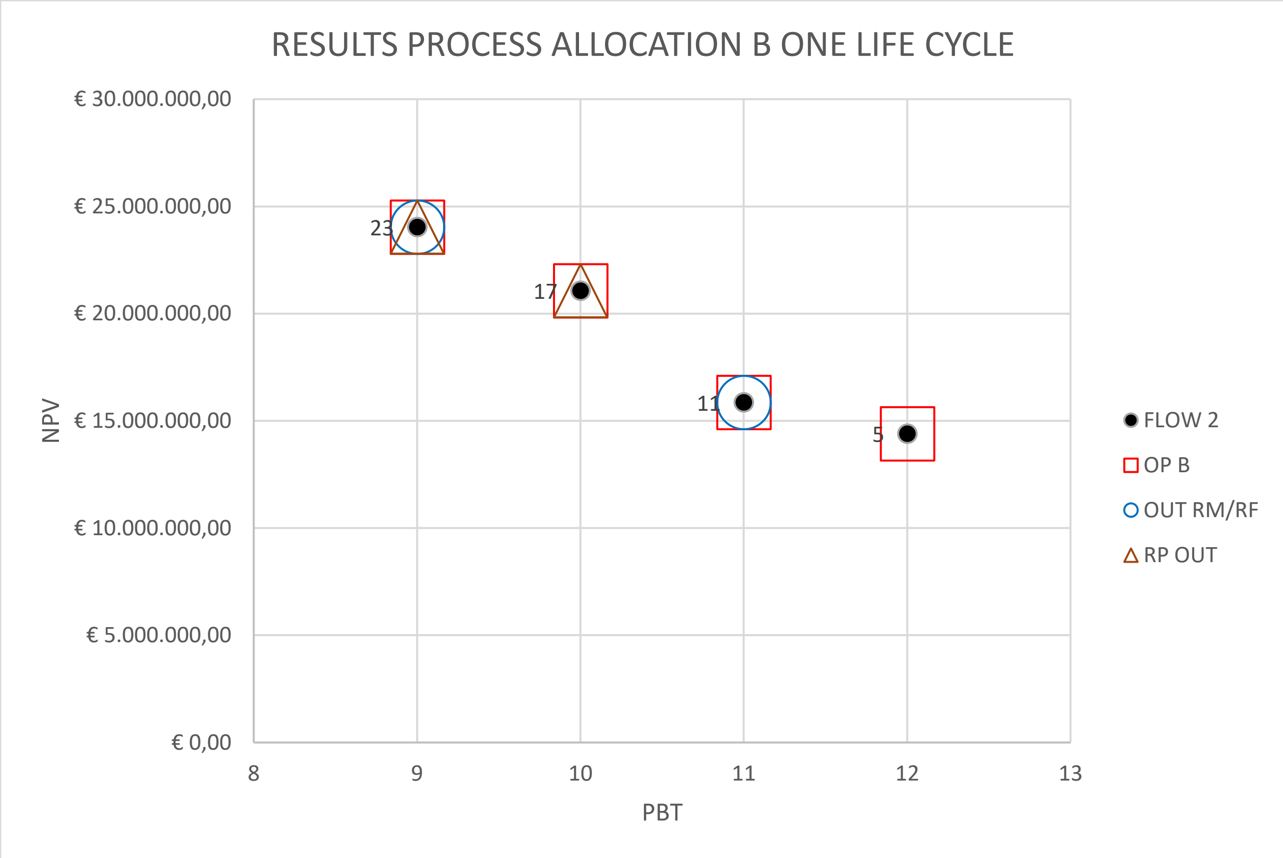


Figure 28: NPV vs PBT results process allocation B one life cycle

It is evident to notice that scenario 23 shows the best economic performances. In case of uncertainty, outsourcing the repurposing activities is always preferable. In fact, it is possible to not [illegible] table 24 how the scenario 17 and 23, characterized by the strategy mentioned previously, shows better PBT and NPV respect the other two scenarios (number 5 and 11).

Following the same path of the first analysis conducted, we focus our attention on the repurposing strategy. In this case seems that following an in-house strategy for RP is the worst choice: in fact, the two scenarios characterised by this configuration has a higher pay back time (12 for scenario 5 and 11 for scenario 11) and a lower NPV. Another consideration is that if the company follows this strategy (in-house repurposing) it is better to outsource the remanufacturing and refurbishing activities. In fact, scenario 11 shows better pay back time and a higher NPV respect scenario 5.

Analysing now more in details the two best scenarios, both characterised by outsourcing of repurposing activities, some consideration can be made. Exactly as for the scenario previously mentioned, the outsourcing strategy for remanufacturing and repurposing activities seems to be the best choice. We have a remarkable decrease of the payback time (from 10 to 9) and the difference between the NPV is not negligible (around 3 million euro).

Looking at the different layout of the scenarios some patterns can be found. Regarding warehouses the location 2 (Karlstad),3 (Skovde),4 (Eindhoven) is always open while location 1 (Ghent) is open only for scenario 17. In addition, Skovde is the warehouse open since year 1 of simulation while Eindhoven and Karlstad are opened only during year 11 for all the scenarios under consideration. The model decides to open the remanufacturing/refurbishing and repurposing activities in Skovde since year 1. It is possible to state that the model chooses to have a centralized strategy or the first 10 years of simulation instead of a non-centralized one.

Regarding core hub's location the model choose in all the case the same configuration. All the possible location are opened (Ghent, Flen, Skovde and Utrecht) except for location number 4 (Cracow). Also looking at the previous analysis it is possible to underline how Cracow is opened only in particular cases and always in the last year of simulation. This may lead to the conclusion that this location is the worst in terms of economic performances.

Moving on to the repurposing factories we can acknowledge that location 1 (Ghent) and 3 (Skovde) are always opened in case of in-house strategy (scenario 5 and 11). The model prefers to increase gradually the capacity of these factories instead of opens a new one. Factories 3 (Skovde) is open till year 1 while Ghent is open only at year 11. The increase of Skovde is gradual while Ghent shows an exponential increase (in two years he almost even the capacity of Skovde).

Remanufacturing and refurbishing factories shows an interesting path: location 3 (Skovde) is the first one open at year one while location 2 (Flen) is always open at year 11. The model chooses to perform both RM/RF and RP activities in Skovde and centralize for the first 10 years of simulation. Then in the final 2 years the decision taken is to open a new RM/RF facility nearest to the centre of Europe in order to minimize the transportation costs. Regarding these cost for the first 10 years, they can be considered negligible (the demand is low) respect to the last two years in which they increase exponentially following the demand path.

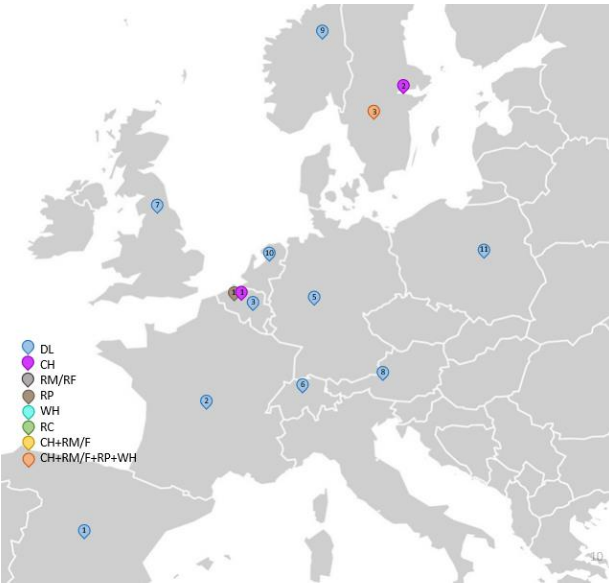


Figure 29: Scenario 23 year 1

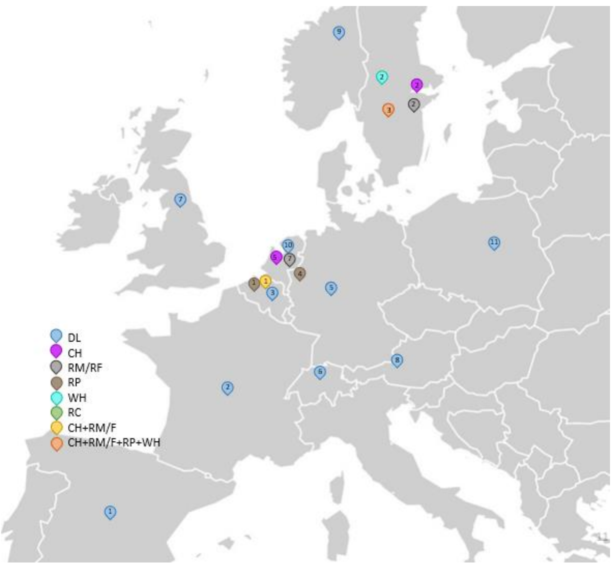


Figure 30: Scenario 23 year 12

Focusing on the map of the best scenario (number 23) it is possible to discover how the models prefers to centralize factories when it is possible. In fact, most of the factories are opened close to others and in specific countries. As it is possible to see factories are opened mainly in two strategic points: Sweden and the field between Belgium, Holland, and north-west Germany. To sum up, we can point out that also with the introduction of uncertainty the simulation model prefers to have a centralized setup.

Looking at the circularity indicators some considerations can be made. For all the scenarios the percentage of batteries reintroduced in the model is the same for all the years (83%=70% of refurbished batteries and 13% of repurposed). Uncertainty does not affect circularity parameters because of the introduction of the reverse flow called AMMAG. Thanks to this flow the amount of batteries used in the refurbishing factories remains always the same.

5.6 CONSIDERATION OF TWO LIFE CYCLE WITH UNCERTAINTY PROCESS ALLOCATION B FOR FLOW TYPE 2

In this section, the introduction of uncertainty with the second life cycle of the batteries will be discussed. Simulation tests are done only on scenarios characterised by flow type 2 and operation type B (as in the paragraph above). Results are shown in the following tables.

Table 22: Economic parameters of scenarios characterised by process allocation type B and two life cycle

scenario nr	FL	OP	RM_RF_OUT	RP_OUT	PBT	NPV
5	2	B	In-House rm/rf	In-House Rp	11	€ 17.044.601,77
11	2	B	OutSourced rm/rf	In-House Rp	11	€ 20.087.928,47
17	2	B	In-House rm/rf	OutSourced Rp	9	€ 26.046.515,67
23	2	B	OutSourced rm/rf	OutSourced Rp	8	€ 29.679.561,40

Looking at the results it is easy to notice that the best economic solution is the flow 23. It shows the lowest PBT (8 years) and the higher NPV (almost 30 million euro). As in the situation with only one life cycle, uncertainty seems to not have a big impact on the scenario regarding the economic parameter.

Table 23:Configurations of scenarios characterised by process allocation type B and two life cycle

scenario n	CH (n=5)	RM/RF (n=7)	RP (n=4)	WH (n=4)
5	5	3(1,2,3)	2(1,3)	3(1,2,3)
11	5	4(1,2,3,7)	2(1,3)	4
17	5	3(2,3,7)	4	3(2,3,4)
23	5	4(1,2,3,7)	3(1,3,4)	4

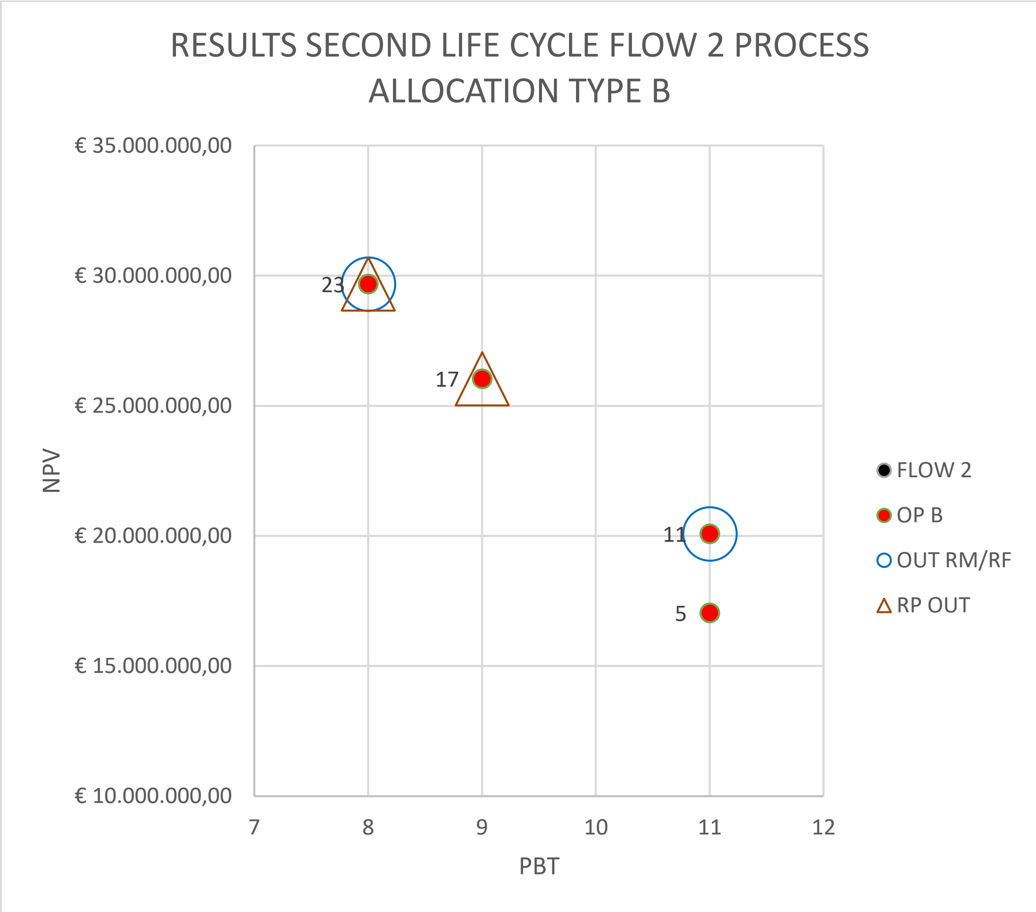


Figure 31: Results second life cycle flow 2 process allocation type B

Looking at the configuration that the model choose it is possible to understand why uncertainty has a lower impact of what it is expected. In fact, the model also in case of operation type B prefers always to centralize the remanufacturing/refurbishing and repurposing factories when there is the possibility. In this way the cost linked to the operator's mistake are limited since the transportation costs linked to the flow called AMMAG are almost negligible due to the low distances between factories.

In this case the best scenario is the number 23. It would be interesting to see if this scenario will remain the same also if we extend the year of simulation. Accordingly, to the economic logic, the increasing of the demand linked to the second life cycle will impact more year after year and it is possible to think that this fact will lead to a change in the best scenario. In fact, focusing on an in-house solution for remanufacturing and repurposing activities could be the best strategy to exploit scale economy and to increase the technological knowledge of the company.

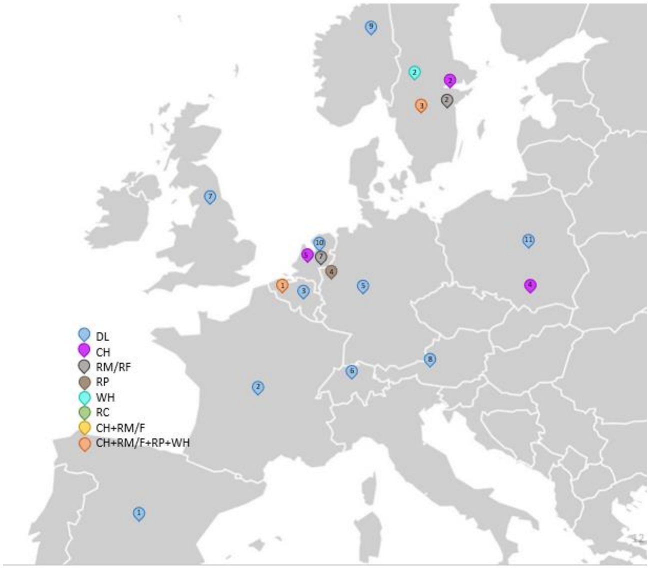


Figure 32: Scenario 23 year 12

Focusing on the best scenario configuration at year 12 (at year 1 it is the same as the one with only one life cycle) it is possible to point out another time how the model tries to centralize factories. The only exception is the same of the scenario 14 in the paragraph above ("Second life cycle analysis for OP. A). In fact, core hub located in Cracow is opened during the last years of simulation in order to cope with the demand.

Looking at the circularity indicators the same consideration done in paragraph above can be made. As already state the uncertainty does not affect the indicators of circularity.

5.7 COMPARISON BETWEEN PROCESS ALLOCATION TYPE B ONE LIFE CYCLE AND TWO LIFE CYCLE

As previously done, it is interesting to analyse how the introduction of uncertainty impacts on the economic and circularity indicator also for scenarios characterised by flow type 2 and operations B.

Table 24:Comparison between one life cycle and two life cycle scenarios with process allocation type B economic parameters:

	ONE LIFE CYCLE		TWO LIFE CYCLE	
scenario nr	**PBT**	**NPV**	**PBT**	**NPV**
5	12	€ 14.396.575,15	11	€ 17.044.601,77
11	11	€ 15.858.290,82	11	€ 20.087.928,47
17	10	€ 21.075.043,24	9	€ 26.046.515,67
23	9	€ 24.035.109,22	8	€ 29.679.561,40

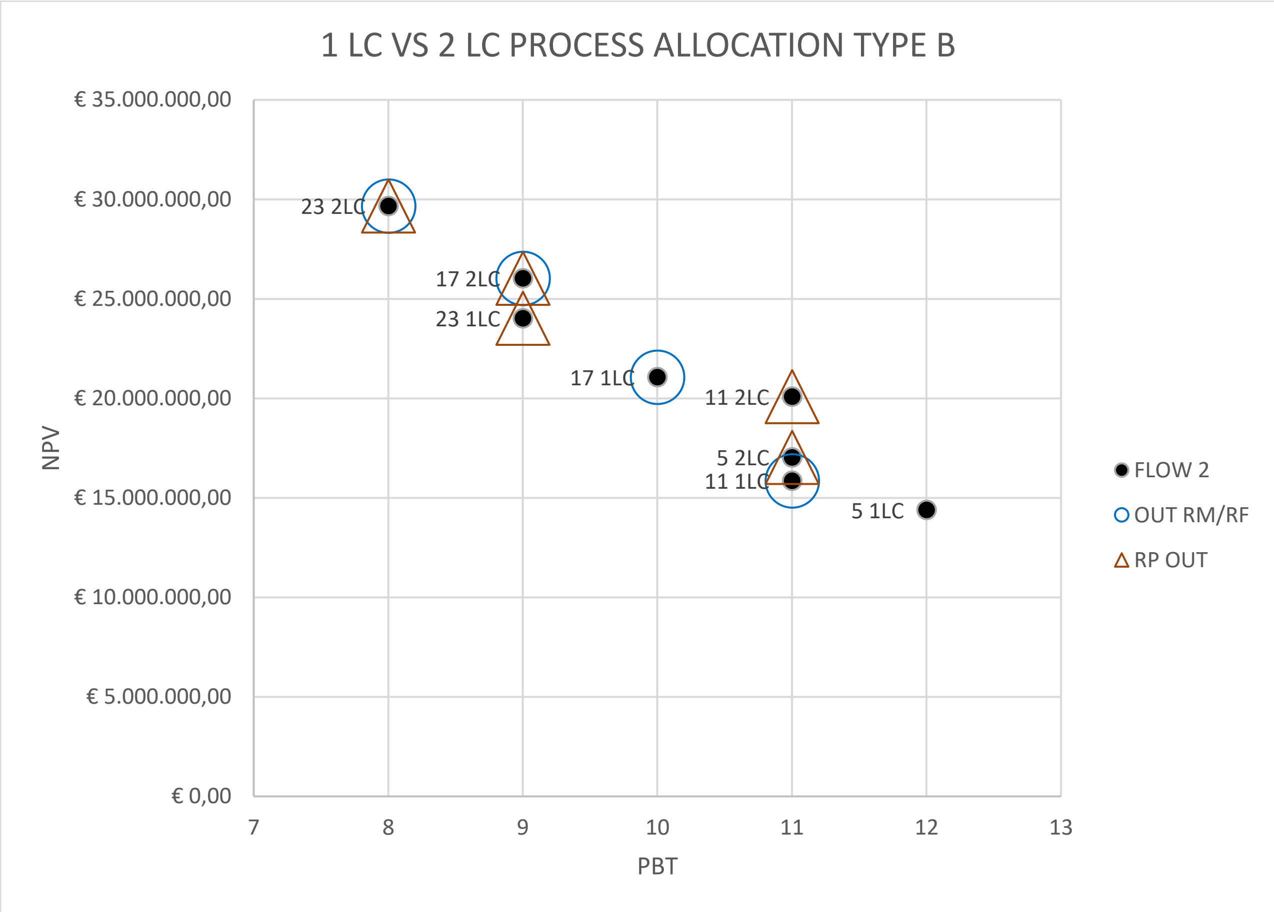


Figure 33: 1LC VS 2LC process allocation type B flow 2

Starting from an economic point of view it is possible to state that the introduction of the second life cycle creates benefits on both the indicators. The gaps between scenarios in terms of NPV remain basically the same because all of them increase similarly.

In both cases the best scenario remains the number 23 characterised by a strategy of totally outsourcing of the activities. Thanks to this fact it is possible to assume that in case of uncertainty the best strategy to pursue is a total outsourcing of the critical activities to increase flexibility managing better eventually mistakes.

Table 25: Comparison between one life cycle and two life cycle scenarios with process allocation type B configurations

	ONE LIFE CYCLE				TWO LIFE CYCLE			
scenario nr	**CH (n=5)**	**RM/RF (n=**	**RP (n=4)**	**WH (n=4)**	**CH (n=5)**	**RM/RF (n=**	**RP (n=4)**	**WH (n=4)**
5	4(1,2,3,5)	3(2,3,7)	2(1,3)	3(2,3,4)	5	3(1,2,3)	2(1,3)	3(1,2,3)
11	4(1,2,3,5)	4(1,2,3,7)	2(1,3)	3(2,3,4)	5	4(1,2,3,7)	2(1,3)	4
17	4(1,2,3,5)	3(1,2,3)	4	4	5	3(2,3,7)	4	3(2,3,4)
23	4(1,2,3,5)	4(1,2,3,7)	3(1,3,4)	3(2,3,4)	5	4(1,2,3,7)	3(1,3,4)	4

Looking now at the configuration of the different scenarios, the model works exactly in the same way in both cases. Core hubs number 4 is open in all the scenario of the second life cycle: this fact is explained by the increasing demand faced by the model in the simulation. Moreover, looking both at RM/RF and RP factories there is not a clear difference between the two models: as already explained location number 5 and 6 for RM and RF factories is never opened and in this case of operation B also location number 4 (Limoges).

Focusing only on the best scenario (23) the main differences are the opening of the fourth warehouse (located in Eindhoven) and the opening of the fifth core hubs (located in Utrecht). Both of the openings are linked to the increase of demand faced by the two-life cycle model.

Figure 34: Scenario 23 year 12 one life cycle

Figure 35: Scenario 23 year 12 two life cycle

Looking at the two best scenarios some differences can be highlighted. The model logic remains always the same (centralization of the factories); however, the necessity to cope with the increase of the demand in case of the second life cycle force the model to open the last available core hub in Cracow during the last year. In addition, the increase of the demand pushes the model to open a new remanufacturing and refurbishing plant in Ghent. As it is possible to see, the location opened is the closest one to the other factories (core hub and repurposing).

Taking into consideration the circularity indicators the situation is the same of the analyses done for operation type A. The introduction of the second life cycle increases the profitability of the model with also an important enviromental impact. In fact, the introduction of the second cycle for batteries lead to an increase utilization of the material and to a longer usage of the batteries. The results are the same of the table 23.

5.8 COMPARISON BETWEEN ONE LIFE CYCLE FLOW 2 PROCESS ALLOCATION A VS PROCESS ALLOCATION B

Stated that flow number 2 is the best one (both by an economical and a circularity point of view) it is interesting to analyse how the different operation types influence the result.

Table 26: One life cycle scenarios OP. A vs OP. B economic parameters

scenario n	FL	OP	RM_RF_OUT	RP_OUT	PBT	NPV
2	2	A	In-House rm/rf	In-House Rp	11	€ 20.417.105,73
5	2	B	In-House rm/rf	In-House Rp	12	€ 14.396.575,15
8	2	A	OutSourced rm/rf	In-House Rp	11	€ 21.246.965,58
11	2	B	OutSourced rm/rf	In-House Rp	11	€ 15.858.290,82
14	2	A	In-House rm/rf	OutSourced Rp	10	€ 23.491.387,52
17	2	B	In-House rm/rf	OutSourced Rp	10	€ 21.075.043,24
20	2	A	OutSourced rm/rf	OutSourced Rp	10	€ 23.419.535,16
23	2	B	OutSourced rm/rf	OutSourced Rp	9	€ 24.035.109,22

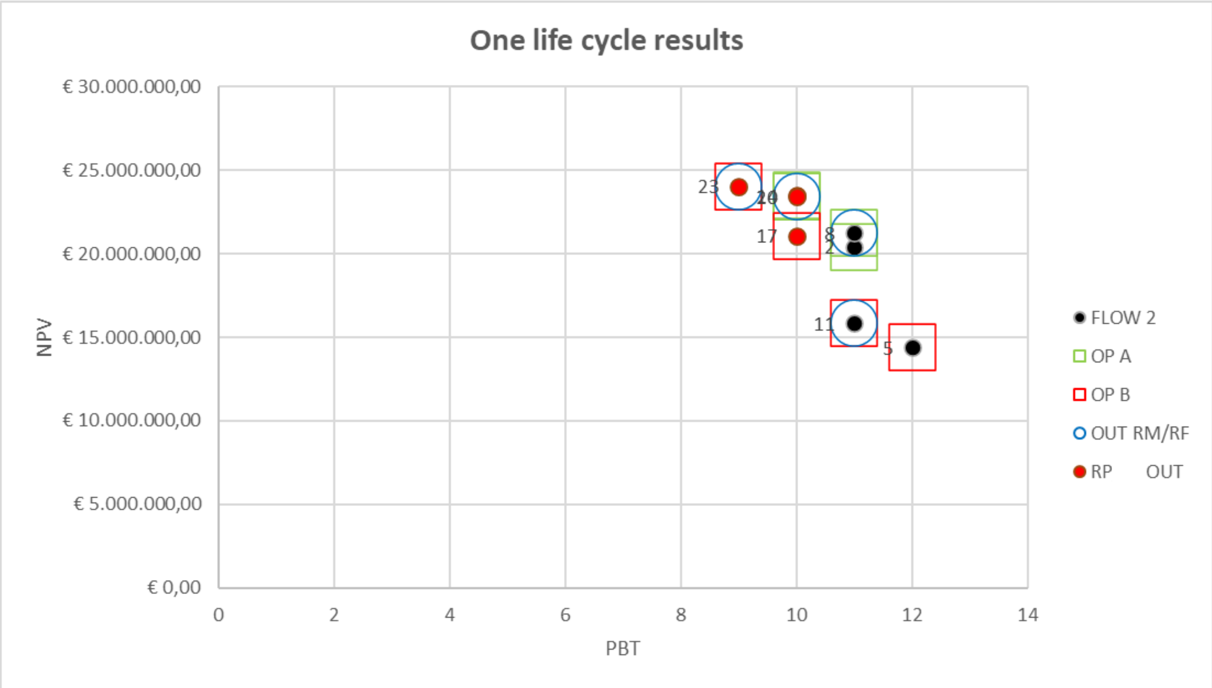


Figure 36: NPV vs PBT one life cycle scenarios process allocation A vs process allocation B

Scenario number 23 shows the best PBT (9 years) and NPV. Analysing deeper the results, scenario with the best PBT and NPV are characterised by the outsourcing of the repurposing facilities. It is really interesting the fact that operation A is better respect operation B in all the scenarios that have the same strategy, in terms of outsourcing or in-house factories (scenario 2 vs scenario 5, scenario 8 vs scenario 11 and scenario 14 vs scenario 17), except for the last two scenarios (20 vs 23).

It is difficult to understand in case of only one life cycle which strategy is the best one to pursue. On one hand it is possible to maximize the economic parameters using operation type B but only in case of totally outsourcing; on the other hand, operation type A shows better economic results using different strategies.

Table 27: One life cycle scenarios OP. A vs OP. B configurations

scenario n	CH (n=5)	RM/RF (n=7)	RP (n=4)	WH (n=4)
2	5	3(1,2,3)	1(3)	3(1,2,3)
5	4(1,2,3,5)	3(2,3,7)	2(1,3)	3(2,3,4)
8	4(1,2,3,5)	4(1,2,3,7)	1(3)	3(2,3,4)
11	4(1,2,3,5)	4(1,2,3,7)	2(1,3)	3(2,3,4)
14	4(1,2,3,5)	3(1,3,7)	3(1,2,3)	3(2,3,4)
17	4(1,2,3,5)	3(1,2,3)	4	4
20	5	4(1,2,3,7)	4	4
23	4(1,2,3,5)	4(1,2,3,7)	3(1,3,4)	3(2,3,4)

Focusing on the configuration analysis some consideration can be made. Looking at the core hubs we are in the same situation as before in which core hub number 4 is opened only in some cases (scenario 2 and 20) while the other 4 are always opened.

Warehouses number 2 and 3 are always opened during the simulation while scenario 1 is opened only in 3 out of 8 scenarios. Analysing the RM/RF plants it is possible to see the same pattern already faced in the previous analysis: the model decides when it is possible to have a centralized configuration and due to this it opens the closer factories (number 1, 2, 3 and 7). It is interesting to see the changes that the model does in case of in-house or outsourcing logic of repurposing: in fact, in case of an in-house strategy the model prefers to minimize the number of factories opened to exploit the scale economy. On the contrary, in case of an outsourcing policy the model prefers to use a decentralized approach and to use as many as possible repurposing factories.

Looking also at the table 25 results, it is possible to see how uncertainty plays an important role in minimizing the distances between operation A and operation B. If we do not consider uncertainty in operation B this is preferable in most of the scenario respect the operation type A; on the other hand, the introduction of this factor tends to decrease the economic distances and operation type A results preferable in most of the situation (but not in the most profitable one).

Figure 37: Scenario 23 year 12 two life cycle

Figure 38: Scenario 14 year 12 one life cycle

Focusing now on the differences between the two best scenario the model decides in both cases to centralize factories in the same two areas (Sweden and the field between Holland, Belgium and the north west of the Germany). The main differences are linked to the fact that in scenario 23 remanufacturing/refurbishing and repurposing factories are outsourced. In this case simulation shows how it is better to have a greater number of outsourced factories.

Looking at the circularity parameters due to the fact that only flow type 2 is taken under consideration they are the same for all the scenarios.

5.9 COMPARISON BETWEEN 2 LC FLOW 2 OP. A VS OP. B

The same type of analysis done in the previous paragraph will be performed in this section for the scenarios characterised by operation type A and B and flow type 2 with the introduction of the second life cycle.

Table 28: Two life cycle scenarios OP. A vs OP. B economic parameters

scenario nr	FL	OP	RM_RF_OUT	RP_OUT	PBT	NPV
2	2	A	In-House rm/rf	In-House Rp	11	€ 25.215.622,78
5	2	B	In-House rm/rf	In-House Rp	11	€ 17.044.601,77
8	2	A	OutSourced rm/rf	In-House Rp	10	€ 25.529.956,08
11	2	B	OutSourced rm/rf	In-House Rp	11	€ 20.087.928,47
14	2	A	In-House rm/rf	OutSourced Rp	11	€ 27.722.595,86
17	2	B	In-House rm/rf	OutSourced Rp	9	€ 26.046.515,67
20	2	A	OutSourced rm/rf	OutSourced Rp	10	€ 26.965.148,14
23	2	B	OutSourced rm/rf	OutSourced Rp	8	€ 29.679.561,40

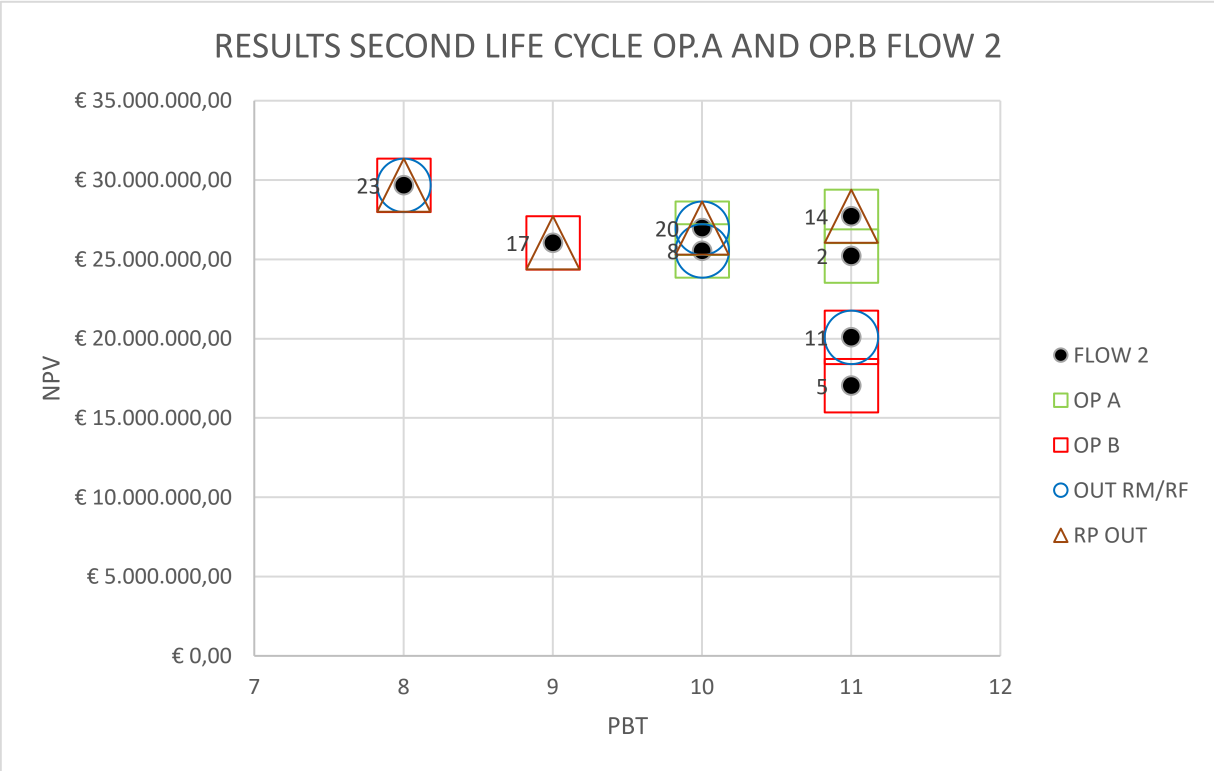


Figure 39: NPV vs PBT OP.A vs OP. B 2 life cycle

Looking at the economic performances of the different scenarios it is possible to notice how scenario number 23 shows the best performances overall. This scenario is the one characterised by the total outsourcing strategy and in the periods under consideration is the most profitable. Focusing on the differences between operation, type A has an average PBT of 10,5 years while operation type B has 10,25 years.

It is interesting the fact that operation B is better respect operation A only if the strategy regarding the repurposing factories is to outsource. In general, it seems that in case of second life cycle of batteries the best strategy to pursue is to use third parties for repurposing activities. In fact, the best 4 scenarios in terms of NPV are the ones characterised by this approach.

As regards the remanufacturing and refurbishing strategy it is difficult to find a pattern: operation type B shoes the best results with an outsourcing strategy while for operation type A it is impossible to do this type of consideration.

Table 29: Two life cycle scenarios OP. A vs OP. B configurations

scenario n	CH (n=5)	RM/RF (n=7)	RP (n=4)	WH (n=4)
2	5	3(1,2,3)	2(3,4)	3(1,2,3)
5	5	3(1,2,3)	2(1,3)	3(1,2,3)
8	5	4(1,2,3,7)	1(3)	4
11	5	4(1,2,3,7)	2(1,3)	4
14	5	3(1,2,3)	4	3(1,2,3)
17	5	3(2,3,7)	4	3(2,3,4)
20	5	5(1,2,3,4,7)	4	4
23	5	4(1,2,3,7)	3(1,3,4)	4

Configurations of the scenarios are similar to the ones of the paragraph below: all the core hubs are opened (and as previously explain the location number 4 is the last one to be opened), location number 5 and 6 for remanufacturing and refurbishing capacity are never used and for the repurposing factories the model adopts a centralized strategy if activities are performed in-house while it adopts a decentralized strategy if activities are outsourced.

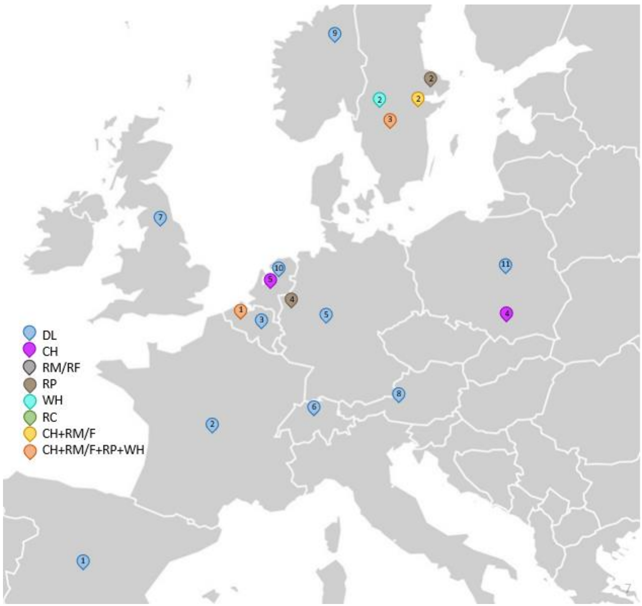


Figure 41: Scenario 14 year 12 two life cycle

Figure 40: Scenario 23 year 12 two life cycle

Looking now at the two best scenarios (scenario 14 and 23) it is interesting to see how the model follows basically the same logic. In both cases (as in the previous paragraph) centralization is the main strategy pursued. Core hub number 4 is opened for scenario 14 and scenario 23 to face the increase of the demand. The consideration can be the same of the paragraph above, in case of an outsourcing strategy the model prefers to open more remanufacturing and refurbishing factories as it is possible to see from the remanufacturing factory opened in Mulheim der Ruhr.

6. DISCUSSION

The focus of this study was to find a suitable and profitable way to examine the transition process of reverse supply chain development though the comparison of economic and circularity indicators.

The shift of the transportation from ICEV to EVs is one of the main challenges that automotive manufacturer has ever faced: firstly, because it is important to find profitable solution from an economic point of view and secondly because this solution must be with low enviromental impact.

Introduction of the second life cycle in the simulation model has been the focus of this thesis. The aim of this research was to find if this change creates benefits in terms of economic and circularity indicators or was dangerous for the model.

Looking at the results mentioned in chapters "Comparison between process allocation type B one life cycle and two life cycle" and "comparison between one life cycle and 2 life cycles for process allocation A" it can be stated that the introduction of the second life cycle of batteries have a positive impact on all the parameters for most of the scenarios. From an economic perspective, only scenarios characterised by flow type 3 suffer the second life cycle introduction, while scenarios characterised by flows 1 and 3 show economic benefits linked to this change. The automotive company should enlarge lifetime of batteries introducing the second life cycle avoiding flow type 3. In this way it will be possible to reach better NPV and PBT.

Taking a circularity point of view, second life cycle shows important benefits in terms of kWh reintroduced in the market for all the flows. Looking at table 18 the introduction of the second life cycle permits to increase the number of kWh from 15000 (for flow type 1) to more than 25000 (for flow type 2). It is always preferable for car manufacturer to introduce second life cycle taking a circularity viewpoint.

Scenarios characterised by flow type 2 shows every time the best economic results both in case of one life cycle and two life cycle. Looking at the circularity indicators it is interesting to notice how also in this case flow type 2 is the one that benefits most of the second life cycle of batteries and it is always preferable respect the other two.

Looking at the best strategy to develop the RSC model it is possible to make two different considerations. Scenario 23 shows overall the best results with the shorter pay-back time (only 8 years) and almost 30 million Euro of NPV at year 12. Scenario's characteristics are:

- Total outsourcing strategy, both remanufacturing/refurbishing and repurposing are outsourced.
- Process allocation type B.
- Flow type 2.

From an economic point of view this is the best strategy to pursue to introduce the reverse supply chain. Some criticalities may emerge by the fact that RM/RF and RP factories are outsourced and so collaboration and cooperation with actors involved in these factories are necessary to gain all the benefits of reverse supply chain. In addition, as it is possible to see from the configuration of this scenario the best way to introduce this operational setup is linked to a centralization strategy with facilities close one to each other. According to this, it will be easier for companies to have a better management and control of the flow of batteries and minimize transportation costs.

The second consideration is linked to the process allocation type of scenarios. The results shown in paragraph "comparison between two life cycles flow 2 process allocation A vs process allocation B" an interesting fact about the process allocation type A: if the strategy of totally outsourcing of the factories (both RM/RF and RP) is not followed, process allocation type A is always preferable instead of type B. In particular, if RM/RF factories are owned by the company, process allocation type A has more than 5 million Euro of difference in terms of NPV respect type B. This fact leads to the conclusion that uncertainty reduces the positive economic effects that second life cycle could have if company pursue an in-house strategy.

RSC development could be seen as a profitable and sustainable way to manage the transition process linked to electrification of transportation. Looking at the results of the previous paragraph it is possible to state that this type of configuration should have a long-term orientation. In fact, for the first years RSC requires important investments from the company; starting from year 10 (that is the year in which the demand growth consistently) it is possible to see the economic advantages linked to this operational setup for most of the scenarios.

It is better for the company to use process allocation type A if some criticalities in the outsourcing of factories appear, particularly for RP factories. The best strategy to follow looking at the NPV parameter is to use the same configuration of scenario 14: flow type 2, outsourcing of RP and RM/RF in-house. In this case the NPV is close to 28 million Euro and the PBT is of 11 years. Taking PBT as the main indicator, scenario type 8 shows the best performances: 25,5 million Euro of NPV and 10 years of pay-back-time. This scenario is characterised by the only outsourcing of RP factories and by flow type 2.

To enlarge the analysis, as already explained in the previous paragraphs, centralization of factories seems to be the most profitable solutions in all the scenarios. It is important for the company to enlarge existing factories instead of building new ones and select correctly the most strategical location to gain advantages on competitors.

To sum up all the considerations done, the best strategy to follow for the company to develop a RSC model is to introduce the second life cycle of batteries and use a set-up equal to the one of scenario 23. In this way, it will be possible to maximize all the indicators taken into consideration in the analyses. It is also important to underline the long-term orientation of this strategy that requires important investments during the initial periods.

7. CONCLUSIONS

The world is facing one of the biggest challenges that has ever faced. Global warming effects are day by day more dangerous and a drastic reorientation of companies and people' culture is needed to slow it down.

After the agreement of Paris 2015, government of all over the world are asking to all companies to readapt their business model to greener and more sustainable solution. The main objective is to reduce the CO2 emission down almost to zero no later than 2050. To do that, companies need to adapt quickly to this change to be competitive in future markets.

The automotive sector is undergoing a deep change from ICEV car to EVs. Car manufacturer are worried about this transition process and a lot of studies has been undertaken to find the right way to manage this shift.

The aim of this thesis was to examine the circularity of the transition process of the reverse supply chain development for heavy EVs market to find the best solutions in terms of economic and circularity parameters. Results explained in the previous paragraph shown that this process brings benefits for car manufacturer both in terms of economic and enviromental impact.

Focusing on the development of RSC for managing this transition process, centralized configurations show overall best performances, and flow type 2 is always preferable respect the others. Depending on the configuration of outsourcing of RM/RF and RP factories company should decide to use process allocation type A or B: in case of a total outsourcing strategy process allocation type B is preferable (as shown from the results of scenario 23), otherwise is better to use process A.

Looking at the second life cycle introduction (useful to avoid the disposal of batteries issue and to enlarge the life cycle of the product) it is possible to state that car manufacturer will benefit from that. Starting from the economic parameter it is possible to increase the NPV thanks to the reintroduction in the market of used batteries and in some cases also reducing PBT (as for example in the case of scenario 23). Focusing on the circularity indicators, the introduction of the second life cycle increases consistently the parameters for all the flows under consideration. It can be stated that second life cycle of batteries help companies in creating more sustainable business from an enviromental point of view. To conclude, the last analyses performed in the thesis showed that uncertainty introduced in the sorting of batteries does not heavily affects economic performances, mainly thanks to the centralization of factories that the model performs.

All these studies have been conducted using assumptions to create the model. This leads to some limitations of the work and results might be different if assumptions change.

First, customer demand has been forecasted using actual data. There is no absolute certainty about the fact that it will follow this type of distribution in future and due to this fact, simulation results could be different from real ones.

In addition, simulation is performed over 12 time-step (one corresponds to one year) and processing times are considered negligible. Taking into consideration a longer period of simulation could lead to different results in terms of best scenario and best configuration. Moreover, cost parameters are considered fixed during the years under consideration, and all the factory and transportation costs are shaped as linear function. Obviously, if this fact does not represent the reality results will not be the same.

Looking now at the facilities, one limitation is related to the constraints linked to them: there are constraints about capacities and expansion during the years that could differ from the reality. If these constraints will be changed results of the model will probably differ from the ones shown.

To sum up, all the assumptions done in the sections "Mathematical Model" are limitations to this study, if the constraints are different obviously results can differ.

Another issue of this study relates to price volatility of lithium-ion batteries. In the as-is situation, new batteries are sold for more than 100€/kWh, however this price could decrease in future years due to an introduction of new technologies and the increase of the market demand. This fact could lead to an important consequence for the recovery options of batteries. At the moment, all of them seems to be profitable and sustainable in the long term; however, if the new battery price decrease under a set threshold these types of solution could become not cost effective. This could lead manufacturer to avoid the recovery of batteries creating enviromental issues. In this sense, governments laws will play a focal role in trying to avoid this problem.

After having talked about the limitations of the study, it is interesting to discuss what could be the next steps. An analysis on the market volume could be useful to see how the model reacts to this variation. In this way, it is possible to perform a sensitivity analysis of best scenarios and see how the customer demand affect the parameters considered during the study.

Moreover, it could be interesting to introduce a new revenue stream linked to the recycling factory. In the as-is situation, recycling activities are considered only as a cost during the simulation: however, it is possible for the company to gain profits from the resell of raw materials or decrease costs to produce new battery modules thanks to the reutilisation of themselves.

Another future analysis could be performed changing the locations of the facilities. In this way, it could be possible to see if locations considered in the first analysis are the most profitable one or not.

To sum up all the considerations done, the ease of changing the model permits a lot of different studies that could be useful to find the best solution to introduce the RSC for car manufacturers. It is really important that this shift towards greener business model for companies happens quickly. Otherwise, it may be too late to slow down climate changes and long-term consequences can have a devastating effect.

8. BIBLIOGRAPHY

Earl, J., & Fell, M. J. (2019). Electric vehicle manufacturers' perceptions of the market potential for demand-side flexibility using electric vehicles in the United Kingdom. *Energy Policy*, *129*(July 2018), 646–652. https://doi.org/10.1016/j.enpol.2019.02.040

Gao, X., & Cao, C. (2020). A novel multi-objective scenario-based optimization model for sustainable reverse logistics supply chain network redesign considering facility reconstruction. *Journal of Cleaner Production*, *270*, 122405. https://doi.org/10.1016/j.jclepro.2020.122405

Logan, K. G., Nelson, J. D., & Hastings, A. (2020). Electric and hydrogen buses: Shifting from conventionally fuelled cars in the UK. *Transportation Research Part D: Transport and Environment*, *85*(May), 102350. https://doi.org/10.1016/j.trd.2020.102350

Nagasawa, K., Morikawa, K., Takahashi, K., & Hirotani, D. (2019). Sustainability and corporate social responsibility in closed loop supply chain. *Procedia Manufacturing*, *39*, 1658–1665. https://doi.org/10.1016/j.promfg.2020.01.275

Nallusamy, N., Sakthivel, P., Chausalkar, A., & Ramadhas, A. S. (2016). Electric vehicles. *Alternative Fuels for Transportation*, 295–320.

Regulation (EU) 2019/1242. (2019). Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 Setting CO2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament. *Official Journal of the European Union*, *L 198*(April), 202–240. https://eur-lex.europa.eu/eli/reg/2019/1242/oj

Van Engeland, J., Beliën, J., De Boeck, L., & De Jaeger, S. (2020). Literature review: Strategic network optimization models in waste reverse supply chains. *Omega (United Kingdom)*, *91*, 102012. https://doi.org/10.1016/j.omega.2018.12.001

Vu, F., Rahic, M., & Chirumalla, K. (2020). Exploring Second Life Applications for Electric Vehicle Batteries. *Advances in Transdisciplinary Engineering*, *13*, 273–284. https://doi.org/10.3233/ATDE200165

World Economic Forum; Global Battery Alliance. (2019a). *A Vision for a Sustainable Battery Value Chain in 2030*. *September*, 10–11. www.weforum.org

World Economic Forum; Global Battery Alliance. (2019b). *A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation including photocopying and recording, or by any information storage and retrieval system. 3 A Vision for a S*. *September*. www.weforum.org

Zhang, H., Liu, W., Dong, Y., Zhang, H., & Chen, H. (2014). A method for pre-determining the optimal remanufacturing point of lithium ion batteries. *Procedia CIRP*, *15*, 218–222. https://doi.org/10.1016/j.procir.2014.06.064

APPENDICES

FIRST LIFE CYCLE DEMAND

Demand of the first life cycle.

Table 10:One life cycle demand of batteries in kWh

	YEAR											
DEALERS	1	2	3	4	5	6	7	8	9	10	11	12
1	8	10	13	27	472	603	761	957	1222	1573	2036	2641
2	2	2	3	4	119	155	202	262	341	443	576	749
3	62	92	151	949	3604	3988	3832	2863	2370	1944	1958	2225
4	5	704	1243	2657	4352	4306	9225	11760	15093	19427	63608	129798
5	6	7	11	52	316	376	420	440	503	598	748	956
6	6	8	13	75	312	351	350	289	270	262	296	360
7	12	16	22	75	726	901	1083	1273	1569	1968	2524	3259
8	1	1	1	1	27	35	46	60	78	101	132	171
9	0	355	627	1320	2079	2038	4539	5851	7550	9754	32207	65842
10	0	647	1144	2408	3792	3717	8277	10670	13770	17788	58736	120076
11	5	410	724	1563	2662	2661	5519	6984	8930	11467	37059	75396
TOTAL [KWh]	107	2252	3952	9131	18461	19131	34254	41409	51696	65325	199880	401473

SECOND LIFE CYCLE DEMAND

	YEAR											
DEALERS	1	2	3	4	5	6	7	8	9	10	11	12
1	8	10	13	29	475	607	769	1104	1410	1810	2342	3338
2	2	2	3	5	120	156	203	299	389	506	657	935
3	62	92	151	968	3632	4033	4117	3988	3631	3199	3481	5459
4	5	704	1243	2659	4563	4679	10022	13069	16878	23065	68996	137372
5	6	7	11	54	318	379	436	539	621	732	916	1328
6	6	8	13	77	314	355	373	387	381	376	435	659
7	12	16	22	79	731	908	1106	1499	1851	2308	2958	4238
8	1	1	1	1	27	35	46	69	89	116	151	213
9	0	355	627	1320	2186	2226	4935	6475	8410	11555	34886	69562
10	0	647	1144	2408	3986	4060	8999	11808	15338	21072	63623	126861
11	5	410	724	1565	2785	2878	5988	7786	10015	13630	40248	79938
TOTAL [KWh]	107	2252	3952	9163,1	19136,6	20316,6	36993,3	47022,2	59011,7	78367,6	218694,4	429904,5

Figure 20 New demand (rb) for Flow type 1

	YEAR											
DEALERS	1	2	3	4	5	6	7	8	9	10	11	12
1	8	10	13	33	479	612	780	1290	1647	2110	2714	3638
2	2	2	3	5	120	157	205	346	450	585	761	1023
3	62	92	151	992	3668	4094	4515	5404	5189	4672	4247	4965
4	5	704	1243	2661	4845	5176	11086	14808	18318	26257	72637	141669
5	6	7	11	56	321	384	458	663	768	895	1072	1403
6	6	8	13	79	318	360	404	509	518	511	521	643
7	12	16	22	83	737	916	1139	1785	2205	2733	3438	4575
8	1	1	1	2	28	36	47	79	103	134	174	234
9	0	355	627	1320	2328	2477	5463	7306	9083	13119	36699	71751
10	0	647	1144	2408	4245	4518	9963	13324	16566	23925	66927	130853
11	5	410	724	1567	2949	3168	6615	8849	10916	15548	42417	82446
TOTAL [KWh]	107	2252	3952	9205,9	20037,4	21897,4	40675,4	54363,8	65763,3	90488,4	231605,6	443198,5

Figure 21 New demand (rb) for Flow type 2 and 3

MATLAB CODE

The highlighted parts are raws of the code modified to perform the analyses of the thesis.

```
clc
clear
close all
%% %%SCENARIOS
load scen_param1
load macro
for macro_scenario=23
for scenario=1:1

%% Parameters to be changed to define the scenarios


FL=macro(macro_scenario,1);%parameter set by the user to choose the
corresponding flow scenario (1,2,3,4)
OP=macro(macro_scenario,2); %it is 1 if we refer for operations type A, 2 for
type B
RM_RF_OUT=macro(macro_scenario,3); %it is 1 if RF/RM are outsourced, 0 otherwise
RP_OUT=macro(macro_scenario,4);%it is 1 if RP is outsourced, 0 otherwise

%% Interest rate for NPV

int_rate=scen_param1(scenario,1);

%% Problem definition

prob=optimproblem('ObjectiveSense','max');

%% Indexes

I=11; %V10_NEW:DEALERS in order
(TOLEDO,AHUN,WALHAIN,OREBRO,HAINA,MENZBERG,SKIPTON,WAGRAIN,FOLLDAL,DRONTEN,Gmina
Lyszkowice):these locations are in found considering the geographical centroid
of each country (countries considered are the EU countries in the document B14
and B15)
J=5;  %V10_NEW:CORE HUBS  in order(GENT,FLEN,SKOVDE,CRACOW,UTRECHT): first three
CH are real existing locations, the other two are added as possible locations.
Cracow and Utrecht added because of their proximity to the other most important
Dealers (in terms of returned batteries received) and also in order to cover
quite all the EU area.
K=7;  %V10_NEW:REMANUFACTURING/REFURBISHING PLANTS in
order(GENT,FLEN,SKOVDE,LIMOGES,VARSAW,HOL,EDE):first 4 ones are the suggested
ones. The 5th and 6th are added as possible location in order to get closer to
CH locations. The 7th is the location in the Netherlands for outsourcing, that
is given. In case only in-housing is considered, then the Ede plant is added as
a possible location to build a new rm/rf plant.
P=4;  %V10_NEW:WAREHOUSES in order(GENT,KARLSTAD,SKOVDE,EINDHOVEN): the first
one is the suggested location. The others are added as possibility in order to
get closer to the most important Dealers(in terms of quantity or returned
batteries) and trying to get closer also to most of the remanufacturing plants
L=3;  %V4_NEW:RECYCLING PLANTS in order (ANTWERP,VIVIEZ,HALMSTAD): the locations
are where the principal recycling plants of the following companies are located:
Accurec,Stena Recycling and Umicore.
M=4;  %V10_ repurposing plants in order(GENT,VASTERAS,SKOVDE,MULHEIM AN DER
RUHR)
T=12; %V4_NEW:these are the number of years considered in the optimization



%% Battery related Data
```

```
BM_size=1.5; %KWh/mod
BM_in_BP=25; % nr. of module in a battery pack
BP_size=BM_size*BM_in_BP; %KWh/BP
mean_wh=12.282; % kg/Kwh
mean_batt_wh=492.19; % kg/ battery
BP_trip=2; % equivalent transported quantity expressed as nr. of BP
BP_transp=BP_trip*BP_size; %Kwh/trip



%% EMISSION RELATED DATA
truck_wh=0; %empty weight per truck
co2=66; % CO2/km*ton
ton_per_truck=truck_wh+mean_batt_wh*BP_trip/1000; %ton per truck
%% Capacity data
CH_initial=2500; % initial capacity in Kwh of the existing CH (J=1,2; T=1)
Max_exp_CH_initial=50000; % max cumulative expansion in Kwh  allowed at initial
CH
Max_exp=100000;% max cumulative expansion in Kwh  allowed at initial CH
Min_cap=2500; %minimum capacity in Kwh for a new plant
Max_cap=280000; %max capacity




RM_max_cap_out=250000;% max capacity in KWh of a RM-RF third party plant
RP_max_cap_out=250000;

BIG=1000000; %big number, it deserves to express some of the constraints



CH_min=3; % min number of extablished CH at each time t
RM_min=1; % min number of extablished RM at each time t
RP_min=1; % min number of extablished RP at each time t
WH_min=1; % min number of extablished WH at each time t

%% Battery input at the Dealer in Kwh

% rb(i,t) is the quantity in Kwh that is arriving to Dealer i in time t
rb=[ 8  10  13  33  479 612 780 1290    1647    2110    2714    3638;
2   2   3   5   120 157 205 346 450 585 761 1023;
62  92  151 992 3668    4094    4515    5404    5189    4672    4247    4965;
5   704 1243    2661    4845    5176    11086   14808   18318   26257   72637
141669;
6   7   11  56  321 384 458 663 768 895 1072    1403;
6   8   13  79  318 360 404 509 518 511 521 643;
12  16  22  83  737 916 1139    1785    2205    2733    3438    4575;
1   1   1   2   28  36  47  79  103 134 174 234;
0   355 627 1320    2328    2477    5463    7306    9083    13119   36699
71751;
0   647 1144    2408    4245    4518    9963    13324   16566   23925   66927
130853;
5   410 724 1567    2949    3168    6615    8849    10916   15548   42417
82446]; % in kwh
%rb=rb(:,3:end);
%% REVENUES FROM SOLD BATTERIES
```

```
BP_price_new=scen_param1(scenario,4); % Eur/Kwh ,price of a new battery pack

HF_Rem=1;% theoretical health factor associated to remanufactured battery pack
RM_rev=BP_price_new*HF_Rem; %Eur/Kwh, price of a remanufactured battery pack

HF_Ref=0.8;% theoretical health factor associated to refurbished battery pack
RF_rev=BP_price_new*HF_Ref; %Eur/Kwh, price of a refurbished battery pack

HF_Rep=0.5;% theoretical health factor associated to repurposed battery pack
RP_rev=BP_price_new*HF_Rep; %Eur/Kwh, price of a repurposed battery pack

BM_cost_new=250;  %Eur/Kwh, cost of a new module

%% Facility Establishing Costs

% Flow type A

[m9,q9]=line_fn(1000,962971,150000,5782298);
costfun_ch_A_estab_lin=@(xx) m9*xx + q9;

[m15,q15]=line_fn(1000,998068,150000,2033164);
costfun_rx_A_estab_lin=@(xx) m15*xx + q15;

costfun_rm_A_estab_lin=costfun_rx_A_estab_lin;
costfun_rp_A_estab_lin=costfun_rx_A_estab_lin;



% Flow type B

[m3,q3]=line_fn(1000,840111,150000,1372751);
costfun_ch_B_estab_lin=@(xx) m3*xx + q3;


[m21,q21]=line_fn(1000,1120928,150000,6442708);
costfun_rx_B_estab_lin=@(xx) m21*xx + q21;

costfun_rm_B_estab_lin=costfun_rx_B_estab_lin;
costfun_rp_B_estab_lin=costfun_rx_B_estab_lin;

costfun_wh_estab_lin=costfun_ch_B_estab_lin;% indipendent from the flow type

%% Facility Expansion costs

% flow type A


[m11,q11]=line_fn(0,0,200000,5259291);
costfun_ch_A_renov_lin=@(xx,yy) m11*yy + q11 - (m11*xx + q11) ;

[m111,q111]=line_fn(1471,7500,10080,150000);%ft2 per th
costfun_ch_A_build_lin=@(xx) m111*xx + q111;

[m17,q17]=line_fn(0,0,200000,984782);
costfun_rx_A_renov_lin=@(xx,yy) m17*yy + q17 - (m17*xx + q17) ;

[m171,q171]=line_fn(1171,7500,3414,150000);%ft2 per th
```

```
costfun_rx_A_build_lin=@(xx) m171*xx + q171;

costfun_rm_A_renov_lin=costfun_rx_A_renov_lin;
costfun_rp_A_renov_lin=costfun_rx_A_renov_lin;

costfun_rm_A_build_lin=costfun_rx_A_build_lin;
costfun_rp_A_build_lin=costfun_rx_A_build_lin;




% flow type B
[m5,q5]=line_fn(0,0,200000,460867);
costfun_ch_B_renov_lin=@(xx,yy) m5*yy + q5 - (m5*xx + q5) ;

[m55,q55]=line_fn(887,7500,1917,150000);%ft2 per th
costfun_ch_B_build_lin=@(xx) m55*xx + q55;

[m23,q23]=line_fn(0,0,200000,5793744);
costfun_rx_B_renov_lin=@(xx,yy) m23*yy + q23 - (m23*xx + q23) ;

[m233,q233]=line_fn(1755,7500,11504,150000);%ft2 per th
costfun_rx_B_build_lin=@(xx) m233*xx + q233;

costfun_rm_B_renov_lin=costfun_rx_B_renov_lin;
costfun_rp_B_renov_lin=costfun_rx_B_renov_lin;

costfun_rm_B_build_lin=costfun_rx_B_build_lin;
costfun_rp_B_build_lin=costfun_rx_B_build_lin;

costfun_wh_renov_lin=costfun_ch_B_renov_lin;% indipendent from the flow type
costfun_wh_build_lin=costfun_ch_B_build_lin;

%% Facility fixed costs

%flow A
[m7,q7]=line_fn(1000,258062,150000,1732981);
costfun_ch_A_fix_lin=@(xx) m7*xx + q7;


[m13,q13]=line_fn(1000,247904,150000,1169992);
costfun_rx_A_fix_lin=@(xx) m13*xx + q13;

costfun_rm_A_fix_lin=costfun_rx_A_fix_lin;
costfun_rp_A_fix_lin=costfun_rx_A_fix_lin;

%flow B


[m1,q1]=line_fn(1000,136181,150000,946392);
costfun_ch_B_fix_lin=@(xx) m1*xx + q1;

costfun_wh_fix_lin=costfun_ch_B_fix_lin;% indipendent from flow type
```

```
[m19,q19]=line_fn(1000,369778,150000,1956581);
costfun_rx_B_fix_lin=@(xx) m19*xx + q19;

costfun_rm_B_fix_lin=costfun_rx_B_fix_lin;
costfun_rp_B_fix_lin=costfun_rx_B_fix_lin;

%% Facility variable costs

%flow A

[m8,q8]=line_fn(5000,40.2225*5000,150000,22.3175*150000);
costfun_ch_A_var_lin=@(xx) m8*xx + q8;



[m14,q14]=line_fn(5000,32.4925*5000,150000,14.2675*150000);
costfun_rx_A_var_lin=@(xx) m14*xx + q14;

costfun_rp_A_var_lin=costfun_rx_A_var_lin;
costfun_rm_A_var_lin=costfun_rx_A_var_lin;




%flow B

[m2,q2]=line_fn(5000,32.0225*5000,150000,14.2275*150000);
costfun_ch_B_var_lin=@(xx) m2*xx + q2;

costfun_wh_var_lin=costfun_ch_B_var_lin;% indipendent from flow type


[m20,q20]=line_fn(5000,40.69625*5000,150000,22.3575*150000);
costfun_rx_B_var_lin=@(xx) m20*xx + q20;

costfun_rm_B_var_lin=costfun_rx_B_var_lin;
costfun_rp_B_var_lin=costfun_rx_B_var_lin;

%variable costs related to new material needed for RP and RM

percentage_material_rp=0.2;
percentage_material_rm=0.8;
percentage_insurance=0.03;
percentage_R_D=0.03;
percentage_G_A=0.05;
percentage_warranty=scen_param1(scenario,5);

material_related_rm=@(XX) (BM_cost_new*percentage_material_rm)*XX*(1+
percentage_insurance+percentage_R_D+percentage_G_A) ; % only in case of inhouse
warranty_cost_rm=@(XX) (RM_rev*percentage_warranty*XX);
warranty_cost_rf=@(XX) (RF_rev*percentage_warranty*XX);

material_related_rp=@(XX) (BM_cost_new*percentage_material_rp)*XX*(1+
percentage_insurance+percentage_R_D+percentage_G_A) ;
warranty_cost_rp=@(XX) (RP_rev*percentage_warranty*XX);
```

```
%% Outsourcing costs
% flow A
x=[0 1000 5000 10000 30000 50000 100000 150000 200000 250000 300000 400000
500000];
RF_A_price=[    776.86  776.86  159.07  90.45   43.47   39.67   34.73   32.23
30.00  30.00  30.00 30.00 30.00];
costfun_rf_A_price=@(xx) interp1(x,RF_A_price,xx);




x_rp_A=[ 0        1000        5000       10000       30000       50000
100000      150000  200000 250000 300000 400000 500000];
y_rp_A=[150 250 350];
[a,b]=meshgrid(x_rp_A,y_rp_A);
z_rp_A=[820.18  820.18  202.39  133.77  86.79   82.99   78.05   75.55 75.55
75.55 75.55 75.55 75.55;849.0584    849.0584    231.2727    162.6545    115.6748
111.8671    106.9274    104.4345 104.4345 104.4345 104.4345 104.4345 104.4345;
877.9385 877.9385    260.1528    191.5346    144.5549    140.7472    135.8075
133.3146 133.3146 133.3146 133.3146 133.3146 133.3146];
costfun_rp_A_price=@(xx,yy) interp2(a,b,z_rp_A,xx,yy); %the input for this
function are parameters given in the problem


%flow B

x=[0 1000 5000 10000 30000 50000 100000 150000   200000 250000 300000 400000
500000];
RF_B_price=[    970.6   970.6   213.7   127.8   74.8    67.4    58.5    57.2
57.2 57.2 57.2 57.2 57.2];
costfun_rf_B_price=@(xx) interp1(x,RF_B_price,xx);

z_rp_B=[1013.94 1013.94 256.97  171.12  118.07  110.74  101.82  100.55 100.55
100.55 100.55 100.55 100.55; 1042.82  1042.82 285.85  200.00  146.95  139.62
130.70  129.43 129.43 129.43 129.43 129.43 129.43;1071.70   1071.70 314.73
228.88  175.83  168.50  159.58  158.31 158.31 158.31 158.31 158.31 158.31];
costfun_rp_B_price=@(xx,yy) interp2(a,b,z_rp_B,xx,yy);


RM_out=[141.51  235.84  330.00];

costfun_rm_price=@(xx) interp1(y_rp_A,RM_out,xx);% here the input is the price
of the new BP per Kwh

%% Distances between plants

DL_CH_DIST=[1629 3120 2970 2890 1807; 684 2175 2025 1766 862; 102 1493 1343 1296
204; 1476 101 146 1566 1302;461 1257 1107 928 359;689 1781 1631 1270 788;741
2239 2014  2054 925; 996 1744 1594 783 990;1724 651 596 1929 1550;264 298 1148
1160 72;1243 1488 1327 322 1098];% distances in KM calculated for each pair of
nodes with Google Maps taking the shortest path

CH_RC_DIST=[64,890,1120;1449,2391,418;1300,2242,226;1287,1960,1202;137,1079,939]
;
```

```
CH_RM_DIST=[0 1502 1352 681  1318 1534 238; 1502 0 226 2170 1392 644 1294;1352
226 0 2020 1414 576 1145 ; 1317 1591 1442 1940  293 1801 1163; 188 1328 1179 857
1174 1361 49 ];
CH_RP_DIST=[0,1607,1352,247;1502,89,226,1265;1352,240,0,1118;1317,1662,1443,1072
;188,1339,1180,172];

RM_WH_DIST=[ 0 1492 1352 147; 1502  209 226 1369;1352 156 0 1219 ; 681 2160 2020
818; 1318 1383 1414 1181; 1534 436 576 1400;238 1284 1145 91 ];
RM_RC_DIST=[64,890,1120;1449,2391,418;1300 2242
226;733,214,1780;1266,2066,1173;1482,2418,649;168,1110,904];
RM_RP_DIST=[0,1607,1352,247;1502,89,226,1265;1352,240,0,1118;681,2250,2020,914;1
319,1461,1414,1077;1539,646,576,1310;220,1362,1145,127];
RP_RM_DIST=[0, 1502, 1352, 681, 1319, 1539, 220; 1607, 89, 240, 2250, 1461, 646,
1362; 1352, 226, 0, 2020, 1414, 576, 1145; 247, 1265, 1118, 914, 1077, 1310,
127];

RP_RC_DIST= [64,890,1120;1506,2454,473;1300,2242,226;188,1145,878];

WH_DL_DIST=[ 1631 684 103 1476 459 690 741 1037 1724 264 1243;3110 2165 1483 109
1247 1771 2229 1734 443 1288 1478;2970 2025 1343 146 1107 1631 2014 1594 596
1148 1327 ;1766 821 162 1341 304 698 884 926 1589 166 1104];
WH_RM_DIST=RM_WH_DIST';



%% Transportation costs

fix_transp_cost=55+55+220; % Eur/trip

var_transp_cost= 1.40; % eur/km; HP: this cost is costant with the path and the
time.

% Transportation towards recycling centers

RC_cost_BP_transp=ones(L,1); % transp cost for severely damaged BP
RC_cost_BM_transp=ones(L,1);% transp cost for defective BM

RC_cost_BP_transp(1,1)=8; %Eur/kg
RC_cost_BM_transp(1,1)=2.5;

RC_cost_BP_transp(2,1)=7.4; %Eur/kg
RC_cost_BM_transp(2,1)=2.07;

RC_cost_BP_transp(3,1)=4; %Eur/kg
RC_cost_BM_transp(3,1)=2.085;

%% Recycling costs
RC_cost_BP=ones(L,1); % cost for severely damaged BP
RC_cost_BM=ones(L,1);% cost for defective BM

RC_cost_BP(1,1)=2.75; %Eur/kg
RC_cost_BM(1,1)=2.75;


RC_cost_BP(2,1)=0.69; %Eur/kg
RC_cost_BM(2,1)=0.38;

RC_cost_BP(3,1)=1.13; %Eur/kg
```

```
RC_cost_BM(3,1)=0.9;

%% FLOW COEFFICIENTS

if FL==1
    CH_RM = 0.7;
    CH_RP=0.22;
    CH_RC=0.08;

    CH_RC_BP=0.7;
    CH_RC_BM=0.3;

    RM_WH=0.7;
    RF_WH=0.3;

    RM_RF_RC=0.02;
    RM_RF_RP=0.34;

    RP_RC=0.07;

    WH_RM=0.7;

elseif FL==2
    CH_RM=[0.6  0.6 0.6 0.595118348 0.552796271 0.52419922  0.50575188
0.464477465 0.482472139 0.451312875 0.532158894 0.551282055];
    CH_RP=[0.3  0.3 0.3 0.304881652 0.347203729 0.37580078  0.39424812
0.435522535 0.417527861 0.448687125 0.367841106 0.348717945];
    CH_RC=0.1;

    CH_RC_BP=0.7;
    CH_RC_BM=0.3;

    RM_WH=0.3;
    RF_WH=0.7;

    RM_RF_RC=0.02;
    RM_RF_RP=[0.04   0.04     0.04     0.039674557 0.036853085 0.034946615
0.033716792 0.030965164 0.032164809 0.030087525 0.03547726  0.036752137];
    RP_RM_RF=[0.16   0.16     0.16     0.158698226 0.147412339 0.139786459
0.134867168 0.123860657 0.128659237 0.1203501   0.141909038 0.147008548];
    RP_RC=0.07;

    WH_RM=[0.3  0.3 0.3 0.305857982 0.356644475 0.390960936 0.413097745
0.462627042 0.441033434 0.478424549 0.381409327 0.358461534];
elseif FL==3
    CH_RM=0.62;
    CH_RP=0.3;
    CH_RC=0.08;

    CH_RC_BP=0.7;
    CH_RC_BM=0.3;

    RM_WH=0.3;
    RF_WH=0.7;

    RM_RF_RC=0.02;
    RM_RF_RP=0.05;

    RP_RC=0.07;
```

```
    WH_RM=0.32;
elseif FL==4
    CH_RM=0.7;
    CH_RP=0.22;
    CH_RC=0.08;

    CH_RC_BP=0.875;
    CH_RC_BM=0.125;

    RM_WH=0.3;
    RF_WH=0.7;

    RM_RF_RC=0.03;
    RM_RF_RP=0.03;

    RP_RC=0.06;

    WH_RM=0.36;


else

    error('FL is an integer between 1 and 4');
end

%% DECISION VARIABLES

CH=optimvar('CH',J,T,'Type','integer','Lowerbound',0,'UpperBound',1);  % 1 if
core hub j is open at time t, 0 otherwise
RM=optimvar('RM',K,T,'Type','integer','LowerBound',0,'UpperBound',1);
WH=optimvar('WH',P,T,'Type','integer','LowerBound',0,'UpperBound',1);
RP=optimvar('RP',M,T,'Type','integer','LowerBound',0,'UpperBound',1);

CH_cap=optimvar('CH_cap',J,T,'Lowerbound',0);%  production capacity in Kwh of
the core hub j in time t; the maximum capacity is set at 'Max_cap' for each core
hub since the establishing, fixed and variable costs calculated are valid within
this range
RM_cap=optimvar('RM_cap',K,T,'LowerBound',0);
WH_cap=optimvar('WH_cap',P,T,'LowerBound',0);
RP_cap=optimvar('RP_cap',M,T,'LowerBound',0);

CH_exp=optimvar('CH_exp',J,T,'Lowerbound',0);%  production capacity expansion in
Kwh of the core hub j in time t; as a first attempt it has been asssumed that
the max capacity expansion should not overcome 'Max_exp' KWh due to the possible
lack of floor space.
RM_exp=optimvar('RM_exp',K,T,'LowerBound',0);
WH_exp=optimvar('WH_exp',P,T,'LowerBound',0);
RP_exp=optimvar('RP_exp',M,T,'LowerBound',0);


CH_estab_cap=optimvar('CH_estab_cap',J,T,'Lowerbound',0); % capacity of CH j at
the establishing point in time t
RM_estab_cap=optimvar('RM_estab_cap',K,T,'LowerBound',0);
WH_estab_cap=optimvar('WH_estab_cap',P,T,'LowerBound',0);
RP_estab_cap=optimvar('RP_estab_cap',M,T,'LowerBound',0);

CH_estab_year=optimvar('CH_estab_year',J,T,'Type','integer','Lowerbound',0,'Uppe
rBound',1);% 1 if core hub j is established at time t, 0 otherwise
```

```
RM_estab_year=optimvar('RM_estab_year',K,T,'Type','integer','LowerBound',0,'Uppe
rBound',1);
WH_estab_year=optimvar('WH_estab_year',P,T,'Type','integer','LowerBound',0,'Uppe
rBound',1);
RP_estab_year=optimvar('RP_estab_year',M,T,'Type','integer','LowerBound',0,'Uppe
rBound',1);




X=optimvar('X',I,J,T,'LowerBound',0);% number of batteries in Kwh that are going
from Dealer i to Core Hub j within t

Z=optimvar('Z',J,K,T,'LowerBound',0);
THETA=optimvar('THETA',J,L,T,'LowerBound',0);
Y=optimvar('Y',J,M,T,'LowerBound',0);

OMEGA=optimvar('OMEGA',K,P,T,'LowerBound',0);
W=optimvar('W',K,L,T,'LowerBound',0);

BETA=optimvar('BETA',P,I,T,'LowerBound',0);
ALPHA=optimvar('ALPHA',P,K,T,'LowerBound',0);%V5_NEW: this flow is the one of
the NEW modules/accessories that are sent from the WH to the RM in order to
complete the remanufacturing process and to cope with the wasted/scrapped
batteries at the RM

ALPHA_RM=optimvar('ALPHA_RM',P,K,T,'LowerBound',0);
ALPHA_RF=optimvar('ALPHA_RF',P,K,T,'LowerBound',0);

DELTA=optimvar('DELTA',M,L,T,'LowerBound',0);
GAMMA=optimvar('GAMMA',K,M,T,'LowerBound',0);%flow of used modules from RM to RP

IOTA=optimvar('IOTA',M,T,'LowerBound',0); %flow from repurposing facilities to
customers
AMMAG=optimvar('AMMAG',M,K,T,'LowerBound',0); %flow from repurposing facilities
to remanufacturing/refurbishing


%% CAPACITY CONSTRAINTS

% CH level
constr1=optimconstr(J,T);


for j=1:J
    for t=1:T
constr1(j,t)=sum(Z(j,:,t))+sum(Y(j,:,t))+sum(THETA(j,:,t))<= CH_cap(j,t);
    end
end

prob.Constraints.constr1=constr1;


% RM-RF level

if RM_RF_OUT==0

    constr2=optimconstr(K,T);
```

```
    for k=1:K
    for t=1:T


constr2(k,t)=sum(OMEGA(k,:,t))+sum(W(k,:,t))+sum(GAMMA(k,:,t))+sum(AMMAG(:,k,t))
<= RM_cap(k,t); %+sum(AMMAG(:,k,t))
    end
    end
    prob.Constraints.constr2=constr2;

elseif RM_RF_OUT==1

    constr2=optimconstr(K,T);

    for k=1:K
    for t=1:T


constr2(k,t)=RF_WH*sum(OMEGA(k,:,t))+sum(W(k,:,t))+sum(GAMMA(k,:,t))+sum(AMMAG(:
,k,t))<= RM_cap(k,t);
    end
    end
    prob.Constraints.constr2=constr2;

end


% RP level

if RP_OUT==0

    constr3=optimconstr(M,T);
    for m=1:M
    for t=1:T

    constr3(m,t)=IOTA(m,t)+sum(DELTA(m,:,t))+sum(AMMAG(m,:,t))<= RP_cap(m,t);
%+sum(AMMAG(m,:,t))
    end
    end
    prob.Constraints.constr3=constr3;

elseif  RP_OUT==1

    constr3=optimconstr(M,T);
    for m=1:M
    for t=1:T

    constr3(m,t)=IOTA(m,t)+sum(DELTA(m,:,t))+sum(AMMAG(m,:,t))<= RP_cap(m,t);
%+sum(AMMAG(m,:,t))
    end
    end
    prob.Constraints.constr3=constr3;

end


 % WH level
```

```
constr4=optimconstr(P,T);
for p=1:P
    for t=1:T

    constr4(p,t)=sum(BETA(p,:,t))+sum(ALPHA(p,:,t))<= WH_cap(p,t);
    end
end

prob.Constraints.constr4=constr4;

%% FLOW CONSTRAINTS

% balance at the DL plants

constr5=optimconstr(I,T);

for i=1:I
    for t=1:T

        constr5(i,t)=  sum(X(i,:,t))==rb(i,t);
    end
end

prob.Constraints.constr5=constr5;

% balance at the CH plants

constr6=optimconstr(J,T,3);

for j=1:J
    for t=1:T

        constr6(j,t,1)= sum(Z(j,:,t))==CH_RM(t)*sum(X(:,j,t));
        constr6(j,t,2)=sum(Y(j,:,t))== CH_RP(t)*sum(X(:,j,t));
        constr6(j,t,3)=sum(THETA(j,:,t))== CH_RC*sum(X(:,j,t));
    end
end

prob.Constraints.constr6=constr6;

% balance at the RM-RF plants

constr7=optimconstr(K,T,3);

for k=1:K
    for t=1:T

        constr7(k,t,1)=(RF_WH)*sum(OMEGA(k,:,t))== (sum(Z(:,k,t))+
sum(ALPHA_RF(:,k,t))- sum(GAMMA(k,:,t))- sum(W(k,:,t))+sum(AMMAG(:,k,t)));
%+sum(AMMAG(:.K.T))
        constr7(k,t,2)= (RM_WH)*sum(OMEGA(k,:,t))== sum(ALPHA_RM(:,k,t));

        constr7(k,t,3)= sum(W(k,:,t))== (RM_RF_RC/CH_RM(t))*sum(Z(:,k,t));


    end
end
```

```
prob.Constraints.constr7=constr7;

% balance at RP plants

constr8=optimconstr(M,T,2);

for m=1:M
    for t=1:T

        constr8(m,t,1)= IOTA(m,t)==(sum(Y(:,m,t))+sum(GAMMA(:,m,t))-
sum(DELTA(m,:,t))-sum(AMMAG(m,:,t))); %-sum(AMMAG(m,:,t))
        constr8(m,t,2)= sum(DELTA(m,:,t))== (RP_RC/CH_RP(t))*( sum(Y(:,m,t)));
    end
end

prob.Constraints.constr8=constr8;

% balance at WH

constr9=optimconstr(P,T);

for p=1:P
    for t=1:T

       constr9(p,t)= sum(BETA(p,:,t))== sum(OMEGA(:,p,t));
    end
end

prob.Constraints.constr9=constr9;


% returned flow constraint

constr10=optimconstr(I,T);
 for i=1:I
        for t=1:T

            constr10(i,t)= sum(BETA(:,i,t))==rb(i,t);
        end
 end

 prob.Constraints.constr10=constr10;

 constr101= ALPHA== ALPHA_RM + ALPHA_RF;
 prob.Constraints.constr101=constr101;


%% Facility Opening Constraints

constr11=CH(1:3,1)==1; %V10 the existing CH plants has to be open during t=1;
prob.Constraints.constr11=constr11;



constr12=optimconstr(T); % min number of RM to be open for each time t
for t=1:T
```

```
    constr12(t)= sum(RM(:,t))>=RM_min;
end

prob.Constraints.constr12=constr12;

constr13=optimconstr(T);% min number of RP to be open for each time t
for t=1:T

    constr13(t)= sum(RP(:,t))>=RP_min;
end

prob.Constraints.constr13=constr13;


constr14=optimconstr(T);% min number of WH to be open for each time t
for t=1:T

    constr14(t)= sum(WH(:,t))>=WH_min;
end

prob.Constraints.constr14=constr14;

constr15=optimconstr(J,T-1);% a CH that is open at time t cannot be closed at
time t+1
for j=1:J
    for t=1:T-1

       constr15(j,t)= CH(j,t+1)>= CH(j,t);
    end
end

prob.Constraints.constr15=constr15;


constr16=optimconstr(P,T-1);% a WH that is open at time t cannot be closed at
time t+1
for p=1:P
    for t=1:T-1

       constr16(p,t)= WH(p,t+1)>= WH(p,t);
    end
end

prob.Constraints.constr16=constr16;

if RM_RF_OUT==0 % only in case of in-housing operations; in case of outsourced
operations it can be possible to change the third party RM company/plant yearly

    constr17=optimconstr(K,T-1);% a RM-RF plant that is open at time t cannot be
closed at time t+1
    for k=1:K
    for t=1:T-1

       constr17(k,t)= RM(k,t+1)>= RM(k,t);
    end
    end
```

```
    prob.Constraints.constr17=constr17;



end


if RP_OUT==0 % only in case of in-housing operations; in case of outsourced
operations it can be possible to change the third party RP company/plant yearly

    constr18=optimconstr(M,T-1);% a RP plant that is open at time t cannot be
closed at time t+1

    for m=1:M
    for t=1:T-1

       constr18(m,t)= RP(m,t+1)>= RP(m,t);
    end
    end

    prob.Constraints.constr18=constr18;
end

%% Capacity and Expansion Constraints

constr19=optimconstr(J,T-1); % CH capacity at time t is equal to the capacity at
time t-1 plus the capacity expansion happened at time t

for t=2:T
    constr19(:,t)= CH_cap(:,t)>=CH_cap(:,t-1)+CH_exp(:,t);
end

prob.Constraints.constr19=constr19;

% constr20=CH_cap(:,1)==CH_cap(:,1)+CH_exp(:,1);
% prob.Constraints.constr20=constr20;

constr191=optimconstr(J,T-1);
constr1911=optimconstr(J,T-1);
constr1912=optimconstr(J,T-1);

for t=2:T
    constr191(:,t,1)=CH_estab_cap(:,t)<= (CH(:,t)-CH(:,t-1))*Max_cap;
    constr1911(:,t)=CH_estab_cap(:,t)>=CH_cap(:,t)-CH_cap(:,t-1)-CH_exp(:,t);
    constr1912(:,t)=CH_estab_year(:,t)>=(CH(:,t)-CH(:,t-1));
end
prob.Constraints.constr191=constr191;
prob.Constraints.constr1911=constr1911;
prob.Constraints.constr1912=constr1912;
constr192=CH_estab_year<=CH_estab_cap;
prob.Constraints.constr192=constr192;

constr193=CH_estab_cap(:,1)<=CH(:,1)*Max_cap;
prob.Constraints.constr193=constr193;

constr194= CH_estab_cap(:,1)>=CH_cap(:,1)-CH_exp(:,1);
prob.Constraints.constr194=constr194;
```

```
constr195=CH_estab_year(:,1)>=CH(:,1);
prob.Constraints.constr195=constr195;



constr20=optimconstr(J,T-1);

for t=2:T

        constr20(:,t)= CH_cap(:,t)-CH_cap(:,t-1)<= CH_exp(:,t) + (CH(:,t)-
CH(:,t-1))*Max_cap;
end
prob.Constraints.constr20=constr20;




constr21=optimconstr(P,T-1); % WH capacity at time t is equal to the capacity at
time t-1 plus the capacity expansion happened at time t

for t=2:T
    constr21(:,t)= WH_cap(:,t)>=WH_cap(:,t-1)+WH_exp(:,t);
end

prob.Constraints.constr21=constr21;

% constr22=WH_cap(:,1)==WH_cap(:,1)+WH_exp(:,1);
% prob.Constraints.constr22=constr22;


constr211=optimconstr(P,T-1);
constr2111=optimconstr(P,T-1);
constr2112=optimconstr(P,T-1);
for t=2:T
    constr211(:,t)=WH_estab_cap(:,t)<= (WH(:,t)-WH(:,t-1))*Max_cap;
    constr2111(:,t)=WH_estab_cap(:,t)>=WH_cap(:,t)-WH_cap(:,t-1)-WH_exp(:,t);
    constr2112(:,t)=WH_estab_year(:,t)>=(WH(:,t)-WH(:,t-1));
end

prob.Constraints.constr211=constr211;
prob.Constraints.constr2111=constr2111;
prob.Constraints.constr2112=constr2112;

constr212=WH_estab_year<=WH_estab_cap;
prob.Constraints.constr212=constr212;

constr213=WH_estab_cap(:,1)<=WH(:,1)*Max_cap;
prob.Constraints.constr213=constr213;

constr214= WH_estab_cap(:,1)>=WH_cap(:,1)-WH_exp(:,1);
prob.Constraints.constr214=constr214;

constr215=WH_estab_year(:,1)>=WH(:,1);
prob.Constraints.constr215=constr215;


constr22=optimconstr(P,T-1);
```

```
for t=2:T

        constr22(:,t)= WH_cap(:,t)-WH_cap(:,t-1)<= WH_exp(:,t) + (WH(:,t)-
WH(:,t-1))*Max_cap;
end
prob.Constraints.constr22=constr22;

if RM_RF_OUT==0
    constr23=optimconstr(K,T-1);% RM-RF capacity at time t is equal to the
capacity at time t-1 plus the capacity expansion happened at time t

    for t=2:T
    constr23(:,t)= RM_cap(:,t)>=RM_cap(:,t-1)+RM_exp(:,t);
    end

    prob.Constraints.constr23=constr23;

%     constr24=RM_cap(:,1)== RM_cap(:,1)+RM_exp(:,1);
%     prob.Constraints.constr24=constr24;

constr231=optimconstr(K,T-1);
constr2311=optimconstr(K,T-1);
constr2312=optimconstr(K,T-1);
for t=2:T
    constr231(:,t)=RM_estab_cap(:,t)<= (RM(:,t)-RM(:,t-1))*Max_cap;
    constr2311(:,t)=RM_estab_cap(:,t)>=RM_cap(:,t)-RM_cap(:,t-1)-RM_exp(:,t);
    constr2312(:,t)=RM_estab_year(:,t)>=(RM(:,t)-RM(:,t-1));
end

prob.Constraints.constr231=constr231;
prob.Constraints.constr2311=constr2311;
prob.Constraints.constr2312=constr2312;

constr232=RM_estab_year<=RM_estab_cap;
prob.Constraints.constr232=constr232;

constr233=RM_estab_cap(:,1)<=RM(:,1)*Max_cap;
prob.Constraints.constr233=constr233;

constr234= RM_estab_cap(:,1)>=RM_cap(:,1)-RM_exp(:,1);
prob.Constraints.constr234=constr234;

constr235=RM_estab_year(:,1)>=RM(:,1);
prob.Constraints.constr235=constr235;



    constr24=optimconstr(K,T-1);

    for t=2:T

        constr24(:,t)= RM_cap(:,t)-RM_cap(:,t-1)<= RM_exp(:,t) + (RM(:,t)-
RM(:,t-1))*Max_cap;
    end
    prob.Constraints.constr24=constr24;

elseif RM_RF_OUT==1
```

```
%     constr23= RM_cap==0;
%     prob.Constraints.constr23=constr23;

    constr24= RM_exp==0;
    prob.Constraints.constr24=constr24;
end



if RP_OUT==0
    constr25=optimconstr(M,T-1);% RP capacity at time t is equal to the capacity
at time t-1 plus the capacity expansion happened at time t

    for t=2:T
    constr25(:,t)= RP_cap(:,t)>=RP_cap(:,t-1)+RP_exp(:,t);
    end

    prob.Constraints.constr25=constr25;

%     constr26=RP_cap(:,1)>= RP_cap(:,1)+RP_exp(:,1);
%     prob.Constraints.constr26=constr26;

constr251=optimconstr(M,T-1);
constr2511=optimconstr(M,T-1);
constr2512=optimconstr(M,T-1);
for t=2:T
    constr251(:,t)=RP_estab_cap(:,t)<= (RP(:,t)-RP(:,t-1))*Max_cap;
    constr2511(:,t)=RP_estab_cap(:,t)>=RP_cap(:,t)-RP_cap(:,t-1)-RP_exp(:,t);
    constr2512(:,t)=RP_estab_year(:,t)>=(RP(:,t)-RP(:,t-1));
end

prob.Constraints.constr251=constr251;
prob.Constraints.constr2511=constr2511;
prob.Constraints.constr2512=constr2512;

constr252=RP_estab_year<=RP_estab_cap;
prob.Constraints.constr252=constr252;


constr253=RP_estab_cap(:,1)<=RP(:,1)*Max_cap;
prob.Constraints.constr253=constr253;

constr254= RP_estab_cap(:,1)>=RP_cap(:,1)-RP_exp(:,1);
prob.Constraints.constr254=constr254;

constr255=RP_estab_year(:,1)>=RP(:,1);
prob.Constraints.constr255=constr255;

    constr26=optimconstr(M,T-1);

    for t=2:T

        constr26(:,t)= RP_cap(:,t)-RP_cap(:,t-1)<= RP_exp(:,t) + (RP(:,t)-
RP(:,t-1))*Max_cap;
    end
    prob.Constraints.constr26=constr26;
```

```
elseif RP_OUT==1

%     constr25= RP_cap==0;
%     prob.Constraints.constr25=constr25;

    constr26= RP_exp==0;
    prob.Constraints.constr26=constr26;
end



% Limitation in the cumulative capacity expansion over t for each facility

constr27=optimconstr(J); % CH capacity expansion limitation
for j=1:3%V10

    constr27(j)=sum(CH_exp(j,:))<=Max_exp_CH_initial;
end
for j=4:J%V10

    constr27(j)=sum(CH_exp(j,:))<=Max_exp;
end
prob.Constraints.constr27=constr27;

constr28= CH_cap(1:3,1)==CH_initial; %V10 this constraint is valid only for CH,
in which there are 3 existing plants; it states that the initial capacity of
these plants is equal to CH_initial that is a parameter.
prob.Constraints.constr28=constr28;



constr29=optimconstr(P); % WH capacity expansion limitation
for p=1:P

    constr29(p)=sum(WH_exp(p,:))<=Max_exp;
end
prob.Constraints.constr29=constr29;


constr30=optimconstr(K); % RM-RF capacity expansion limitation
for k=1:K



    for k=1:K

    constr30(k)=sum(RM_exp(k,:))<=Max_exp;
    end

end
prob.Constraints.constr30=constr30;



constr31=optimconstr(M); % RM-RF capacity expansion limitation
```

```
for m=1:M

    constr31(m)=sum(RP_exp(m,:))<=Max_exp;
end
prob.Constraints.constr31=constr31;


% Facility establishing capacity and expansion are zero for not established
% facilities


constr32=CH_cap<=CH*BIG;
prob.Constraints.constr32=constr32;

constr33=CH_exp<=CH*BIG;
prob.Constraints.constr33=constr33;


constr34=WH_cap<=WH*BIG;
prob.Constraints.constr34=constr34;

constr35=WH_exp<=WH*BIG;
prob.Constraints.constr35=constr35;


constr36=RM_cap<=RM*BIG;
prob.Constraints.constr36=constr36;

constr37=RM_exp<=RM*BIG;
prob.Constraints.constr37=constr37;


constr38=RP_cap<=RP*BIG;
prob.Constraints.constr38=constr38;

constr39=RP_exp<=RP*BIG;
prob.Constraints.constr39=constr39;


% MIN AND MAX CAPACITY FOR EACH PLANT


constr40=CH_cap>= CH* Min_cap;
prob.Constraints.constr40=constr40;

constr41=CH_cap <= CH* Max_cap;
prob.Constraints.constr41=constr41;

constr42=WH_cap>= WH* Min_cap;
prob.Constraints.constr42=constr42;

constr43=WH_cap <= WH* Max_cap;
prob.Constraints.constr43=constr43;


if RM_RF_OUT==0
```

```
constr44=RM_cap>= RM* Min_cap;
prob.Constraints.constr44=constr44;

constr45=RM_cap <= RM* Max_cap;
prob.Constraints.constr45=constr45;

elseif RM_RF_OUT==1

    constr441=RM_cap>= RM* Min_cap;
    prob.Constraints.constr441=constr441;

    constr451=RM_cap == RM *RM_max_cap_out;
    prob.Constraints.constr451=constr451;




%
%     constr452=optimconstr(J,K,T)
%
%     for t=1:T
%         for k=1:K
%             for j=1:J
%             constr452(j,k,t)=RM(k,t)<=Z(j,k,t);
%         end
%     end
%
%         prob.Constraints.constr452=constr452;



    end



if RP_OUT==0

constr46=RP_cap>= RP* Min_cap;
prob.Constraints.constr46=constr46;

constr47=RP_cap <= RP* Max_cap;
prob.Constraints.constr47=constr47;


elseif RP_OUT==1

    constr461=RP_cap>= RP* Min_cap;
    prob.Constraints.constr461=constr461;

    constr471=RP_cap == RP* RP_max_cap_out;
    prob.Constraints.constr471=constr471;


%     constr462=optimconstr(J,M,T);
%
%     for t=1:T
%         for m=1:M
%             for j=1:J
```

```
%               constr462(j,m,t)=RP(m,t)<=Y(j,m,t);
%               end
%           end
%       end
%
%           prob.Constraints.constr462=constr462;

end


% Limitation on the possibility to expand a plant in the same year it is
% opened


constr48=optimconstr(J,T-1); %  CH level
for j=1:J
    for t=2:T
        constr48(j,t)= CH_exp(j,t)<= (1-(CH(j,t)-CH(j,t-1)))*BIG;
    end
end
prob.Constraints.constr48=constr48;

constr49=CH_exp(4:J,1)==0; %V10 at the first year there cannot be any expansion
for new established plants
prob.Constraints.constr49=constr49;


constr50=optimconstr(P,T-1); %  WH level
for p=1:P
    for t=2:T
        constr50(p,t)= WH_exp(p,t)<= (1-(WH(p,t)-WH(p,t-1)))*BIG;
    end
end
prob.Constraints.constr50=constr50;

constr51=WH_exp(:,1)==0;
prob.Constraints.constr51=constr51;


if RM_RF_OUT==0
    constr52=optimconstr(K,T-1); %  RM level
    for k=1:K
        for t=2:T
        constr52(k,t)= RM_exp(k,t)<= (1-(RM(k,t)-RM(k,t-1)))*BIG;
        end
    end
    prob.Constraints.constr52=constr52;

    constr53=RM_exp(:,1)==0;
    prob.Constraints.constr53=constr53;



end


if RP_OUT==0
    constr54=optimconstr(M,T-1); %  RP level
    for m=1:M
```

```matlab
        for t=2:T
        constr54(m,t)= RP_exp(m,t)<= (1-(RP(m,t)-RP(m,t-1)))*BIG;
        end
    end
    prob.Constraints.constr54=constr54;

    constr55=RP_exp(:,1)==0;
    prob.Constraints.constr55=constr55;
end


%% Flow Constraints linked to Plant Openings

% CH level
constr56=optimconstr(J,M,T);

for j=1:J
    for m=1:M
        for t=1:T

            constr56(j,m,t)= Y(j,m,t)<= CH(j,t)*BIG;
        end
    end
end

prob.Constraints.constr56=constr56;

constr57=optimconstr(J,L,T);

for j=1:J
    for l=1:L
        for t=1:T

            constr57(j,l,t)= THETA(j,l,t)<= CH(j,t)*BIG;
        end
    end
end

prob.Constraints.constr57=constr57;


constr58=optimconstr(J,K,T);

for j=1:J
    for k=1:K
        for t=1:T

            constr58(j,k,t)= Z(j,k,t)<= CH(j,t)*BIG;
        end
    end
end

prob.Constraints.constr58=constr58;

constr59=optimconstr(I,J,T);

for i=1:I
    for j=1:J
```

```
        for t=1:T

            constr59(i,j,t)= X(i,j,t)<= CH(j,t)*BIG;
        end
    end
end

prob.Constraints.constr59=constr59;

%RM level

constr72=optimconstr(M,K,T);
for m=1:M
    for k=1:K
        for t=1:T
        constr72(m,k,t)=AMMAG(m,k,t)<= RM(k,t)*BIG;
        end
    end
end

prob.Constraints.constr72=constr72;
constr60=optimconstr(K,M,T);

for k=1:K
    for m=1:M
        for t=1:T

            constr60(k,m,t)= GAMMA(k,m,t)<= RM(k,t)*BIG;
        end
    end
end

prob.Constraints.constr60=constr60;

constr61=optimconstr(K,P,T);

for k=1:K
    for p=1:P
        for t=1:T

            constr61(k,p,t)= OMEGA(k,p,t)<= RM(k,t)*BIG;
        end
    end
end

prob.Constraints.constr61=constr61;

constr62=optimconstr(J,K,T);

for j=1:J
    for k=1:K
        for t=1:T

            constr62(j,k,t)= Z(j,k,t)<= RM(k,t)*BIG;
        end
    end
end

prob.Constraints.constr62=constr62;
```

```
constr63=optimconstr(K,L,T);

for k=1:K
    for l=1:L
        for t=1:T

            constr63(k,l,t)= W(k,l,t)<= RM(k,t)*BIG;
        end
    end
end

prob.Constraints.constr63=constr63;

constr64=optimconstr(P,K,T);

for p=1:P
    for k=1:K
        for t=1:T

            constr64(p,k,t)= ALPHA(p,k,t)<= RM(k,t)*BIG;
        end
    end
end

prob.Constraints.constr64=constr64;

%WH level


constr65=optimconstr(K,P,T);

for k=1:K
    for p=1:P
        for t=1:T

            constr65(k,p,t)= OMEGA(k,p,t)<= WH(p,t)*BIG;
        end
    end
end

prob.Constraints.constr65=constr65;


constr66=optimconstr(P,I,T);

for p=1:P
    for i=1:I
        for t=1:T

            constr66(p,i,t)= BETA(p,i,t)<= WH(p,t)*BIG;
        end
    end
end

prob.Constraints.constr66=constr66;

constr67=optimconstr(P,K,T);
```

```
for p=1:P
    for k=1:K
        for t=1:T

            constr67(p,k,t)= ALPHA(p,k,t)<= WH(p,t)*BIG;
        end
    end
end

prob.Constraints.constr67=constr67;


% RP level
constr73=optimconstr(M,K,T);

for m=1:M
    for k=1:K
       for t=1:T

            constr73(m,k,t)= AMMAG(m,k,t)<= RP(m,t)*BIG;
       end
    end
end
prob.Constraints.constr73=constr73;
constr68=optimconstr(J,M,T);

for j=1:J
    for m=1:M
        for t=1:T

            constr68(j,m,t)= Y(j,m,t)<= RP(m,t)*BIG;
        end
    end
end

prob.Constraints.constr68=constr68;

constr69=optimconstr(K,M,T);

for k=1:K
    for m=1:M
        for t=1:T

            constr69(k,m,t)= GAMMA(k,m,t)<= RP(m,t)*BIG;
        end
    end
end

prob.Constraints.constr69=constr69;

constr70=optimconstr(M,L,T);

for l=1:L
    for m=1:M
        for t=1:T

            constr70(m,l,t)= DELTA(m,l,t)<= RP(m,t)*BIG;
        end
```

```
    end
end

prob.Constraints.constr70=constr70;


constr71=optimconstr(M,T);


    for m=1:M
        for t=1:T

            constr71(m,t)= IOTA(m,t)<= RP(m,t)*BIG;
        end
    end


prob.Constraints.constr71=constr71;

%constr72=optimconstr(M,K,T);

%for k=1:K
    %for m=1:M
        %for t=1:T

          %  constr72(m,k,t)= GAMMA(m,k,t)<= RP(m,t)*BIG;
         % end
     % end
%end

%prob.Constraints.constr72=constr72;
% returned flow constraint

% constr72=optimconstr(I,T);
%  for i=1:I
%         for t=1:T
%
%             constr72(i,t)= sum(BETA(:,i,t))==(CH_RM)*rb(i,t);
%         end
%  end
%
%  prob.Constraints.constr72=constr72;





%% INTEGER FLOWS
% constr72= X_BP==X/BP_size;
% prob.Constraints.constr72=constr72;
%
% constr73= Z_BM==Z/BM_size;
% prob.Constraints.constr73=constr73;
%
% constr74= Y_BM==Y/BM_size;
% prob.Constraints.constr74=constr74;
%
% constr75= THETA_BM==THETA/BM_size;
```

```
% prob.Constraints.constr75=constr75;
%
% constr76= OMEGA_BP==OMEGA/BP_size;
% prob.Constraints.constr76=constr76;
%
% constr77= GAMMA_BM==GAMMA/BM_size;
% prob.Constraints.constr77=constr77;
%
% constr78= ALPHA_BM==ALPHA/BM_size;
% prob.Constraints.constr78=constr78;
%
% constr79= W_BM==W/BM_size;
% prob.Constraints.constr79=constr79;
%
% constr80= DELTA_BM==DELTA/BM_size;
% prob.Constraints.constr80=constr80;
%
% constr81= IOTA_BP==IOTA/BP_size;
% prob.Constraints.constr81=constr81;
%
% constr82= BETA_BP==BETA/BP_size;
% prob.Constraints.constr82=constr82;




%% Objective Function Components

%Revenues

Revenues=optimexpr(T);
RP_revenues=optimexpr(T);
RM_revenues=optimexpr(T);
RF_revenues=optimexpr(T);


for t=1:T


    RP_revenues(t)=sum(IOTA(:,t))*RP_rev;
    RM_revenues(t)=(sum(sum(BETA(:,:,t)))* RM_WH*RM_rev);
    RF_revenues(t)=(sum(sum(BETA(:,:,t)))* RF_WH*RF_rev);



end

Revenues=RP_revenues+RM_revenues+RF_revenues;

% Transportation Costs


FTC=optimexpr(T); %fixed transportation costs

for t=1:T
```

```
    FTC(t)=(fix_transp_cost/BP_transp)*
(sum(sum(X(:,:,t)))+sum(sum(BETA(:,:,t)))+sum(sum(OMEGA(:,:,t)))+
sum(IOTA(:,t))+
sum(sum(ALPHA(:,:,t)))+sum(sum(Z(:,:,t)))+sum(sum(Y(:,:,t)))+sum(sum(THETA(:,:,t
)))+sum(sum(W(:,:,t)))+sum(sum(GAMMA(:,:,t)))+sum(sum(DELTA(:,:,t)))+sum(sum(AMM
AG(:,:,t))));
end



VTC=optimexpr(T); % variable transportation costs
Emission=optimexpr(T);% emission of CO2/year in grams
for t=1:T

    VTC(t)=(var_transp_cost/BP_transp)*(
sum(sum(X(:,:,t).*DL_CH_DIST))+sum(sum(BETA(:,:,t).*WH_DL_DIST))+sum(sum(OMEGA(:
,:,t).*RM_WH_DIST))+sum(sum(ALPHA(:,:,t).*WH_RM_DIST))+sum(sum(Z(:,:,t).*CH_RM_D
IST))+sum(sum(Y(:,:,t).*CH_RP_DIST))+sum(sum(THETA(:,:,t).*CH_RC_DIST))+sum(sum(
W(:,:,t).*RM_RC_DIST))+sum(sum(GAMMA(:,:,t).*RM_RP_DIST))+sum(sum(DELTA(:,:,t).*
RP_RC_DIST))+sum(sum(AMMAG(:,:,t).*RP_RM_DIST)));
    Emission(t)=(ton_per_truck*co2/BP_transp)*(
sum(sum(X(:,:,t).*DL_CH_DIST))+sum(sum(BETA(:,:,t).*WH_DL_DIST))+sum(sum(OMEGA(:
,:,t).*RM_WH_DIST))+sum(sum(ALPHA(:,:,t).*WH_RM_DIST))+sum(sum(Z(:,:,t).*CH_RM_D
IST))+sum(sum(Y(:,:,t).*CH_RP_DIST))+sum(sum(THETA(:,:,t).*CH_RC_DIST))+sum(sum(
W(:,:,t).*RM_RC_DIST))+sum(sum(GAMMA(:,:,t).*RM_RP_DIST))+sum(sum(DELTA(:,:,t).*
RP_RC_DIST))+sum(sum(AMMAG(:,:,t).*RP_RM_DIST)));
end

emission_tot=optimexpr(1,1);
emission_tot=sum(Emission)/1000;% co2 in kg


RCTC=optimexpr(T);% transportation costs towards recycling plants


for t=1:T

    RCTC(t)= mean_wh*(CH_RC_BM* sum( THETA(:,:,t)*RC_cost_BM_transp) + CH_RC_BP*
sum( THETA(:,:,t)*RC_cost_BP_transp)+ sum( W(:,:,t)*RC_cost_BM_transp)+sum(
DELTA(:,:,t)*RC_cost_BM_transp));
end


TC=optimexpr(T);% trasportation costs
TC=FTC+VTC+RCTC;

% Recycling processing costs
RCPC=optimexpr(T);
for t=1:T

    RCPC(t)= mean_wh*(CH_RC_BM* sum( THETA(:,:,t)*RC_cost_BM) + CH_RC_BP* sum(
THETA(:,:,t)*RC_cost_BP)+ sum( W(:,:,t)*RC_cost_BM)+sum(
DELTA(:,:,t)*RC_cost_BM));
end
```

```
% Establishing costs

Estab_cost=optimexpr(T);
Estab_cost_CH=optimexpr(T);
Estab_cost_WH=optimexpr(T);
Estab_cost_RM=optimexpr(T);
Estab_cost_RP=optimexpr(T);

if OP==1

     for t=1:T
         Estab_cost_CH(t)=sum(costfun_ch_A_estab_lin(CH_estab_cap(4:end,t))-
costfun_ch_A_estab_lin(0)*(1-CH_estab_year(4:end,t)));%V10
         Estab_cost_WH(t)= sum(costfun_wh_estab_lin(WH_estab_cap(:,t))-
costfun_wh_estab_lin(0)*(1-WH_estab_year(:,t)));
         Estab_cost_RM(t)=(1-
RM_RF_OUT)*sum(costfun_rm_A_estab_lin(RM_estab_cap(:,t))-
costfun_rm_A_estab_lin(0)*(1-RM_estab_year(:,t)));
         Estab_cost_RP(t)=(1-
RP_OUT)*sum(costfun_rp_A_estab_lin(RP_estab_cap(:,t))-
costfun_rp_A_estab_lin(0)*(1-RP_estab_year(:,t)));

     end

elseif OP==2

     for t=1:T

         Estab_cost_CH(t)=sum(costfun_ch_B_estab_lin(CH_estab_cap(4:end,t))-
costfun_ch_B_estab_lin(0)*(1-CH_estab_year(4:end,t)));%V10
         Estab_cost_WH(t)= sum(costfun_wh_estab_lin(WH_estab_cap(:,t))-
costfun_wh_estab_lin(0)*(1-WH_estab_year(:,t)));
         Estab_cost_RM(t)=(1-
RM_RF_OUT)*sum(costfun_rm_B_estab_lin(RM_estab_cap(:,t))-
costfun_rm_B_estab_lin(0)*(1-RM_estab_year(:,t)));
         Estab_cost_RP(t)=(1-
RP_OUT)*sum(costfun_rp_B_estab_lin(RP_estab_cap(:,t))-
costfun_rp_B_estab_lin(0)*(1-RP_estab_year(:,t)));

     end

end

Estab_cost=Estab_cost_CH+Estab_cost_WH+Estab_cost_RM+Estab_cost_RP;
```

```
% Expansion costs

Exp_cost=optimexpr(T);
Exp_cost_CH=optimexpr(T);
Exp_cost_WH=optimexpr(T);
Exp_cost_RM=optimexpr(T);
Exp_cost_RP=optimexpr(T);



if OP==1

    for t=1:T

    Exp_cost_CH(t)=sum(costfun_ch_A_renov_lin(0,CH_exp(:,t)));
    Exp_cost_WH(t)=sum(costfun_wh_renov_lin(0,WH_exp(:,t)));
    Exp_cost_RM(t)=(1-RM_RF_OUT)*sum(costfun_rm_A_renov_lin(0,RM_exp(:,t)));
    Exp_cost_RP(t)=(1-RP_OUT)*sum(costfun_rp_A_renov_lin(0,RP_exp(:,t)));



    end


elseif OP==2
    for t=1:T
         Exp_cost_CH(t)= sum(costfun_ch_B_renov_lin(0,CH_exp(:,t)));
         Exp_cost_WH(t)=sum(costfun_wh_renov_lin(0,WH_exp(:,t)));
         Exp_cost_RM(t)=(1-
RM_RF_OUT)*sum(costfun_rm_B_renov_lin(0,RM_exp(:,t)));
         Exp_cost_RP(t)=(1-RP_OUT)*sum(costfun_rp_B_renov_lin(0,RP_exp(:,t)));


    end
end
Exp_cost=Exp_cost_CH+Exp_cost_WH+Exp_cost_RM+Exp_cost_RP;

% Fixed Costs of company plants


Fix_cost=optimexpr(T);
Fix_cost_CH=optimexpr(T);
Fix_cost_WH=optimexpr(T);
Fix_cost_RM=optimexpr(T);
Fix_cost_RP=optimexpr(T);








if OP==1

    for t=1:T
```

```
        Fix_cost_CH(t)=sum(costfun_ch_A_fix_lin(CH_cap(:,t))-
costfun_ch_A_fix_lin(0)*(1-CH(:,t)));
        Fix_cost_WH(t)=sum(costfun_wh_fix_lin(WH_cap(:,t))-
costfun_wh_fix_lin(0)*(1-WH(:,t)));
        Fix_cost_RM(t)=(1-RM_RF_OUT)* sum(costfun_rm_A_fix_lin(RM_cap(:,t))-
costfun_rm_A_fix_lin(0)*(1-RM(:,t)));
        Fix_cost_RP(t)=(1-RP_OUT)*sum(costfun_rp_A_fix_lin(RP_cap(:,t))-
costfun_rp_A_fix_lin(0)*(1-RP(:,t)));



    end

elseif OP==2
     for t=1:T
        Fix_cost_CH(t)= sum(costfun_ch_B_fix_lin(CH_cap(:,t))-
costfun_ch_B_fix_lin(0)*(1-CH(:,t)));
        Fix_cost_WH(t)=sum(costfun_wh_fix_lin(WH_cap(:,t))-
costfun_wh_fix_lin(0)*(1-WH(:,t)));
        Fix_cost_RM(t)=(1-RM_RF_OUT)*sum(costfun_rm_B_fix_lin(RM_cap(:,t))-
costfun_rm_B_fix_lin(0)*(1-RM(:,t)));
        Fix_cost_RP(t)=(1-RP_OUT)*sum(costfun_rp_B_fix_lin(RP_cap(:,t))-
costfun_rp_B_fix_lin(0)*(1-RP(:,t)));



     end

end
Fix_cost=Fix_cost_CH+Fix_cost_WH+Fix_cost_RM+Fix_cost_RP;


% Variable costs

Var_cost=optimexpr(T);
Var_cost_CH=optimexpr(T);
Var_cost_WH=optimexpr(T);
Var_cost_RM=optimexpr(T);
Var_cost_RP=optimexpr(T);
Var_cost_warranty=optimexpr(T);


if OP==1
    for t=1:T

%     Var_cost(t)= sum(X(:,:,t),1)*costfun_ch_A_var_lin(CH_cap(:,t))+
(sum(BETA(:,:,t),2))' * costfun_wh_var_lin(WH_cap(:,t))+ (sum(OMEGA(:,:,t),2))'
* costfun_rm_A_var_lin(RM_cap(:,t))* (1-RM_RF_OUT)+
IOTA(:,t)'*costfun_rp_A_var_lin(RP_cap(:,t))*(1-RP_OUT)+
material_related_rm(sum(sum(ALPHA(:,:,t))))*(1-RM_RF_OUT)+
material_related_rp(sum(IOTA(:,t)))*(1-RP_OUT)+
warranty_cost_rm(RM_WH*sum(sum(BETA(:,:,t))))+warranty_cost_rp(sum(IOTA(:,t)));

        Var_cost_CH(t)=sum(costfun_ch_A_var_lin(sum(X(:,:,t),1))' -
costfun_ch_A_var_lin(0)*(1-CH(:,t)));
        Var_cost_WH(t)=sum(costfun_wh_var_lin(sum(BETA(:,:,t),2))-
costfun_wh_var_lin(0)*(1-WH(:,t)));
```

```
        Var_cost_RM(t)=sum(costfun_rm_A_var_lin(sum(OMEGA(:,:,t),2))-
costfun_rm_A_var_lin(0)*(1-RM(:,t)))* (1-
RM_RF_OUT)+material_related_rm(sum(sum(ALPHA(:,:,t))))*(1-RM_RF_OUT);
        Var_cost_RP(t)=sum(costfun_rp_A_var_lin(IOTA(:,t))-
costfun_rp_A_var_lin(0)*(1-RP(:,t)))*(1-RP_OUT)+
material_related_rp(sum(IOTA(:,t)))*(1-RP_OUT);

Var_cost_warranty(t)=warranty_cost_rm(RM_WH*sum(sum(BETA(:,:,t))))+warranty_cost
_rp(sum(IOTA(:,t)))+warranty_cost_rm(RF_WH*sum(sum(BETA(:,:,t))));



    end

elseif OP==2

    for t=1:T


%   Var_cost(t)= sum(X(:,:,t),1)*costfun_ch_B_var_lin(CH_cap(:,t))+
(sum(BETA(:,:,t),2))' * costfun_wh_var_lin(WH_cap(:,t))+ (sum(OMEGA(:,:,t),2))'
* costfun_rm_B_var_lin(RM_cap(:,t))* (1-RM_RF_OUT)+
IOTA(:,t)'*costfun_rp_B_var_lin(RP_cap(:,t))*(1-RP_OUT)+
material_related_rm(sum(sum(ALPHA(:,:,t))))*(1-RM_RF_OUT)+
material_related_rp(sum(IOTA(:,t)))*(1-RP_OUT)+
warranty_cost_rm(RM_WH*sum(sum(BETA(:,:,t))))+warranty_cost_rp(sum(IOTA(:,t)));
     Var_cost_CH(t)=sum(costfun_ch_B_var_lin(sum(X(:,:,t),1))'-
costfun_ch_B_var_lin(0)*(1-CH(:,t)));
        Var_cost_WH(t)=sum(costfun_wh_var_lin(sum(BETA(:,:,t),2))-
costfun_wh_var_lin(0)*(1-WH(:,t)));
        Var_cost_RM(t)=sum(costfun_rm_B_var_lin(sum(OMEGA(:,:,t),2))-
costfun_rm_B_var_lin(0)*(1-RM(:,t)))* (1-
RM_RF_OUT)+material_related_rm(sum(sum(ALPHA(:,:,t))))*(1-RM_RF_OUT);
        Var_cost_RP(t)=sum(costfun_rp_B_var_lin(IOTA(:,t))-
costfun_rp_B_var_lin(0)*(1-RP(:,t)))*(1-RP_OUT)+
material_related_rp(sum(IOTA(:,t)))*(1-RP_OUT);

Var_cost_warranty(t)=warranty_cost_rm(RM_WH*sum(sum(BETA(:,:,t))))+warranty_cost
_rp(sum(IOTA(:,t)))+warranty_cost_rm(RF_WH*sum(sum(BETA(:,:,t))));



    end
end

Var_cost=Var_cost_CH+Var_cost_WH+Var_cost_RM+Var_cost_RP+Var_cost_warranty;



%Outsourcing costs

Out_cost=optimexpr(T);
Out_cost_RM_RF=optimexpr(T);
Out_cost_RP=optimexpr(T);
```

```
if OP==1

    for t=1:T


Out_cost_RM_RF(t)=costfun_rf_A_price(RM_max_cap_out)*sum(sum(OMEGA(:,:,t)))*RM_R
F_OUT + costfun_rm_price(BM_cost_new)*sum(sum(ALPHA(:,:,t)))*RM_RF_OUT;
    Out_cost_RP(t)=costfun_rp_A_price(RP_max_cap_out,BM_cost_new) *
sum(IOTA(:,t))*RP_OUT;


    end

elseif OP==2


    for t=1:T

Out_cost_RM_RF(t)=costfun_rf_B_price(RM_max_cap_out)*sum(sum(OMEGA(:,:,t)))*RM_R
F_OUT + costfun_rm_price(BM_cost_new)*sum(sum(ALPHA(:,:,t)))*RM_RF_OUT;
    Out_cost_RP(t)=costfun_rp_B_price(RP_max_cap_out,BM_cost_new) *
sum(IOTA(:,t))*RP_OUT;



    end


end

Out_cost=Out_cost_RM_RF+Out_cost_RP;


%% NET CASH FLOW

NCF=optimexpr(T);
NCF=Revenues-TC-RCPC-Estab_cost-Exp_cost-Fix_cost-Var_cost-Out_cost;

NPV=optimexpr(T);
for t=1:T

    NPV(t)= (NCF(t))/((1+int_rate)^t) ;% residual value is zero; effect of
taxation within the interest rate, Modigliani formula
end



%% Objective function and solution
prob.Objective=sum(NPV);

[sol,fval,exitflag,output,lambda] = solve(prob);

%% Evaluation of useful indicators

NCF_eval=evaluate(NCF,sol);
Revenues_eval=evaluate(Revenues,sol);
TC_eval=evaluate(TC,sol);
```

```
RCPC_eval=evaluate(RCPC,sol);
Estab_cost_eval=evaluate(Estab_cost,sol);
Exp_cost_eval=evaluate(Exp_cost,sol);
Fix_cost_eval=evaluate(Fix_cost,sol);
Var_cost_eval=evaluate(Var_cost,sol);
Out_cost_eval=evaluate(Out_cost,sol);
NPV_eval=evaluate(NPV,sol);
Emission_tot_eval=evaluate(emission_tot,sol);


RP_rev_eval=evaluate(RP_revenues,sol);
RM_rev_eval=evaluate(RM_revenues,sol);
RF_rev_eval=evaluate(RF_revenues,sol);
FTC_eval=evaluate(FTC,sol);
VTC_eval=evaluate(VTC,sol);
RCTC_eval=evaluate(RCTC,sol);
RCPC_eval=evaluate(RCPC,sol);
Estab_cost_CH_eval=evaluate(Estab_cost_CH,sol);
Estab_cost_WH_eval=evaluate(Estab_cost_WH,sol);
Estab_cost_RM_eval=evaluate(Estab_cost_RM,sol);
Estab_cost_RP_eval=evaluate(Estab_cost_RP,sol);
Exp_cost_CH_eval=evaluate(Exp_cost_CH,sol);
Exp_cost_WH_eval=evaluate(Exp_cost_WH,sol);
Exp_cost_RM_eval=evaluate(Exp_cost_RM,sol);
Exp_cost_RP_eval=evaluate(Exp_cost_RP,sol);
Fix_cost_CH_eval=evaluate(Fix_cost_CH,sol);
Fix_cost_WH_eval=evaluate(Fix_cost_WH,sol);
Fix_cost_RM_eval=evaluate(Fix_cost_RM,sol);
Fix_cost_RP_eval=evaluate(Fix_cost_RP,sol);
Var_cost_CH_eval=evaluate(Var_cost_CH,sol);
Var_cost_WH_eval=evaluate(Var_cost_WH,sol);
Var_cost_RM_eval=evaluate(Var_cost_RM,sol);
Var_cost_RP_eval=evaluate(Var_cost_RP,sol);
Var_cost_warranty_eval=evaluate(Var_cost_warranty,sol);
Out_cost_RM_RF_eval=evaluate(Out_cost_RM_RF,sol);
Out_cost_RP_eval=evaluate(Out_cost_RP,sol);

RM_OUT_open=zeros(K,T);

    for k=1:K
        for t=1:T
            RM_OUT_open(k,t)=max(sol.Z(:,k,t)>0);
        end
    end


RP_OUT_open=zeros(M,T);


    for m=1:M
        for t=1:T
            RP_OUT_open(m,t)=max(sol.Y(:,m,t)>0);
        end
    end



%evaluate(NPV) for each year and calculate PBT
```

```
%PBT
NPV_eval_cum=zeros(T,1);
NPV_eval_cum(1)=NPV_eval(1);
for t=2:T
NPV_eval_cum(t)=NPV_eval(t)+NPV_eval_cum(t-1);
end

PBT=[];


   if fval>0
        PBT=find(NPV_eval_cum>0);
        PBT=min(PBT);
   elseif fval<=0
       PBT=13;

   end





%% Write to Excel

filename='CLSC_v10_update_constr_pack_cost_no_logistics.xlsx';
%filename= sprintf(filename_start,macro_scenario);
%save('clsc_SCEN_29_1.mat');

% formatSpec = 'clsc_SCEN_%d_%d.mat';
% str= sprintf(formatSpec,macro_scenario,scenario);
% save (str);





% extract a vector from matlab that is readible from a mapping tool>
% virtual desktop>geomapping.  Tabloo>maps
% compare NPV and Cash flows>int rate
% cf stratification (division btw opex,capex,revenues etc)
timeline=(1:12)';

FL_rec=table(FL);
OP_rec=table(OP);
RM_RF_OUT_rec=table(RM_RF_OUT);
RP_OUT_rec=table(RP_OUT);
PBT_rec=table(PBT);


int_rate_rec=table(int_rate);
BM_size_rec=table(BM_size);
BM_in_BP_rec=table(BM_in_BP);
mean_wh_rec=table(mean_wh);

BP_trip_rec=table(BP_trip);
BP_transp_rec=table(BP_transp);
```

```
CH_initial_rec=table(CH_initial);

Emission_tot_rec=table(Emission_tot_eval);writetable(Emission_tot_rec,filename,'
Sheet',macro_scenario,'Range','AG1');

Max_exp_rec=table(Max_exp);writetable(Max_exp_rec,filename,'Sheet',macro_scenari
o,'Range','N1');
Min_cap_rec=table(Min_cap);writetable(Min_cap_rec,filename,'Sheet',macro_scenari
o,'Range','O1');
Max_cap_rec=table(Max_cap);writetable(Max_cap_rec,filename,'Sheet',macro_scenari
o,'Range','P1');
RM_max_cap_out_rec=table(RM_max_cap_out);writetable(RM_max_cap_out_rec,filename,
'Sheet',macro_scenario,'Range','Q1');
RP_max_cap_out_rec=table(RP_max_cap_out);writetable(RP_max_cap_out_rec,filename,
'Sheet',macro_scenario,'Range','R1');

BP_price_new_rec=table(BP_price_new);writetable(BP_price_new_rec,filename,'Sheet
',macro_scenario,'Range','S1');
HF_Rem_rec=table(HF_Rem);writetable(HF_Rem_rec,filename,'Sheet',macro_scenario,'
Range','T1');
HF_Ref_rec=table(HF_Ref);writetable(HF_Ref_rec,filename,'Sheet',macro_scenario,'
Range','U1');
HF_Rep_rec=table(HF_Rep);writetable(HF_Rep_rec,filename,'Sheet',macro_scenario,'
Range','V1');
BM_cost_new_rec=table(BM_cost_new);writetable(BM_cost_new_rec,filename,'Sheet',m
acro_scenario,'Range','W1');

percentage_material_rp_rec=table(percentage_material_rp);writetable(percentage_m
aterial_rp_rec,filename,'Sheet',macro_scenario,'Range','X1');
percentage_material_rm_rec=table(percentage_material_rm);writetable(percentage_m
aterial_rm_rec,filename,'Sheet',macro_scenario,'Range','Y1');
percentage_R_D_rec=table(percentage_R_D);writetable(percentage_R_D_rec,filename,
'Sheet',macro_scenario,'Range','Z1');
percentage_G_A_rec=table(percentage_G_A);writetable(percentage_G_A_rec,filename,
'Sheet',macro_scenario,'Range','AA1');
percentage_insurance_rec=table(percentage_insurance);writetable(percentage_insur
ance_rec,filename,'Sheet',macro_scenario,'Range','AB1');
percentage_warranty_rec=table(percentage_warranty);writetable(percentage_warrant
y_rec,filename,'Sheet',macro_scenario,'Range','AC1');
fix_transp_cost_rec=table(fix_transp_cost);writetable(fix_transp_cost_rec,filena
me,'Sheet',macro_scenario,'Range','AD1');
var_transp_cost_rec=table(var_transp_cost);writetable(var_transp_cost_rec,filena
me,'Sheet',macro_scenario,'Range','AE1');

WH_param=
table(timeline,sol.WH',sol.WH_cap',sol.WH_exp');writetable(WH_param,filename,'Sh
eet',macro_scenario,'Range','A20:M32','WriteVariableNames',0);
CH_param=
table(timeline,sol.CH',sol.CH_cap',sol.CH_exp');writetable(CH_param,filename,'Sh
eet',macro_scenario,'Range','A38:P49','WriteVariableNames',0);
RM_param=
table(timeline,sol.RM',sol.RM_cap',sol.RM_exp',RM_OUT_open');writetable(RM_param
,filename,'Sheet',macro_scenario,'Range','A55:AC66','WriteVariableNames',0);
RP_param=
table(timeline,sol.RP',sol.RP_cap',sol.RP_exp',RP_OUT_open');writetable(RP_param
,filename,'Sheet',macro_scenario,'Range','A72:Q83','WriteVariableNames',0);

Cost_param1=table(timeline,NCF_eval,Revenues_eval,TC_eval,RCPC_eval,Estab_cost_e
val,Exp_cost_eval,Fix_cost_eval,Var_cost_eval,Out_cost_eval,NPV_eval,NPV_eval_cu
m);
```

```
Cost_param2=table(timeline,RP_rev_eval,RM_rev_eval,RF_rev_eval,FTC_eval,VTC_eval
,RCTC_eval,RCPC_eval,Estab_cost_CH_eval,Estab_cost_WH_eval,Estab_cost_RM_eval,Es
tab_cost_RP_eval,Exp_cost_RP_eval,Exp_cost_CH_eval,Exp_cost_WH_eval,Exp_cost_RM_
eval,Fix_cost_CH_eval,Fix_cost_RM_eval,Fix_cost_RP_eval,Var_cost_CH_eval,Var_cos
t_WH_eval,Var_cost_RM_eval,Var_cost_RP_eval,Var_cost_warranty_eval,Out_cost_RM_R
F_eval,Out_cost_RP_eval);

fval_rec=table(fval);
writetable(fval_rec,filename,'Sheet',macro_scenario,'Range','F1');



writetable(FL_rec,filename,'Sheet',macro_scenario,'Range','A1');
writetable(OP_rec,filename,'Sheet',macro_scenario,'Range','B1');
writetable(RM_RF_OUT_rec,filename,'Sheet',macro_scenario,'Range','C1');
writetable(RP_OUT_rec,filename,'Sheet',macro_scenario,'Range','D1');
writetable(PBT_rec,filename,'Sheet',macro_scenario,'Range','E1');
writetable(int_rate_rec,filename,'Sheet',macro_scenario,'Range','AF1');
writetable(BM_size_rec,filename,'Sheet',macro_scenario,'Range','G1');
writetable(BM_in_BP_rec,filename,'Sheet',macro_scenario,'Range','H1');
writetable(mean_wh_rec,filename,'Sheet',macro_scenario,'Range','I1');
writetable(BP_trip_rec,filename,'Sheet',macro_scenario,'Range','J1');
writetable(BP_transp_rec,filename,'Sheet',macro_scenario,'Range','K1');

writetable(CH_initial_rec,filename,'Sheet',macro_scenario,'Range','M1');

writetable(Cost_param1,filename,'Sheet',macro_scenario,'Range','A4:L16');
writetable(Cost_param2,filename,'Sheet',macro_scenario,'Range','N4:AM16');

X_flow=[];
for t=1:T

X_flow=[X_flow,sol.X(:,:,t)];
end

X_flow_rec=table(X_flow);writetable(X_flow_rec,filename,'Sheet',macro_scenario,'
Range','B90:BI100','WriteVariableNames',0);


Z_flow=[];
for t=1:T

Z_flow=[Z_flow,sol.Z(:,:,t)];
end

Z_flow_rec=table(Z_flow);
writetable(Z_flow_rec,filename,'Sheet',macro_scenario,'Range','B106:CG110','Writ
eVariableNames',0);

Y_flow=[];
for t=1:T

Y_flow=[Y_flow,sol.Y(:,:,t)];
end

Y_flow_rec=table(Y_flow);
writetable(Y_flow_rec,filename,'Sheet',macro_scenario,'Range','B116:AW120','Writ
eVariableNames',0);
```

```
THETA_flow=[];
for t=1:T

THETA_flow=[THETA_flow,sol.THETA(:,:,t)];
end

THETA_flow_rec=table(THETA_flow);
writetable(THETA_flow_rec,filename,'Sheet',macro_scenario,'Range','B126:AK130','
WriteVariableNames',0);


OMEGA_flow=[];
for t=1:T

OMEGA_flow=[OMEGA_flow,sol.OMEGA(:,:,t)];
end

OMEGA_flow_rec=table(OMEGA_flow);
writetable(OMEGA_flow_rec,filename,'Sheet',macro_scenario,'Range','B136:AW142','
WriteVariableNames',0);


ALPHA_flow=[];
for t=1:T

ALPHA_flow=[ALPHA_flow,sol.ALPHA(:,:,t)];
end

ALPHA_flow_rec=table(ALPHA_flow);
writetable(ALPHA_flow_rec,filename,'Sheet',macro_scenario,'Range','B148:CG151','
WriteVariableNames',0);


GAMMA_flow=[];
for t=1:T

GAMMA_flow=[GAMMA_flow,sol.GAMMA(:,:,t)];
end

GAMMA_flow_rec=table(GAMMA_flow);
writetable(GAMMA_flow_rec,filename,'Sheet',macro_scenario,'Range','B159:AW165','
WriteVariableNames',0);


W_flow=[];
for t=1:T

W_flow=[W_flow,sol.W(:,:,t)];
end

W_flow_rec=table(W_flow);
writetable(W_flow_rec,filename,'Sheet',macro_scenario,'Range','B173:AK179','Writ
eVariableNames',0);


BETA_flow=[];
for t=1:T
```

```
BETA_flow=[BETA_flow,sol.BETA(:,:,t)];
end

BETA_flow_rec=table(BETA_flow);
writetable(BETA_flow_rec,filename,'Sheet',macro_scenario,'Range','B188:EC191','W
riteVariableNames',0);


IOTA_flow=[];
for t=1:T

IOTA_flow=[IOTA_flow,sol.IOTA(:,t)];
end

IOTA_flow_rec=table(IOTA_flow);
writetable(IOTA_flow_rec,filename,'Sheet',macro_scenario,'Range','B198:M201','Wr
iteVariableNames',0);


DELTA_flow=[];
for t=1:T

DELTA_flow=[DELTA_flow,sol.DELTA(:,:,t)];
end

DELTA_flow_rec=table(DELTA_flow);
writetable(DELTA_flow_rec,filename,'Sheet',macro_scenario,'Range','B209:AK212','
WriteVariableNames',0);



end

end
```